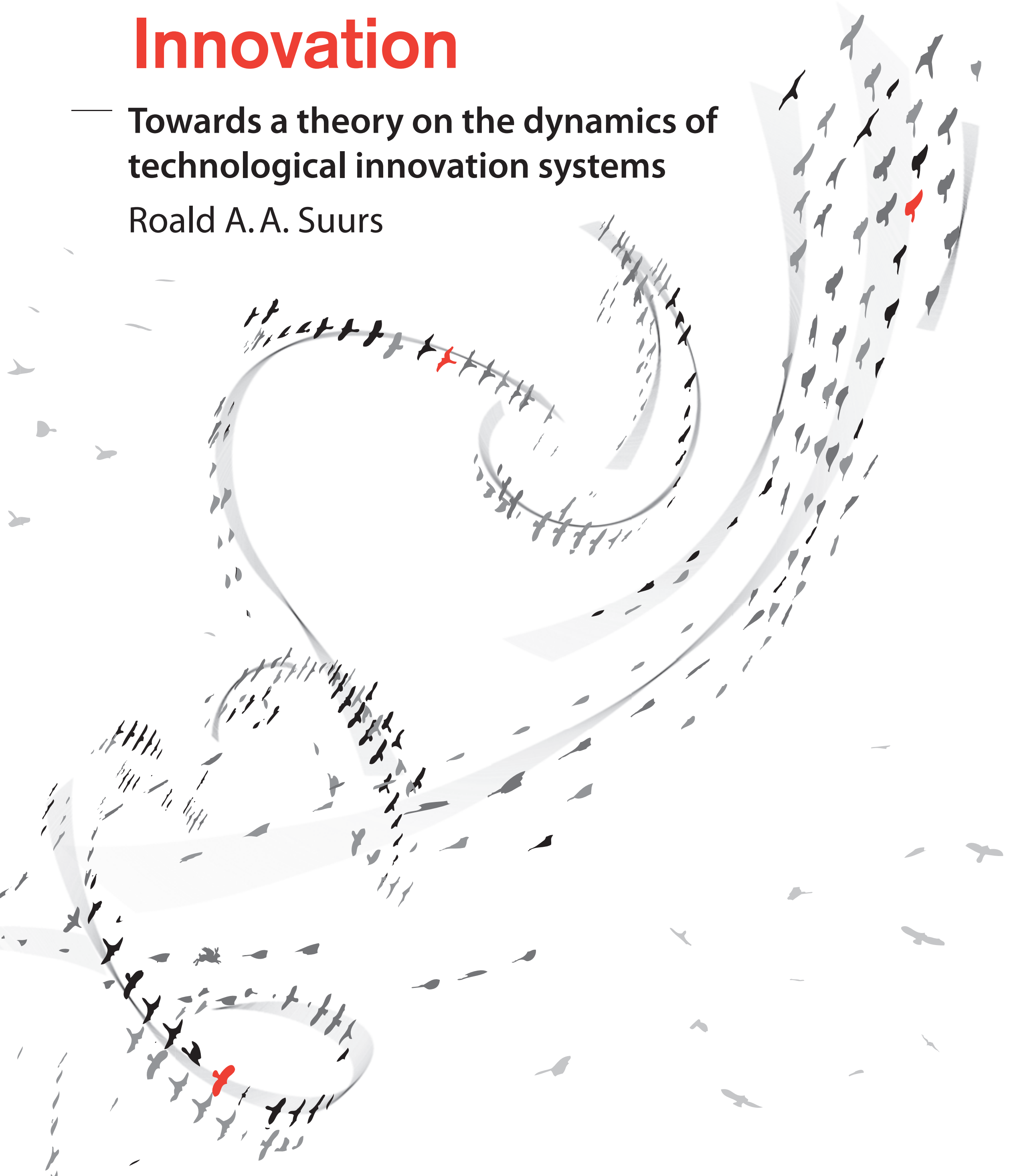
Motors of Sustainable Innovation

Towards a theory on the dynamics of technological innovation systems

Roald A. A. Suurs



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Dit proefschrift werd mede mogelijk gemaakt met financiële steun van de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

ISBN 978-90-6266-264-7

Grafische vormgeving en figuren:
Rien Rabbers en Ton Markus (GeoMedia, Faculty of Geosciences, Utrecht University)

Design cover:
CLEVER°FRANKE by Lude Franke, www.cleverfranke.com

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Motors of sustainable innovation

Towards a theory on the dynamics of technological innovation systems

Motoren van duurzame innovatie
Naar een theorie over de dynamiek
van technologische innovatiesystemen

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht
op gezag van de rector magnificus, prof.dr. J.C. Stoof,
ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen
op vrijdag 27 maart 2009 des middags te 2.30 uur

door

Roald Alphons Anton Suurs

geboren op 9 januari 1977 te 's-Hertogenbosch

Promotoren:

Prof. dr. M.P. Hekkert
Prof. dr.ir R.E.H.M. Smits
Prof. dr. S. Jacobsson

‘Panta rhei’
(*All things are in flux*)

Heraclitus (530-470 BC)

Preface

The work presented in this book was carried out within the framework of the Back Casting programme,[1] financed through NWO[2] and SenterNovem's Energy Research Programme. The Back Casting programme focuses on improving the 'back casting' method and on applying this method to the case(s) of sustainable energy technologies within the domain of automotive fuels.

Back casting can be seen as determining desired future images and describing pathways – i.e., technological trajectories – in order to realise these images. A back casting approach covers different future images and therefore different technological trajectories. With respect to sustainable energy technologies, these trajectories involve a fundamental restructuring of (parts of) our current energy system, involving numerous innovation processes, not just with respect to technologies but also to firms, governments, networks, laws, policies, visions and expectations.

This book provides theoretical insights that help identify the opportunities and bottlenecks related to such trajectories. It does this by developing a 'model of innovation' based on ideas from evolutionary economics and extensive research on historical technological trajectories. This Succession Model of Innovation focuses on the dynamics of emerging sustainable energy systems and thereby provides strategic insights of use to policy makers and other practitioners that aspire to understand and influence emerging sustainable energy technologies in this field.

Besides the work presented in this book, the Back Casting programme involved two other projects. While this project (B) focuses on the 'socio-technical' dynamics that may induce or hamper the successful unfolding of historical trajectories, another project (A) focuses on the technical design properties and the techno-economical features of possible trajectories of the future. A third project (C) aims to combine insights from both project A and B and to set up actual back casting scenarios.

The Back Casting programme was carried out at the Department of Innovation and Environmental Sciences (Project B and C) and at the Department of Science, Technology and Society (Project A). Both are part of the Copernicus Institute of Sustainable Development and Innovation at Utrecht University.

Roald Suurs

Utrecht, December 2008

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[1] The Back Casting programme started in 2003 and will close in 2009.

[2] The Netherlands Organisation for Scientific Research (NWO) funds thousands of top researchers at universities and institutes and steers the course of Dutch science by means of subsidies and research programmes (website: http://www.nwo.nl).

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1 Introduction

1.1 Background

Modern societies nowadays are encountering large problems in the sphere of energy production and distribution (IPCC, 2007; UNEP, 2007). Combustion of fossil fuels causes numerous environmental problems, such as air pollution, acidification and global warming. Moreover, the supply of energy from fossil fuels is limited and it depends for a large part on a small group of politically unstable countries. One possible way to deal with these problems is to develop technologies that tap into renewable energy sources. Examples are hydro, wind, solar photovoltaic and biomass energy. Assessment studies show that the technological and economic potential of wind energy, solar energy and biomass energy technologies on a global scale is enormous (Hoogwijk, 2004; Rogner, 2000; Turkenburg, 2000). In spite of their potential, however, the actual utilisation of these renewables is still marginal. In 2005, 6.2% of Total Primary Energy Supply (TPES) in OECD countries consisted of renewables (IEA, 2007a).[3] The other 94% was made up of oil (41%), gas (22%), coal (20%) and nuclear energy (11%). From 1973 to 2005 the share of renewables in TPES has increased by a meagre 1.7% points (from 4.5% to 6.7% of TPES) (IEA, 2007a).[4] More than 30 years of development in sustainable energy technologies has resulted in little more than a drop in the ocean compared with the dominance of fossil energy technologies. If sustainable energy technologies are to achieve dominance over fossil technologies within, say, a generation, this trend needs to be broken.[5]

This book is not so much about numbers but about what they represent. Underneath the trend of slowly diffusing renewables lies a world of companies, consumers, governments, scientists, even other technologies, all interrelated. This world has been well described by Unruh (2000) who provides an overview of the causes underlying what he calls carbon lock-in. Unruh explains how, over the past decades, an energy (and transport) system has evolved into an interlinked complex of actors, technologies and institutions. This complex continuously provides positive reinforcements – in the form of scale economies, accumulation of knowledge and technology, network externalities and habits – to the further development of carbon based energy technologies (Unruh, 2000).

These reinforcement mechanisms are so strong because they have benefited the growth of economies based on cheap and readily available carbon. This way, the ongoing dominance of

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[3] This figure is made up as follows: 2% hydro energy, 3.5 % combustible renewables (including waste) and 0.7 % geothermal, solar and wind energy (IEA, 2007a).

[4] Total TPES increased from 3762 Mtoe to 5546 Mtoe in this period (IEA, 2007a).

[5] For some sustainable energy technologies, growth rates have recently been impressively high. For example, global wind energy supply has increased by 22% per year in the period 1990-2001. In the same period, solar energy supply has increased by an annual 27% (Jacobsson and Bergek, 2004). But these growth rates conceal the fact that sustainable energy technologies grow from a very small base (IEA, 2007b). Even with a constant double-digit growth rate, it is expected to take decades for sustainable energy technologies to achieve dominance over incumbent energy technologies.

fossil energy use can be understood as a 'side-effect' of the technological systems that have so far been successful in driving forward all the powerful economies in the world (Elzen and Wieczorek, 2005; Freeman, 1996; Kemp and Soete, 1993; Unruh, 2000; Unruh, 2002).

Despite the environmental, political and economic problems to be faced in the near future, the incumbent energy system evolves in the direction that increases these problems. There is a severe misalignment between emerging sustainable energy technologies and the incumbent energy system. Existing markets do not account for the (current and future) costs of carbon-emitting energy technologies and/or for the potential benefits of emerging sustainable technologies. Even governments, which have the responsibility to protect the public good, often tend to exacerbate the problem, e.g. through carbon subsidies (Jacobsson and Lauber, 2006; Unruh, 2000).[6] In order for sustainable energy technologies to prosper, the forces of inertia that prevail in the incumbent energy system have to be broken, implying a reorganisation of the structures that lie at the basis of modern capitalist societies.

This poses a problem, but there is some reason for optimism in that, historically, large transitions are known to occur. In retrospect, several revolutionary developments can be distinguished that have transformed the energy system, or even society as a whole. These transitions were often characterised by the emergence of a new dominant energy source; for example the change-over from the traditional fuel of wood to coal in the nineteenth century and from coal to oil in the twentieth century (Grübler, 1998; Grübler et al., 1999; Unruh, 2000). They were driven by the rise of new conversion technologies (the steam engine), by new applications (the locomotive) and by shifting economic and institutional factors (long distance travelling). Most importantly, transitions are the (collective) result of efforts by individuals. This becomes, for example, especially clear from Hughes' account of Edison's involvement in the mass introduction of electricity in Manhattan in the nineteenth century (Hughes, 1983; Unruh, 2000).

The revolutionary transition from fuel wood to coal took a century (Grübler et al., 1999) but more recent transitions have occurred much faster. For example, the transition from a coal- and oil-dominated system to a natural-gas-dominated system for power generation in the Netherlands took less than a decade (Verbong and Geels, 2007). From an overview of historical transitions by Grübler et al. (1999) it becomes clear that transitions are characterised by a relatively long period of gestation, followed by a rapid take-off. In a take-off, the typical time span to establish an 80% points market share increase (in this overview a shift from 10% to 90% was chosen) is 10-50 years. Compare this with the 1.7% points increase in renewable energy sources in 30 years (from 4.5% to 6.7% of TPES) mentioned above and two things become clear: (i) a take-off has not yet happened and (ii) if such a take-off were to occur, a sustainable energy system could be realised within a generation.

Scholars have compared the shift to a sustainable energy system with historical transitions (Geels, 2002b; Kemp, 1994; Rip and Kemp, 1998; Rotmans, 2003). In this literature, a transition is considered to be a transformation process in which society changes in a fundamental way over one or more generations (Elzen and Wieczorek, 2005; Rotmans, 2003) and in which existing

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[6] On a more general note, the phenomenon of lock-in has been defined as a system failure (Klein Woolthuis et al., 2005; Smits and Den Hertog, 2006).

structures are broken down and new ones are established (Loorbach, 2007). Transitions involve a multitude of innovations, in multiple interrelated societal domains, involving not only technology but also economics, politics, culture, i.e., society at large (Elzen and Wieczorek, 2005; Rotmans, 2003).

The transition concept has been introduced in the field of sustainable development with the idea that, through understanding them, it will be possible to intervene in the course of transition processes (Loorbach, 2007). This book starts from the position that it is indeed possible and even desirable to develop this understanding and, based thereon, to conduct such strategic interventions.

1.2 Technological trajectories

The problem with transitions is that they involve massively complex processes developing over a long period of time, across a broad extent of societal structures and often extending over large geographical areas. Given the holistic nature of transitions it is tempting to take the full extent of this macroscopic process into account when seeking to develop transition theories. Indeed, a broad perspective is needed, but this can only be attained gradually through a solid understanding of the underlying processes, the micro and meso activities, that form the core of a possible sustainable energy transition. Based on historical observations it makes sense to consider technological innovations as being such core processes. This is not to neglect the fact that non-technological innovations are important, or indeed crucial. The focus is on technological innovations because transitions happen to develop around new technologies. After all, it is hard to imagine how a sustainable energy system could get off the ground without the rise of sustainable energy technologies.[7] Besides, technological innovations go together with social innovations.

Despite being more concrete phenomena than transitions, technological innovations are still complex processes, involving a multitude of technological and social factors. The literature on innovation studies stresses that technological innovation can be understood as the development of a set of interlinked technologies and institutions being shaped (and reshaped) through the activities of actors (Fagerberg and Verspagen, 2006). In the course of time, the outcomes of these activities result in an accumulation of structures.[8] With these structures in place, the innovation process typically gains more direction and speed (Jacobsson and Bergek, 2004). Once a technological innovation takes off, it is expected to replace or rearrange important structures that support incumbent technologies, thereby possibly establishing a contribution to a transition. In the case of sustainable innovation it may be one but it is likely to be a variety of sustainable technological innovations that are to be generated, diffused and utilised in society in order to

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[7] Our focus on technological innovation does not mean that a transition is primarily driven by technology. It should be regarded as an entrance point into a complex process related to technological as well as (other) social changes. In fact, as will become clear, my perspective on technological trajectories stresses, rather than downplays, so-called soft factors of innovation.

[8] As soon as technological and institutional structures are in position they form irreversibilities, thereby reducing the fluidity of an emerging technology (Van Merkerk and Van Lente, 2005).

contribute to a sustainable energy transition (Bergek et al., 2008b; Geels, 2008; Sandén and Azar, 2005).[9]

From a historical perspective, the development of a (sustainable) technological innovation as related to the build-up of structures, can be considered as a technological trajectory.[10] The course of technological trajectories can be influenced but to do so in a sensible way is far from trivial. The positive side is that sustainable energy technologies are only just emerging and, hence, they are relatively unstructured. Also, or because of this, they are only loosely coupled to incumbent structures. From the perspective of technology assessment, Collingridge (1980) suggests that intervention is potentially most effective when targeting technologies at the moment that they are just emerging. The downside is that emerging technologies are characterised by fundamental uncertainties (Meijer, 2008).[11]

This fundamental uncertainty leaves practitioners with a weak basis for strategic intervention.[12] A first problem is that the near future of an emerging technology cannot be assessed (Sandén and Karlström, 2005). To understand this, consider that the performance of a technological artefact is determined by the structures in which it is embedded. For example, the usefulness of a car is determined by the presence of roads and the access to a refuelling infrastructure. All of these technological structures are in turn embedded in institutional structures such as lease agreements, logistics and commuting patterns. For an emerging or 'fluid' technology, the alignment with its surrounding structures is by definition weak, hence its current performance is bound to be poor (Christensen, 1998).[13] In fact, the whole meaning of performance is unclear since the normative framework from which judgement derives is linked to the incumbent structures which are supposed to change in the future. A second problem is that, even if trust is placed in an emerging technology, then it is unclear how it should be supported.

So there is a situation that, on one hand, technological trajectories around sustainable energy technologies harbour the potential to contribute to a transition. But on the other hand, due to the uncertainty surrounding the technologies involved, there is hardly a basis for support.[14] Indeed, policy makers and other practitioners have been struggling to develop suitable support policies and strategies. Strategic insight is needed into how emerging sustainable energy technologies are shaped and how this process can be influenced (Coates et al., 2001).

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[9] The structuring effect of technological innovations, called path dependency (Arthur, 1989; Arthur, 1994), is similar to the notion of lock-in as described by Unruh (2000). However, lock-in refers to an undesirable static situation in which an incumbent technology has become so entrenched in structures that there is actually little room for innovation.

[10] The term 'technological trajectory' is not meant to refer the specific concept of Dosi (1982). I use the term loosely, referring to the general idea that technological innovation has a historical dimension.

[11] Fundamental uncertainty is not a function of knowledge; instead it should be conceived as the impossibility of any useful knowledge on future developments (Meijer, 2008).

[12] This uncertainty also opens up possibilities for aggressive strategies to capture early-mover advantages.

[13] They are typically expensive, maladapted to established infrastructure and unreliable; see Christensen (1998).

[14] The uncertainty is related to various aspects of technology development. Meijer (2008, p. 35) distinguishes between technological uncertainty, resource uncertainty, competitive uncertainty, supplier uncertainty, consumer uncertainty and political uncertainty.

The general objective of this book is to contribute to a theoretical understanding that allows for the analysis and evaluation of the dynamics of technological trajectories, focusing on emerging sustainable energy technologies contributing (or expected to contribute) to a sustainable energy transition.

In this book a number of studies are presented with the aim of establishing these insights. In line with historical transition studies, the approach taken is a historical one which aims to derive general lessons from past technological trajectories. These studies specifically aim to find out how the course of technological trajectories may be supported to induce dynamics that lead to a take-off.

1.3 Evolutionary economics

There are numerous theories that place technological innovation in a central position, but there is none which stresses its importance more than that of evolutionary economics. Moreover, evolutionary economists have occasionally even stressed the important role that innovation trajectories have to play in sustainable energy transitions (Freeman, 1996; Kemp and Soete, 1993).

1.3.1 Basics of evolutionary economics

It is important to realise that the approach of evolutionary economics forms a critique of the currently dominant neoclassical economics. This is important, since theories from neoclassical economics are generally not suitable to analyse the type of change processes that are central in this book, whereas the theory of evolutionary economics is actually very suitable. Why this is so will be explained according to four general features based on Boschma et al. (2002).

Innovation

The first feature is that innovation, or technological change, is central to the economy. This notion of innovation as a driving force is based on the work of Schumpeter (1942) who was one of the first to reject the idea of a static equilibrium: the classical idea that an economy behaves as a machine that, through pricing mechanisms, develops in the direction of a single equilibrium.[15] Against this belief in the equilibrating force of pure markets stands Schumpeter's idea of the heroic entrepreneur. The entrepreneur is a risk-taker who chooses to innovate in the face of fundamental uncertainty. If successful, the venture will establish a radical change as compared with existing products and services. The goal is to beat the competition by qualitatively changing products. On the level of the economy, multiple innovations harness the power to destroy incumbent structures and to induce the creation of new ones. This is underlined by Schumpeter

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[15] Schumpeter was not the first to stress disequilibrium. In 1890, Marshall actually also suggested that increasing returns are dominant and unopposed in most parts of the economy: '[W]e say broadly that while the part which nature plays in production shows a tendency to diminishing return, the part which man plays shows a tendency to increasing return. The law of increasing return may be worded thus: An increase of labour and capital leads generally to improved organization, which increases the efficiency of the work of labour and capital. (…)[I]n most of the more delicate branches of manufacturing, where the cost of raw material counts for little, and in most of the modern transport industries the law of increasing return acts almost unopposed.' (Marshall, 1890) (Book IV, Chapter XIII, p. 11-13). This idea never became widespread in neoclassical economic theory, despite the fact that Marshal was one of its founders.

who states that the process of innovation 'incessantly revolutionises the economic structure from within, incessantly destroying the old one, incessantly creating a new one' (Schumpeter, 1942) (p. 83).[16]

Heterogeneity

The economy is not entirely made of entrepreneurs. Evolutionary economists have developed an actor concept in which each actor has its own identity. This identity consists of knowledge, competences, interests, norms, values, etc. The heterogeneity of actors is crucial for understanding the creation of variety within an economy. After all, taking the risk of innovation would be senseless in an economy where all the actors have the same identity. In that situation, any innovation would be imitated within no time. No wonder that in mainstream economics, where actors are considered as uniform agents, innovation is actually not explained at all (Boschma et al., 2002).

Bounded rationality

With the idea that innovations constantly overthrow structures within an economy, the course of technological trajectories becomes fundamentally unpredictable. As a result, actors cannot decide on their course of action in a 'rational' way. Evolutionary economists suggest that actors, instead, make decisions according to routines, which should be considered as search heuristics which limit the possibility space for taking action (Dosi, 1982; Nelson and Winter, 1982; Simon, 1969).[17] Routines exist on the level of individuals (habits) but also on the level of firms and other organisations (institutions). Each actor has a unique position in the economy and is therefore subject to a different set of habits, or routines.

Path dependency

Routines and habits may be conceived as the memory of an economic system. The idea of a system memory points to the notion of path dependency introduced above. The path dependency of innovation points to the tendency of the innovation process to generate structures in the form of technologies themselves but also in the form of routines, or institutions. Once such structures are there, they tend to be maintained and all further development will be shaped according to those structures.

From this discussion it should be clear that evolutionary economics connects very well to the objective of this book. It focuses on change processes and it has conceptualised these processes in terms of technological trajectories. Also, and this is important to remark, evolutionary economists consider the economy in a broad sense, including technological and societal factors.

1.3.2 Evolutionary dynamics

In evolutionary economics, change is considered as unfolding according to a mechanism characterised, as in biology, by the interplay of three principles; variety, retention and selection.[18] Variety is created through innovation processes that arise in a population of heterogeneous actors.

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[16] Part II, Chapter VII.

[17] The notion of routines on a system level is related to the concept of a technological paradigm (Dosi, 1982).

[18] There are important differences between evolution in biology and evolution in society. For an overview and discussion of these differences, see Boschma et al. (2002).

Retention is maintained through the presence and inertia of routines, as well as technological and institutional structures. Finally, selection is conducted through a so-called selection environment. A distinction can be made between the internal and external environment.[19] The internal selection environment involves the selection (usually by firms) of technological options to be developed. The external selection environment may be considered as 'the market'.

It is important to understand that a market, in this sense, is not a predictable environment that is determined by pricing mechanisms and equilibrating forces of supply and demand.[20] The pricing mechanism is crucial, of course, but the structural conditions that shape prices will change. The evolutionary economics literature explains how innovation processes tend to undermine or reform these structures. This means that markets are considered to be in continuous turmoil, not equilibrium. Schumpeter refers to this phenomenon as the 'perennial gale of creative destruction' (Schumpeter, 1942) (p. 87).[21],[22] This idea makes a good starting point for developing an understanding of transition processes. After all, the notion of markets as being continuously (re)shaped, and indeed constituted by structures, corresponds to the logic of the lock-in idea presented above.

A part of the evolutionary economics literature, called industrial dynamics, focuses specifically on technological trajectories on the level of industries (Anderson and Tushman, 1990; Tushman and Anderson, 1986; Utterback, 1994).[23] To explain the nature of technological innovation and the development of markets, or selection environments, this literature studies populations of firms and their products. Based on historical cases, this has resulted in a model that describes how innovation and structural change processes unfold in patterns that are similar across industries and sectors. The most important result from these studies is that, as technologies develop, they tend to pass through typical stages of development. This Technology Life Cycle model shows that, on a system level, technologies can be regarded as organisms which come into being, grow up and

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[19] Compare this to Glynn, who states that '[A] distinction is made in the evolutionary economics literature between the internal and external selection environments [...]. Work on the internal selection environment of firms, examining the range of options that a firm tends to consider regarding technological development has been quite extensive [...]. However, the external selection environment, the environment outside of the firm in which their products have to compete for selection by users, is much less well understood.' (Glynn, 2002) (p. 936).

[20] Kemp and Soete define the concept of selection environment as follows: 'The selection environment consists of the following elements: (1) the nature of the benefits and costs that are weighed by the organizations that will decide to adopt or not to adopt a new innovation; (2) the manner in which consumer or regulatory preferences and rules influence what is 'profitable'; (3) the relationship between 'profit' and the expansion or contraction of particular organizations or units; and (4) the nature of the mechanisms by which one organization learns about the successful innovations of other organizations and the factors that facilitate or deter imitation.' (Kemp and Soete, 1993) (p. 445).

[21] Part II, Chapter VIII.

[22] Note that for some situations, especially short-term analysis, the static idea of a market in equilibrium may be a useful concept (Boschma et al., 2002).

[23] The industrial dynamics literature is a research discipline that 'concerns itself with the analysis of entry, exit and growth of firms, and the relationship between these phenomena and technological development. Industrial dynamics as considered in this way represents a key theme in evolutionary economics.' (Wenting, 2008) (p. 21).

Table 1.1 The three stages of the Technology Life Cycle.

Fluid stage	Transitional stage	Specific stage
Variety in design	Standardisation of design	Dominant design
Dozens of manufacturers	Shake-out among industries	Oligopoly
High rate of product innovation	Product innovation slows down	Product innovation slows down
Low rate of process innovation	Process innovation speeds up	Process innovation slows down
Misalignment of technology and structures	Convergence of technology and structures	Alignment of technology and structures and lock-in

Source: Utterback (1994) (p. 90-102).

eventually die. This idea is important as it connects well to the assumption that a transition will move from a stage of gestation into a take-off.

The three stages are characterised in terms of product design, entry/exit patterns, the rate of technological innovation, and organisational structure; see Table 1.1. An important insight from the literature on industrial dynamics is that, in an emerging technological field, there typically is not one single technology. Instead there exists a variety of competing designs. During the course of development, the technological field becomes more structured and a dominant design emerges.

Another important observation is that industries around emerging technologies are characterised by product innovations, i.e., the creation of new goods and services. As the technological field develops, the rate of product innovation goes down and makes room for an increased rate of process innovation, i.e., changes in the way a product is made. In general, product innovations involve qualitative change with respect to the use of a product whereas process innovations involve mostly cost reductions. Within the context of sustainable energy technologies, this is important as it means that mature technologies do not change very much and cannot be expected to contribute strongly to a sustainable energy system.[24]

What this literature also makes clear is that, in order for an emerging technology to develop, a selection environment needs to be shaped. If an emerging technology matures, this environment increasingly supports the technology and increases its performance. The downside is that the technology becomes more rigid and locked into its own environment. It will then gradually mature and be overthrown by the disrupting influence of a new emerging technology; see Figure 1.1.

1.3.3 Approaches to sustainable innovation

Clearly, evolutionary economics (and the related discipline of industrial dynamics) provides powerful concepts for studying emerging technologies and their role as a potential source of the disruption necessary for a transition to occur. So far I have not discussed the position of *sustainable* innovation in this literature. Also, the role of governments and other societal structures, to play a crucial part in a transition, has not been discussed. In fact, the issue of

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[24] An exception lies in the historical phenomenon that the development of mature technologies is often accelerated in response to the threat of better performing technological substitutes. This phenomenon is known as the 'sailing ship effect' (Rosenberg, 1976).

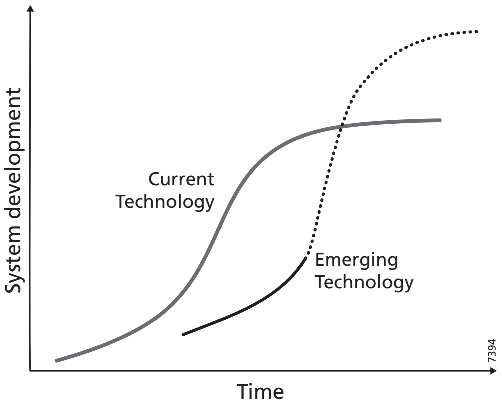

Figure 1.1 An emerging technology has the potential to overtake an incumbent technology.

sustainable innovation has not been central within evolutionary economics. Nevertheless there are two strands of literature, which have been developing in the last ten years or so, that provide an integrated perspective on sustainable innovation. This is the literature of quasi-evolutionary theory (QET) and the literature on (technological) innovation systems (TIS) (Markard and Truffer, 2008; Weber et al., 2006). Both literature strands employ the perspective of a societal system in which important structural problems arise that cannot be dealt with by market forces alone. Both strands have contributed to the literature on sustainable energy transitions by mobilising concepts from evolutionary economics.

Quasi-evolutionary theories

The conceptual framework to be developed in this book is based on the TIS literature but since the QET literature has so far contributed a considerable amount of ideas on transitions, I will first discuss the main features of this approach. The QET literature considers transitions as historical patterns unfolding from three system levels separately; the niche (micro), the regime (meso) and the landscape (macro) (Geels, 2002a; Geels, 2004; Rip and Kemp, 1998). The idea of this multi-level model is that transitions are driven by the interplay of dynamics arising from each level. For instance, one possible scenario is that shifting landscape factors (e.g. oil prices, climate change) put pressure on the regime, leading to its destabilisation (e.g. shifting politico-economic relations among powerful actors), with the result that selection pressure on niche-level experiments starts to change. Eventually, niche experiments may come to fill in larger parts of the regime, and, if niches are sufficiently supported, a full-scale transition may occur.

In the multi-level model, the regime is generally regarded as the main object of research; for sustainable energy transition, this would be the incumbent energy system. The macro level is a source of exogenous change which plays into the structures of the regime but is not (easily) influenced by it. The principal force of innovation is situated on the niche level. In line with Unruh (2000) and the industrial dynamics literature, the regime is generally hostile to niches. As Geels and Schot (2007) state: 'It is on the micro-level that radical novelties emerge. These novelties are initially unstable socio-technical configurations with low performance. Hence, niches act as "incubation rooms" protecting novelties against mainstream market selection […].' (Geels and Schot, 2007) (p. 400). QET studies have been prominent in the literature on transitions. Scholars have successfully provided insights in many historical cases and in long-term and large-scale development processes in general (Geels and Schot, 2007; Hoogma et al., 2002; Kemp, 1994; Raven, 2006; Verbong and Geels, 2007).

Niches have been studied separately as well in the literature on Strategic Niche Management (SNM) (Hoogma et al., 2002; Raven, 2005; Schot et al., 1994). In this literature, a conceptual framework has been developed that explains how niches are shaped and how they can be protected so they can develop in relative isolation from the regime. These studies typically focus on small networks of innovators around a single application context (Markard and Truffer, 2008). For understanding the development of sustainable energy technologies, the niche level is the most interesting part of the QET approach. It is on this level that sustainable innovations are bred. Moreover, whereas regime development remains a rather elusive matter, niche development has been conceptualised quite clearly as a dynamic process. These niche dynamics consist of: (i) learning, (ii) voicing expectations and (iii) network formation. The interplay of these processes is expected to shape the direction and outcome of niche development (Raven, 2006). However, most SNM studies have not been able to show how niches transcend their niche status. As Raven states in his thesis: 'Single experiments do not result in regime changes; they require a long trajectory of many experiments and the emergence and stabilisation of a niche level. Current SNM research pays too little attention to this process.' (Raven, 2005) (p. 45). The more recent SNM studies have began to tackle this issue by considering niches as broader entities that may expand and develop through multiple stages of development, from a local stage to a cosmopolitan stage. The idea is that, gradually, a niche will become more structured and develop into a regime (Raven, 2005).

Technological innovation systems

The second strand of research on sustainable innovation within evolutionary economics is the TIS literature. The TIS approach takes an intermediate stance to the QET approach as it incorporates a systems perspective, including societal factors, but not on the macro level. Instead, it derives from the idea that at the core of a transition process lies technological innovation. These technological innovations are supported by a TIS, which can be defined as:

'A dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology.' (Carlsson and Stankiewicz, 1991) (p. 93).

TIS studies analyse a technological field by referring to systemic features, including actors, institutions, (sometimes) technologies and most importantly, all the interrelations between them (Carlsson et al., 2002b). The TIS concept has been successfully applied to develop an understanding of innovation processes as related to societal structures such as governments, universities, NGOs, intermediary organisations and the like. A recent series of studies focuses especially on TISs around emerging sustainable innovations (Bergek, 2002; Hekkert et al., 2007; Jacobsson et al., 2004). This literature stresses that emerging technologies will pass through a so-called formative stage (compare this to the fluid and transitional stages of the technology life cycle) before they can be subjected to a market environment (Jacobsson and Bergek, 2004). During this formative stage actors are drawn in, networks are formed and institutions are designed and adjusted with the aim of increasingly aligning them to the emerging technology. A TIS approach may focus on these structures and their effects but it may also focus on the processes underlying the formation of the system (Jacobsson et al., 2004). Recently, studies focus more on such processes, by studying the interactions within a set of seven key activities or 'system functions'. It is expected that by mapping the fulfilment of system functions over time a better understanding of the formative stage will be developed.

Taking a stance

There are many similarities between TIS and QET approaches and especially between the concept of a TIS and the concept of a niche. For one thing, both approaches are based on insights from evolutionary economics and consider innovation processes as being at the heart of a transition. Both apply a holistic perspective including a variety of interrelated factors to explain the outcome(s) of these processes. And most importantly, the approaches both stress the importance of sustainable innovation to be understood as a build-up process.

But there are also points of difference.[25] A first point relates to the level of aggregation. A TIS analysis focuses on mesoscopic dynamics, whereas QET studies tend to focus either on macroscopic dynamics, or on microscopic dynamics. This is important since, for the purpose of this book, patterns need to be abstract enough for theoretical generalisations to be made and concrete enough for practitioners to connect to (Hekkert et al., 2007; Negro et al., 2007; Negro et al., 2008; Suurs and Hekkert, 2005; Suurs and Hekkert, 2008b). For example, Geels and Schot (2007) have found interesting macroscopic patterns. Although interesting from a theoretical perspective, the insights provided are not sufficient for the analysis and evaluation of technological systems by practitioners. Studies tend to be too aggregated and too long-term oriented to offer strategic value. On the other hand, the SNM literature tends to be too microscopic. Scholars have mainly addressed the fostering of technological experiments without explicitly relating these experiments (i.e. pilot projects and their direct environment) to the broader range of activities that shape the system around it.

A second point of difference is the 'growth model' that accounts for the type of dynamics involved and the possibility of a rapid take-off. Within QET studies a take-off is regarded as a regime shift. This regime shift is established through an accumulation of niches. This way an accelerating technological trajectory may be regarded as multiple niches that coagulate and then expand into a regime. The TIS approach starts from the perspective of a technological system, which can be considered to cover an intermediate level of analysis between a niche and a regime. In fact, depending on the maturity of the TIS it may cover just one niche (projects and related actors) or an entire regime. In this respect, the TIS concept involves a richer and more complete perspective on dynamics. On top of this, the most recent TIS studies have made a lot of progress, not only with conceptualisation but also with the systematic operationalisation and measurement of dynamics.

For these two reasons it is the TIS approach that will be developed further in the remainder of this book. However, it must be said that recently SNM studies and TIS studies seem to converge

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[25] It is beyond the scope of this book to discuss and compare in detail both literature strands. Moreover, this has already been done extensively by Markard and Truffer (2008).

towards a similar approach.[26] This makes explaining a choice for one or the other a difficult one. In a sense, the choice for either of these theoretical approaches is a matter of style and taste. After all, the drawbacks of both approaches are being worked on. Additional work, conceptual and empirical, will benefit a fruitful dialogue between both literature strands that has existed for some years now (Markard and Truffer, 2008). The superiority of one approach above the other has not (yet) been established and will certainly not be decided upon in this book.

1.4 Motors of sustainable innovation

The TIS approach is essentially a growth model based on the notion of cumulative causation (Jacobsson and Bergek, 2004; Myrdal, 1957). This makes the approach especially suitable for conceptualising the dynamics of system build-up. The meaning of cumulative causation is given in the following passage by Skott (1994) who cites from Myrdal's work on underdeveloped economies:

> 'At the heart of cumulative causation is a notion of instability. A social process, in Myrdal's words, will not normally move towards "a position which in some sense can be described as a state of equilibrium between forces" since "a change does not call forth countervailing changes but, instead, supporting changes, which move the system in the same direction as the first change but much further. Because of such circular causation a social process tends to become cumulative and often to gather speed at an accelerating rate." ' Myrdal (1957) quoted in Skott (1994) (p. 119).

The cumulative causation concept points to the possibility of a TIS massively accelerating its pace of development. This is exactly what can cause the rapid build-up that is needed to establish the diffusion of sustainable energy technology. Recent TIS studies have conceptualised this build-up process in terms of system functions, or key activities. These involve; *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search*, *Market Formation*, *Resource Mobilisation* and *Support from Advocacy Coalitions* (Hekkert et al., 2007; Negro, 2007).

An elaboration of these concepts and definitions will be given in the next chapter. For now, it suffices to say that system functions are likely to interact with each other (Bergek et al., 2008a), and as they do, a cumulative causation process may be set in motion that directs the TIS through its 'formative stage' into a 'take-off' stage (Jacobsson and Bergek, 2004). In the ideal case, the TIS will develop and expand its influence, thereby propelling the emerging sustainable technology towards a stage of market diffusion.

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[26] Weber et al. state: 'In principle, the niche-regime-landscape model could also be re-interpreted using a systems language. Regimes then reflect the rules that govern interactions in innovation systems, whereas the socio-technical landscape can easily be understood as system environment. Technological niches are equally an element that can be easily fitted within a systems framework, e.g. in the sense of innovation and/or policy networks where interaction and learning between developers, users, policy-makers and other stakeholders take place. However, while learning processes in niches are mainly a "bottom-up" process to embed new technologies in new emerging regime, socio-technical change can also be induced from different mechanisms, e.g. "top-down" by way of regulation or regime changes (like e.g. liberalisation of energy or water supply).' (Weber et al., 2006) (p. 7).

This brings me back to my main objective: to improve theoretical understanding of the dynamics of technological trajectories around emerging sustainable energy technologies. Based on this idea I can now formulate the three main contributions of this book to the literature:

- **Contribution 1:** The idea of analysing interactions between system functions is not new. Scholars such as Bergek, Jacobsson and Negro have studied the dynamics of TISs by mapping the fulfilment of system functions in time and by pointing out their interactions (Bergek, 2002; Jacobsson and Bergek, 2004; Negro et al., 2007; Negro et al., 2008). This proves that the approach is valid. However, so far, no attempt has been made to generalise such findings in order to establish a solid theoretical understanding of TIS dynamics. In the light of a possible transition theory, it is extremely important to do so because there is never just one TIS that needs support but there are many, all potentially contributing to a transition. Therefore I attempt to map TIS dynamics across a variety of TISs in order to come up with a typology of dynamics that hold in general. The assumption is that multiple forms of cumulative causation may occur. I will call these variations motors of innovation.

- **Contribution 2:** Motors of innovation cannot be regarded as independent of the structures of a TIS. On the contrary, motors of innovation emerge from a configuration of structural factors and in turn rearrange that configuration. There exists a mutual relation between the structure of a TIS and the system functions which are realised in it. So far this relation has not been conceptualised clearly. An important contribution of this book is to integrate structural and functional TIS concepts in such a way as to make it possible to study this mutual relation. This is especially important as intervention strategies can only be directed towards structures (Bergek et al., 2008a).

- **Contribution 3:** The difficulty with TISs in the formative stage is that there is little basis for evaluation by policy makers and other practitioners. By focusing on system functions, an evaluative approach is possible that is based on a critical assessment of processes that contribute to TIS build-up. The idea is to consider system functions as evaluation criteria. They serve as a heuristic framework for identifying strengths and weaknesses in the development of a TIS. This idea has been developed in earlier studies (Carlsson et al., 2002b; Hekkert et al., 2007; Jacobsson and Bergek, 2004; Negro, 2007) but I attempt to strengthen the approach by also taking into account the mechanisms and impacts of motors of innovation.[27] Evaluative insights will be based on the idea that, for a TIS to develop well, motors of innovation should be supported. Based on the analysis, it should be possible to develop intervention strategies aimed at strengthening the dynamics of different motors of innovation.

With the concepts of motors of sustainable innovation I attempt to establish a theoretical approach that explains the build-up, and eventual take-off of TISs around emerging sustainable energy technologies. Based on the intended three contributions the main research questions of this book are:

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[27] Sustainability itself, as an objective phenomenon, will not be part of the evaluation. The outcomes of technological innovations are so unpredictable in the formative stage of TIS development that any evaluations in terms of sustainability, desirability or feasibility are merely considered as intermediate outcomes of a broad historical process. Obviously, the features of sustainable energy technologies will influence TIS dynamics.

RQ1: Which motors of sustainable innovation can be identified within the domain of emerging sustainable energy technologies?

RQ2: Can the rise, retention (and decline) of motors of sustainable innovation be explained in terms of TIS structures (actors, institutions, technologies, networks) and external influences and to what extent do these motors, in their turn, impact on TIS structures?

RQ3: Based on the motors of sustainable innovation, as identified, how can TISs in the formative stage be evaluated?

1.5 Research design

In the remainder of this book I will answer the three research questions by studying the historical development of a variety of TISs. For each TIS, a set of motors of sustainable innovation will be identified, as well as a set of structural factors that is related to the motors. Based on these results, evaluative insights will be presented and discussed. The results from the case studies will then be compared and synthesised into a typology of motors. An overview of the research design is presented below.

1.5.1 Four case studies

I am looking for deep insights into what brings about progress during the formative stage of TIS development. Moreover, the analysis aims to study the development of contemporary sustainable energy technologies. For answering such questions connected to 'real life' situations, a case study approach is most sensible (Yin, 2003). My aim is to track the dynamics in the recent past by studying activities and interactions between activities. Therefore, a historical approach is most suitable.

Multiple cases need to be studied in order to establish a typology of motors. A disadvantage of case study research is that it is time consuming; within the duration of a book project, typically three to five cases are covered. This limitation implies that a generalisation across cases cannot be done on the basis of statistics. Instead generalisation should be done by comparing and arguing from the content of the cases (Abell, 1987), and by relating these results to theory.

To render an argumentative generalisation feasible, it is important to consider carefully the criteria for selecting cases to be studied. In this situation the main criterion for selecting cases is that they involve TISs around emerging sustainable energy technologies. Also, cases should cover a long enough time-span and include enough variety of activity, i.e. build-up processes. Apart from this, the cases should cover as much variety as possible in order to cover a variety of motors of innovation.

For practical reasons I chose primarily to consider (those parts of) TISs that are situated in the Netherlands. One TIS was situated in Sweden. Table 1.2 provides an overview of the four technological trajectories that form the core of this book.

1.5.2 Event history analysis

Each case study should result in the identification of structures and especially system functions within the TIS. For this, most TIS studies have so far relied on the analysis of documents and interviews. In this book I will take a more systematic approach by adopting (and adapting) the event history analysis as developed by Poole (2000) and Van de Ven (1990; 1999). This method and varieties thereof has earlier been applied by Negro, Suurs, Chappin and Boon (Boon, 2008; Chappin, 2008; Negro et al., 2007; Negro et al., 2008) and has proven to be a useful way to systematically analyse complex longitudinal data. The event history analysis is based on the process approach, a world view that conceives of change processes as sequences of events. Based on the process approach, TIS development will be approached as being a meaningful narrative with plots.

The event history analysis offers the possibility to operationalise and measure system functions by relating them to events, and the interaction between system functions can be measured by tracking sequences of events. These sequences are integrated into a meaningful narrative which can be used in multiple ways, as a basis for further analysis and evaluation. By employing this method each study will reveal particular motors of innovation. The method also allows for an analysis of structures that relate to these motors, either as underlying causes of change (drivers and barriers), or as targets of change (impact). Ideally, the four cases should deliver a variety of motors of innovation; this variety can then be exploited when constructing a typology (see below).

1.5.3 Multiple-case replication

Each case study will yield insights that hold for a particular TIS. In order to provide general insights on how such motors come about, it is necessary to combine results from multiple cases, thereby strengthening the results through a logic of replication (Yin, 2003). To come to an overview I will provide cross-case comparisons and derive differences and similarities. The overview should provide a basis for deriving motors of innovation that are not specific but are general mechanisms. Poole et al. (2000) (p. 43) refer to such mechanisms as 'common narrative forms', system level mechanisms that capture a broad variety of change processes. The main result of this synthesis will be a typology of motors of innovation that provides information on how system functions can develop within TISs in the formative stage. The typology will be used as a basis from which to develop evaluative insights on the build-up of sustainable energy TISs in the formative stage.

1.6 Book outline

The remainder of this book is structured as follows:

Chapter 2 provides a theoretical framework for analysing and evaluating structures and processes of Technological Innovation Systems. Particular attention is paid to the use of the change-oriented world view that lies at the basis of the process approach.

Chapter 3 builds on the ideas of the process approach by developing a method for the measurement of TIS dynamics in the form of an event history analysis. The core of this analysis is the construction of a narrative which is based on the recognition of patterns in event data.

Chapters 4 to 8 contain the four case studies presented in Table 1.2.

Chapter 4 presents the results of the Biomass Gasification (BG) case study. The BG case was conducted in close collaboration with Simona Negro. Research on the BG case involved the first real test of an event history analysis. The focus of this study is on identifying system functions and relating them to specific drivers and barriers within (and outside) the system.

Chapter 5 presents the results of the second case study, on the Dutch TIS around (liquid) BioFuels (BF). In this case study the event history analysis is developed further. A specific feature is the analysis of different technologies (1G and 2G) within a single TIS. The analysis is supported through a quantitative mapping of event data which accounts for the different technological options present.

Chapter 6 broadens the perspective on TIS dynamics by comparing the developments in the Dutch TIS with the Swedish TIS around liquid biofuels. This study was conducted in close collaboration with Karl Hillman from Chalmers University in Gothenburg, Sweden.

Chapter 7 presents the results of a case study on the Dutch TIS around Hydrogen and Fuel cell (HyF) technologies. This study centres much more than the other cases on the identification of structures that explain the rise of particular motors. Also, the analysis of the impact of motors of innovation on TIS structures is more explicitly developed in this case study.

Chapter 8 presents the results of a fourth case study on the Dutch TIS around 'Automotive' Natural Gas (ANG). This technology is a relatively mature one and therefore this case is an opportunity to identify motors of innovation that are particularly related to a take-off. Like the previous case study, the analysis involves a structural analysis as well as a functional analysis.

Chapter 9 and 10 should be considered as the quintessence of this book, as it is here that the main research questions will be answered.

Chapter 9 offers a synthesis of the results from all the separate case studies. Based on the various motors of innovation observed in the case studies, a typology of motors of sustainable innovation is constructed. Moreover, the motors will be related to the development of TIS structures and, based on this, evaluative insights and strategic recommendations will be formulated that are of relevance to practitioners.

Chapter 10 contains a conclusion and discussion of the main results of this book. The main outcomes from the synthesis chapter will be reiterated. The discussion will involve a reflection on theoretical and practical contributions as well as on the methodology developed. Finally, future research avenues will be indicated.

Table 1.2 A short introduction to the four case studies.

Case study 1: Biomass gasification

The biomass gasification TIS involves the production, diffusion and utilisation of biomass gasification, a technology that enables biomass to be converted to syngas, a mixture of CO and H_2. Syngas can be utilised in a gas turbine to produce power and heat. The conversion to syngas enables efficient, clean and flexible bio-energy production, at least that is the promise.

The biomass gasification trajectory was characterised by a build-up in the 1980s followed by a rapid decline in the 1990s. Recently, BG is once again considered as a crucial technology to play a key role in a sustainable energy system.

Case study 2: Liquid biofuels in the Netherlands and Sweden

The focus of the biofuels study is on the production, diffusion and utilisation of liquid biomass-based. Biofuels can be blended with petrol or diesel without large adaptations to vehicles or infrastructure. This means that most of the innovations involved, are about the production of biofuels. Various options exist, but, in general, two product types can be distinguished: first-generation (1G) and second- generation (2G) biofuels. The 1G biofuels are made from conventional agricultural crops, such as rape seed or sugar beet, to produce biodiesel or bioethanol. The 2G biofuels are made from woody biomass, mainly forestry materials. The 1G technologies are commercially available. For the production of 2G biofuels, advanced petro-chemical or biotechnological technologies are required that are relatively immature. The promise of biofuel technologies is that, given the right conditions, they can contribute to CO_2 reduction; moreover biofuels are a renewable energy source.

The TIS dynamics for the biofuels case are characterised by a conflict between advocates of 1G and 2G biofuels. An interesting feature of this case is the reframing over time of a technology as being sustainable or not. Biofuel technologies were studied for both the Netherlands and Sweden.

Case study 3: Hydrogen and fuel cell technologies

This case involves the development, diffusion and utilisation of fuel cells and the hydrogen storage and distribution infrastructure needed to support them. These technologies may be applied in power production or, as an electric power source, in the mobility domain. The technological trajectory involves interdependent innovations across the entire energy value chain – in the production, distribution and utilisation of energy. The utilisation of fuel cells is widely expected to result in high efficiency gains and large emission reductions. Moreover, the technology harbours the possibility to open up the automotive energy system with renewables other than biomass.

The extreme complexity of the HyF trajectory is matched by very high promises that have lasted over a long period of time. Dynamics involve multiple waves of activity, each connected to particular changes within the structure of the TIS.

Case study 4: Automotive natural gas

This case is about the production, diffusion and utilisation of natural gas for automotive purposes. The innovations involved in this trajectory involve mainly the supply-side, where the liquids-based refuelling infrastructure and the vehicle technology requires adjustment to gaseous fuels. In this sense this case differs from 1G and 2G biofuels where this is basically the other way around. Another difference is that the cost structure of automotive natural gas is rather attractive, in some circumstances even competitive with petrol and diesel. The technology offers advantages in the form of a reduced emission of CO_2 and especially of particle matter (PM). A drawback is that natural gas is not a renewable.

The dynamics related to this technological trajectory are characterised by an early build-up in the 1970s, followed by a breakdown in the 1980s and then, again, a build-up from 2000 to 2007.

Part I
Theory and Method

2 The theory of technological innovation systems

In this chapter I provide an outline of theoretical concepts to be used in the remainder of this book. The chapter is devoted to the TIS approach, starting out, in Section 2.1, by positioning the TIS approach within the broader literature of Innovation System (IS) studies. Against this background, Section 2.2 provides the building-blocks of the TIS approach as it may be applied to analyse structures. The analysis of processes in terms of system functions is covered in Section 2.3. I wrap up the chapter in Section 2.4 by discussing three major theoretical contributions of this book.

Parts of this chapter are based on Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S. and Smits, R.E.H.M., 2007. Functions of Innovation Systems: A new approach for analysing technological change. Technological Forecasting & Social Change, 74: 413-432.

2.1 The innovation systems approach

2.1.1 Background

The TIS approach is part of a wider theoretical school, called the Innovation Systems (IS) approach. The central idea behind the IS approach is that determinants of technological change are not (only) to be found in individual firms or in research institutes, but also in a broader societal structure in which firms, as well as knowledge institutes, are embedded (Carlsson and Stankiewicz, 1991; Freeman, 1987; Freeman, 1995; Lundvall, 1988; Lundvall, 1992). Since the 1980s, IS studies have pointed out the influence of such social structures on technological change, and indirectly on long-term economic growth, within nations, sectors or technological fields. This broad societal orientation has resulted in a somewhat diverse set of definitions. Some of the most used are listed below:

'The network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies.' Freeman (1987) (p. 1).

'The elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge … and are either located within or rooted inside the borders of a nation state.' Lundvall (1992) (p. 2).

'That set of distinct institutions which jointly and individually contributes to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process. As such it is a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts which define new technologies.' Metcalfe (1995) (p. 38).

‘The determinants of innovation processes; all important economic, social, political, organisational, institutional, and other factors that influence the development, diffusion, and use of innovations.’ Edquist (2004) (p. 182).

There is variety and ambiguity in the definitions used, but nevertheless IS studies share a common ground. First of all, there is an emphasis on innovation as a learning process (Lundvall, 1992) (p. 2). This means that technological change is not so much considered as a material development but more as a recombination of (often already existing) knowledge: the creation of new combinations, in the terms of Schumpeter (1934) (p. 66). This learning process hinges on the involvement of multiple actors that exchange knowledge (Lundvall, 1992), actors consisting of a variety of organisations, including businesses as well as governments and research institutes.

Secondly, as should be clear from the definitions, there is an emphasis on the role of institutions. The institutions can be regarded as the rules, regulations and routines that shape the possibility space of actors. By this, they are important drivers of and barriers to innovation. Note that the term ‘institution’ is used loosely in the literature (Edquist and Johnson, 1997). Sometimes scholars refer to organisations, as, for instance, in Freeman’s definition given above. In this book I will use the concept only to refer to social rules in their various forms.[28]

The IS definitions tend to stress the relations between actors and institutions. This relates to a third general feature: the notion of a system. The system perspective implies, among other things,[29] a holistic approach. Holism in IS studies means that the performance of an IS cannot be considered as a linear function of its elements. Instead, it is the product of numerous relations between its elements. In this sense, technological change is a complex outcome which is determined by its weakest element(s). Evaluative studies therefore typically point out the *relative* strengths and weaknesses of particular system structures, usually on the basis of national or sectoral comparisons.

A fourth general feature of IS studies is the widespread use of the IS concept as an intervention model to support innovation policies and strategies. Innovation has long been considered the result of a linear development, starting with basic research, followed by applied R&D, and ending with production and diffusion; see Godin (2006) for a discussion on this topic. The different stages of the linear model of innovation were considered as separate, both in terms of time and in terms of the actors and institutions involved. The IS literature, stemming from evolutionary economics (Kline and Rosenberg, 1986), rejects this model and, instead, stresses the importance of a continued interaction between numerous processes, with R&D, production and market formation all running in parallel and reinforcing each other through positive feedback mechanisms. If such feedbacks are neglected, whether by policy makers or entrepreneurs, this is likely to result in the failure of innovation processes across the system. This means the development of undesirable technologies or the absence of technological development altogether (Caniëls and Romijn, 2008; Klein Woolthuis et al., 2005; Kline and Rosenberg, 1986).

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[28] Section 2.2 provides a more elaborate account of institutions.

[29] An elaborate account on the systemic nature of the IS concept is provided by Carlsson et al. (Carlsson et al., 2002a; Carlsson et al., 2002b) and also by Edquist (2004).

Finally, the IS concept has been employed within the context of sustainable innovation in the energy sector (Freeman, 1996; Sagar and Holdren, 2002; Sagar and Zwaan, 2006). This is not all that surprising since the features mentioned so far connect very well to the holistic and long-term orientation that is necessary for supporting the take-off of sustainable energy technologies. In this respect it is important to mention that there is a strong preoccupation with dynamics in IS studies. Positive feedback loops are mentioned as important conditions for innovation processes to prosper. However, as will be discussed in the next section, most IS studies do not actually take dynamics into account when the theory is applied.

2.1.2 Multiple innovation systems approaches

So far the focus of this chapter has been on the general features of the IS approach, whereas, in fact, multiple IS approaches exist. Conceptually, the various approaches are comparable since the difference between them is largely a matter of geographical and/or techno-economical delineation, i.e., of system boundaries. On the other hand, each approach has its own research focus, and this brings with it a research tradition, including preferred methodologies and differences in the relative importance of explanatory variables. The oldest and most applied IS approach is the National Innovation Systems (NIS) approach (Lundvall, 1992). Here the unit of analysis is the nation state. The famous definition, by Lundvall (1992), of the NIS has already been given above. Note that it is the only definition to include a reference to the nation state as a system boundary. The main purpose of most NIS studies is to assess the innovative performance of a nation. NIS studies typically compare a variety of nations in order to explain why some are more successful in realising innovation and economic growth than others (Freeman, 1987; Lundvall, 1992; Nelson, 1993). The comparison usually focuses on the presence and nature of national actors and institutions such as research institutes, industry networks and political systems. The macro perspective of the NIS approach serves as a heuristic tool for policy analysis, but as a research framework its use is limited since it aggregates countless actors and institutions. The complexity of such a massive system, especially where interactions are concerned, is of dramatic proportions. As a result, most studies focus on (comparative) statics (Carlsson et al., 2002a; Carlsson et al., 2002b).

More recently, the Regional Innovation Systems (RIS) approach has been developed. The basic idea is similar to that of the NIS approach, except that, instead, the unit of analysis is a region (Cooke et al., 1997; Saxenian, 1994). The purpose of RIS studies is to assess the innovative performance of a region. A main contribution of RIS scholars is the observation that distance matters; that is, the geographical distance between actors has a significant effect on the region's innovative performance. RIS studies tend to be more micro-oriented, including analyses on the level of (networks of) firms and other organisations. This allows for a dynamic approach, and in fact, many RIS studies incorporate a historical dimension (Carlsson et al., 2002b). The NIS and RIS approaches typically do not take into account a detailed analysis of technological innovation processes.

The Sectoral Innovation Systems (SIS) approach (Breschi and Malerba, 1997; Malerba, 2002; Malerba, 2004) breaks with the geographical orientation and, instead, focuses on the level of the industrial sector. It explicitly takes (aggregated) firm data as a basis of empirical analysis. The structure of a SIS is considered to be shaped by rules that are implicitly present in the technology, the knowledge and the practices, that characterise a sector, for instance, the appropriability conditions or the cumulativeness of knowledge involved. This so-called technological regime (Dosi, 1982; Dosi, 1984), explains the differences in the innovative activities of industries across sectors (Malerba and Orsenigo, 1996). Since the technological regime is likely to change over time as an industry evolves, the analysis offers possibilities for a dynamic perspective, although usually well-defined industries or branches are taken as a point of departure, thereby limiting its perspective on dynamics (Carlsson et al., 2002a).[30]

2.1.3 Technological innovation systems

Finally, some authors focus on Technological Innovation Systems (TIS) (Carlsson and Jacobsson, 2004; Carlsson et al., 2002b; Carlsson and Stankiewicz, 1991; Jacobsson and Johnson, 2000).[31] Let us reiterate the TIS definition as defined by Carlsson and Stankiewicz:

'[A]dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology.' Carlsson and Stankiewicz (1991) (p. 93).

The principal starting point of a TIS analysis is not so much a geographical area or an industrial sector, but a technology or a technological field. The purpose of most TIS studies is to analyse and evaluate the development of a particular technological innovation in terms of the structures and processes that support (or hamper) it. In that sense, the approach can be regarded as a more micro oriented variety of the SIS concept. Indeed, a SIS may be regarded as a bundle of interrelated, and partially overlapping, TISs, each involving another set of core technologies (Hekkert et al., 2007; Markard and Truffer, 2008; Negro, 2007).

The TIS approach is characterised by all the general features mentioned above, but there are two features which set it apart from the other approaches. The first is that the TIS approach emphasises the role of economic competence, the ability to develop and exploit new business opportunities, as a crucial aspect of technological innovation. It stresses that stimulating knowledge flows is not sufficient to induce technological change and economic performance. There is a need to exploit this knowledge, to actively recombine knowledge in order to create new business opportunities. This aspect of the TIS approach stresses the importance of individuals as sources of innovation, something which has been lost in the more macro oriented IS approaches. In that sense it can be regarded as a reinstatement of Schumpeter's heroic entrepreneur (Schumpeter, 1934). The focus on entrepreneurial action complements the emphasis on knowledge flows, mentioned before, in important ways. As Carlsson and Stankiewicz put it:

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[30] In a sense, the SIS approach can be regarded as a criticism of the NIS concept. This becomes clear from a study by Malerba and Orsenigo (1996) (p. 47), who show that 'patterns of innovative activities differ systematically across technological classes, but are remarkably similar across countries for each technological class'. This suggests that differences across NISs are largely the result of differences in a nation's sectoral configuration.

[31] The terms used by different scholars to denote the concept vary. Carlsson and Stankiewicz (1991) actually speak of 'Technological Systems' (not to be confused with Hughes' concept of Large Technological Systems (Hughes, 1987)) and many Swedish scholars use the term 'Technology Specific Innovation Systems' (Bergek, 2002; Edquist, 2004; Jacobsson and Johnson, 2000).

‘[W]e bring into focus the problem of adoption and utilization of technology as contrasted with that of generating and distributing knowledge. If economic competence is a scarce and unequally distributed resource (as we believe it is), creating more knowledge within a nation or region may or may not result in improved economic performance.’ Carlsson and Stankiewicz (1991) (p. 112).

The second feature that distinguishes TIS studies from other approaches is a more serious focus on system dynamics. The focus on entrepreneurial action has encouraged TIS scholars to consider a TIS as something to be built up over time. This was already put forward by Carlsson and Stankiewicz:

‘[T]echnological Innovation Systems are defined in terms of knowledge/competence flows rather than flows of ordinary goods and services. They consist of dynamic knowledge and competence networks. In the presence of an entrepreneur and sufficient critical mass, such networks can be transformed into development blocks, i.e. synergistic clusters of firms and technologies within an industry or a group of industries.’ Carlsson and Stankiewicz (1991) (p. 111).

Since Carlsson and Stankiewicz introduced the concept of a TIS, an increasing number of scholars have started focusing on TIS dynamics (Bergek, 2002; Carlsson and Jacobsson, 1997; Hekkert et al., 2007; Jacobsson and Bergek, 2004; Jacobsson and Johnson, 2000; Negro et al., 2007; Negro et al., 2008; Rickne, 2000). Notions such as critical mass, momentum and cumulative causation play an important role in these studies. Also, these studies have increasingly paid attention to the question of how cumulative causation may be established. A clear example is Jacobsson and Bergek’s study on TIS dynamics around renewable energy technologies, in which an explicit distinction is made between the formative stage and the market expansion stage of a TIS (Jacobsson and Bergek, 2004). These scholars have focused on trajectories of TISs in which the formative stage is characterised by the fluidity of technology in the sense of an absence of technological and institutional structures to support it.

2.1.4 System boundaries

It should be clear by now that the TIS approach has a lot to offer with respect to the objective in this book, which is to adopt (and further develop) a theoretical framework for analysing and evaluating the dynamics of technological trajectories around emerging sustainable energy technologies. After all, the idea of TIS build-up connects with this aim very well. In addition, the examples provided above clearly illustrate that the TIS approach can be applied to emerging sustainable energy technologies. In the remainder of this chapter I will specify the ins and outs of the concept of TIS, including some aspects of deviation from the TIS literature, as it will be employed throughout this book. Before doing so I will specify the concept of TIS more precisely by tailoring it to the research issues of this book.[32]

What’s in, what’s out?

It is easy to say that a TIS consists of anything relevant for the development of a particular technology, as is suggested by Edquist (2004), but this delineation is rather impractical. After

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[32] The delineation of a TIS is a complex issue. This section provides an explanation of the approach taken in the studies of this book. For a more general discussion of this topic, see: Bergek et al. (2008a), Markard and Truffer (2008) and Carlsson et al. (2002a; 2002b).

all, if indirect influences are taken into account – such as policies and other technological infrastructures – the concept will effectively denote the universe and related matters. On the other hand it does not make sense to consider only direct influences either, for this would exclude many important factors, such as governments, intermediaries, financers, etc. A more pragmatic approach to system delineation is to tailor the TIS concept to the specific purpose of an analysis (Markard and Truffer, 2008). Delineation, in this sense, can be considered as a process in which the starting point is a particular set of core structures related to a particular (societal) problem. Subsequently, during the research, as understanding of the system increases, system boundaries can be broadened to incorporate indirect structures that seem to be important to understand this problem. Depending on the choices made, different sets of actors, networks and institutions will be incorporated (Bergek et al., 2008a; Markard and Truffer, 2008).

It is important to realise that as a system develops, delineation is likely to change as well. For instance, the early hydrogen fuel cells were developed for satellites and spaceships, whereas fuel cells for cars were developed much later. In understanding the development of the fuel cell, an early focus on the space industry would have to be complemented by a broader scope, including automotive firms and private consumers.

My approach is therefore circular. Only by iteratively confronting theoretical categories with empirical observations, and vice versa, is it possible to capture the complexity of TIS build-up and learn from this in theoretical terms. Setting system boundaries, in this sense, is a result of each individual study. Setting system boundaries in this way requires a methodology that is sensitive to the activities that take place within a technological field.

Note that the TIS concept, as considered here, refers to an analytical construct of the researcher which is not merely a heuristic model. If applied correctly, it should capture a part of reality that corresponds to the features of a societal (problem) field as identified by the researcher. Indeed system boundaries may also be determined by identifying interactions among a population of actors; the TIS is then defined in terms of the interactions within a group of actors. Such approaches are based on the assumption that system boundaries are 'out there'.

In its most realised form, the TIS, as a concept, will not only reside in the mind of the researcher but also (at least partially) in the mind(s) of the actors involved in it. If this is the case, the TIS may be considered as a social construct, a part of the consciousness of social reality. This view will be further discussed in Section 2.2.1.

Having said all this, it should nevertheless be stressed that the TIS concept is initially defined in loose terms, based on the choices of the researcher. These choices will be different for each individual study, but there are three that will be followed through in all the studies of this book; these are discussed below.

The TIS as related to the NIS

In the remainder of this book I will consider only TISs that are located within the borders of the Netherlands and Sweden. Obviously, a TIS typically stretches across national (and sectoral) borders. Technological development is, after all, an international process which involves industries from a variety of sectors. Nevertheless, there are a number of reasons for limiting a

TIS analysis to the domain of a nation state. First of all, there is Lundvall's famous argument that national institutions are important factors that shape innovation (Lundvall, 1992) (p. 3-5).[33] The effect of national institutions on innovativeness has been observed in many empirical studies that include single technologies (Hillman et al., 2008; Jacobsson and Bergek, 2004; Jacobsson et al., 2004; Kamp, 2002; Sandén and Jonasson, 2006). A convincing case is the story of the Danish versus the Dutch wind turbine development (Kamp, 2002). A second reason is that, in spite of international factors being important, innovation policies and strategies are still mostly being developed on the national level. A final reason for studying a TIS primarily within national borders is a methodological one. Studying the historical development of an international TIS would imply an explosion of the scale of analysis, meaning that only a macro-level analysis would be possible. With such an aggregated perspective the identification of dynamics becomes much more difficult.[34]

The formative stage

In the remainder of this book, only TISs in the formative stage will be considered. The most important reason for doing so is that the focus of all the studies within this book is to uncover dynamics that specifically characterise this stage. Another reason is more practical: there simply are not very many examples of sustainable energy TISs that are currently in a market-expansion stage, let alone ones that have been expanding for a long period of time. This choice of delineation implies that my research will foreground those structures and processes within a TIS that are central to its build-up. At the same time structures and processes which correspond to mature TISs will be backgrounded.

External factors

The focus of analysis will be on the identification of motors of innovation and their connection to factors internal to a TIS. However, external factors are important as well. They will be considered as a part of the analysis wherever they affect the dynamics of the TIS. Important external factors to be aware of are:

- Couplings with other nations or international developments. For example, the importation of technological knowledge or successful technological applications from other countries may affect the expectations of actors within the TIS. Another example would be the influence of activities by organisations such as the EU government and multinationals.

- Couplings with the incumbent energy system. For example, regulations designed to benefit fossil energy technologies may negatively affect the incentives of actors within the TIS. The other way around, actors within the TIS may persuade incumbents to support their activities. This would actually make these incumbents part of the TIS.

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[33] This idea actually conflicts with the empirical observations by Malerba and Orsenigo (1996), nevertheless, the argument remains convincing.

[34] There is also a practical problem involved, related to the method that will be used (Section 3). This method involves a narrative analysis based on qualitative data. The collection and interpretation of such data requires background knowledge of a researcher with respect to the nation(s) studied. The limited knowledge of languages and cultures will pre-empt the possibility of an individual researcher studying the international TIS in any detail.

- Couplings with other emergent TISs. For example, competing and/or complementing technologies may affect the relative advantage of the emerging technology developed within the TIS.

External factors cannot be studied systematically over time but they will be accounted for as much as possible. Within the analyses the relative influence of external factors as compared with internal factors will be assessed.

2.2 Structures of technological innovation systems

So far I have discussed the TIS approach in general terms, outlining its unit of analysis and highlighting a number of important explanatory elements. The most basic explanatory elements, the structural factors, have already been touched upon. Structural factors represent the static aspect of the TIS, meaning that they involve elements which are relatively stable over time.[35] In this book, three basic categories of structural factors will be distinguished; actors, institutions and technologies. Each category will be discussed below. The first two categories derive from the TIS definitions as given by Carlsson and Stankiewicz (1991) and Jacobsson and Johnson (2000).[36] The third category deviates from the literature as technological factors are usually not considered part of a TIS (more on this below). These, as well as some other deviations from the main TIS literature, are discussed below.

2.2.1 Actors

The actor category involves any organisation contributing (with its knowledge and competences) to the emerging technology in focus, either directly as a developer or adopter of technology, or indirectly as a regulator, financer, etc. It is the actors of a TIS that, through choices and actions, actually generate, diffuse and utilise technologies. The build-up of a TIS depends on the presence, the skills and the willingness of actors to take action.

The potential variety of relevant actors in a TIS is enormous, ranging from private actors to public actors, and from technology developers to technology adopters. The development of a TIS will depend on the interrelations between all these actors. For example, entrepreneurs are unlikely to start investing in their businesses if governments are unwilling to support them financially. Vice versa, governments have no clue where financial support is necessary if entrepreneurs do not provide them with the information and the arguments they need to legitimate their support. All of this is especially relevant within the context of sustainable innovation.

Despite recognition of the important role of actors, most TIS studies lack a concept that helps to explain why actors perform certain actions (or do not perform them). One way to approach

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[35] The fact that structural factors are relatively stable should not be taken to mean that they are not subject to change. On the contrary, in the formative stage, structures are expected to change. Nevertheless, their rate of change is slow and is only visible from a historical point of view. This will be explained in Section 2.4.

[36] Some scholars include 'networks' as a separate structural factor (Jacobsson and Johnson, 2000). I deviate from this by suggesting that a network is not a factor in itself but a combination of related factors. I conceptualise a network as a group of interrelated actors, embedded in institutions and technologies. The role of networks is of key importance and will be discussed in Section 2.2.4.

this problem is to elaborate on the idea of the prime mover. A prime mover is an actor that has the power and the will to set a TIS in motion all by itself (Jacobsson and Johnson, 2000). The prime mover concept does not, however, sufficiently explain actions taking place in a TIS; after all, it is impossible to know when an actor will become a prime mover. For this it is necessary to address the reasoning of actors. To be able to do this, I adopt the enactors-selectors perspective as developed by Garud and Ahlstrom (1997).[37]

According to this scheme, enactors are actors that are closely involved in the development of a particular technology and fundamentally dependent on its success, whereas selectors are actors that are engaged with that technology at a distance, for example, because they have access to multiple options and have the possibility to choose between those options. Enactors usually involve relatively small technology developers and industries dedicated to particular technologies, whereas selectors involve regulators, financers, users or large firms that are able to support a variety of technological options.

Enactors and selectors differ in how they frame (their) reality. Enactors tend to stick to specific technological solutions, keep an experience-based approach to knowledge development and emphasise benefits while de-emphasising costs. Selectors, on the other hand, take into account a broad set of technological options, and therefore tend to apply a comparative perspective, using an 'objective' approach to knowledge development and employing broad evaluation frames.

The enactors-selectors perspective is a socio-cognitive perspective based on the principle that, depending on their relative positions in a social system, in this case a TIS, actors will frame their world differently in terms of meaning and act accordingly. Note that this means that depending on the developments within the TIS, the roles of actors may change. An enactor may change into a selector and vice versa.

The main benefit of the enactors-selectors scheme is that it allows for the translation of a large variety of actor characteristics into a relatively simple scheme that provides a foothold for relating these characteristics to a disposition to act in a certain way. For example, the small size of a company, its position as a technology developer, its dependency on a single technological option would all point to its role as an enactor.

The scheme leaves many questions unanswered and is therefore only a slight improvement of the prime mover concept but it nevertheless provides a contribution to a better understanding of actor behaviour within the context of technological innovation systems.

It may be useful to mention that the socio-cognitive assumptions behind the enactors-selectors scheme is in line with the notion that a TIS is a social construct, a system which exists *because* it is perceived (at least partially) by the actors involved in it. It is primarily through actors' perceptions of themselves as being part of a community, of a TIS, that a group of actors gains the coherency that determines its identity as a system. After all, coherency emerges as the result of the mutual recognition among actors of being dependent on each other. The idea of actors being conscious of their positions within a TIS is important for understanding the build-up of a TIS. The more

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[37] See also Rip (2006) and Van Merkerk (2007).

actors perceive themselves as part of a TIS, the more the group they form will actually develop as a TIS.

The possibility exists that actors do not consider themselves as part of a TIS at all. In fact, a TIS may very well start out as a loose and fragmented structure. In that case, strictly speaking, it does not deserve to be called a system; the term should then be considered to refer to the analytical concept in the mind of the researcher. As a concept it may then still serve as a powerful heuristic tool to guide the analysis and evaluation of the formative TIS.

2.2.2 Institutions

Institutions, or institutional structures, are at the core of the innovation system concept (Edquist and Johnson, 1997). It is common to consider institutions as 'the rules of the game in a society, or, more formally, (…) the humanly devised constraints that shape human interaction' (North, 1990) (p. 3). A distinction can be made between formal institutions and informal institutions (North, 1990), with formal institutions being the rules that are codified and enforced by some authority, and informal institutions being more tacit and organically shaped by the collective interaction of actors. Informal institutions can be normative or cognitive. The normative rules are social norms and values with moral significance, whereas cognitive rules can be regarded as collective mind frames, or social paradigms (Scott, 2001) (p. 33-62).

Examples of formal institutions are government laws and policy decisions; firm directives or contracts also belong to this category. An example of a normative rule is the responsibility felt by a company to prevent or clean up waste. Examples of cognitive rules are search heuristics or problem-solving routines; cf. Dosi (1982; 1984). They also involve dominant visions and expectations held by the actors within the TIS. The latter refers to what Van Lente calls a prospective structure (Van Lente, 1993; Van Lente and Rip, 1998), an arrangement of shared, future-oriented projections.

For a TIS in the formative stage, the institutional configuration is typically underdeveloped, meaning that few institutional rules, especially formal ones, are present, and those which are in place are maladapted to the emerging technology.[38] It is expected that cognitive rules are especially important in guiding the first steps of actors, especially enactors, in supporting an emerging technology. After all, visions and expectations are, in a sense, the sole reason for supporting an emerging technology. This relates to the concept of the risk-taking entrepreneur who, driven by a sense of opportunity, attempts to undermine incumbent structures by adjusting them or developing new ones.

In terms of intervention, institutional factors are of key importance, as they are usually the main target of government policies and often also of business strategies. After all, the presence, skills and willingness of enactors and selectors can only be affected indirectly, through the institutional structure of the TIS, that is, through support programmes, tax incentives, etc. Also, the nature of technological structure is outside the direct sphere of influence of many actors, particularly governments.

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[38] Formal institutions are typically the product of a long and cumbersome political process which involves a multitude of actors.

2.2.3 Technology

Technological factors consist of artefacts and the technological infrastructures – which are themselves artefacts as well – in which they are integrated. The techno-economic workings of such artefacts, including cost structures, safety, reliability, effects of up-scaling etc., are of crucial importance to understanding the progress of technological change. It also makes sense to consider less material aspects of technology, such as the knowledge embodied in it and the characteristics of the value chain that is made up by it. In the case of sustainable energy innovations, it is especially important to consider emission characteristics and other environmental externalities as well. After all, if a technology turns out to have negative environmental effects, a TIS may stop developing altogether, even if it has attracted a rich set of actors and developed the institutions to go with them.

The importance of technological features in explaining TIS development has been largely neglected by TIS scholars (positive exceptions are Markard and Truffer (2008) and Sandén and Jonasson (2005)).[39] This is understandable since the TIS approach has evolved from the NIS approach in which technological change was largely considered as an outcome of the system; a dependent variable (Edquist, 2004). Not considering technological features as part of the TIS implies that a crucial feedback mechanism – between technological change and institutional change – is neglected. For example, if R&D subsidy schemes supporting an emerging technology should result in improvements with regard to the safety and reliability of applications, this would pave the way for more elaborate support schemes, including practical demonstrations. These may in turn benefit technological improvements even more.

For the work presented in this book I initially decided to follow the tradition in the literature by not including technological factors as a separate focus. To nevertheless incorporate technological factors in the analysis I regarded them as existing within the TIS, not materially but in the form of knowledge, skills and actions related to the actors and institutions. This position was taken for the first two case studies (biomass gasification and biofuels). Carlsson et al. (2002a) (p. 12-14) take a comparable position by conceptualising technology as a design space characterised in terms of 'capabilities', 'know-how' and 'design languages'.

Later on, I decided to abandon this compromise and consider the realm of technology as something which is analytically independent of the actors and institutions that support it. The main reason is that, like institutions, technology enforces rules upon actors, it constrains and enables their actions. However, technological rules differ from institutional rules in the sense that they cannot be moulded according to the same logic. Even if they can be shaped, which is not always the case, this typically requires a different set of actions, to be executed by a different set of actors, than for institutional rules. This position was taken for the last two case studies. This was important because in these studies my second research question – related to the identification of structural conditions that drive cumulative causation – was more central than in the first two studies.

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[39] This observation is shared by Metcalfe (1995) (p. 34), who states that for the purpose of analysing 'technology policy', it makes sense to consider technology as being made up of three 'interrelated forms'; knowledge, skills and artefacts. He suggests that the IS concept concerns the knowledge structure, covering mainly knowledge and skills. For studying the material form of technology, another framework is needed, for example the design hierarchy concept; cf. Murmann and Frenken (2006).

It should be stressed that to distinguish between categories analytically does not mean that they exist separately. In fact, technology, institutions and actors cannot exist separately. There is no such thing as a technological artefact which is not related to the actors that use it. There are no actors which are not subject to any institutions. And there are no institutions which do not affect the material and economic domain of technology, and vice versa. Nevertheless these factors represent very different aspects of a TIS, and should therefore be studied separately as much as possible.

The fact that technological factors are considered as a separate world may seem to conflict with the idea that a TIS, in this sense, is still a socially constructed system. In my opinion this is misguided, the reason being that technological rules, as well as institutional rules, are considered as part of the TIS only in as much as they are perceived and acted upon by actors within the TIS.

2.2.4 Relationships and networks

Structural factors are merely elements, or building blocks. In an actual TIS, structural factors are intricately linked to each other. This section provides a conceptual overview of all possible relations.

Relationships

The possible relationships among structural factors are manifold (Markard and Truffer, 2008). They involve relations between actors, relations between institutions, and relations between technologies, but also between actors and institutions, actors and technologies, and technologies and institutions.

The actor-actor relationships involve relations of action, for example, transaction, collaboration, construction, projection, whereas the technology-technology and institution-institution relationship involves relations of design (Murmann and Frenken, 2006). To understand this, consider institutions and technologies as parts of a system of rules wherein each rule refers to other rules. The rules may contradict each other (misalignment) or reinforce each other (alignment) on particular issues. This way, institutions may benefit (or detriment) particular technological features, and vice versa. For example, a directive that aims for a ban on vehicle emissions benefits the use of zero-emission technology. Another example would be the effect of road infrastructure on the commuting patterns of users.

The actor-institution and actor-technology relationships are analogous. Both are characterised by a subject-object relation (Markard and Truffer, 2008). This is best explained by considering two differences with the actor-actor (subject-subject) relationship:

Firstly, the actor-actor relationship is characterised by a mutual autonomy in the sense that actors are usually not in the position directly to change, adjust or 'eliminate' each other at will; instead they have to 'work' through the system of institutional and technological rules in which they are embedded. In taking action, actors may deliberately change the architecture of rules and thereby (indirectly) affect the conditions for other actors to perform. The extent to which this is possible is determined by the actors' competences and by their position in the TIS.

Secondly, the actor-actor relationship is characterised by two-way interactions, whereas the actor-technology and actor-institution relationship is not truly interactive. The architecture of technological and institutional rules provides incentives for actors to perform certain actions and to avoid others but, in the end, the initiative to take action always lies on the actor side of the relationship. A similar argument is put forward by Markard and Truffer (2008).

Networks

In certain cases, the linkages within a particular group of actors, institutions and technologies will be stronger than the linkages with the outside of that group. If these structural factors form a dense configuration, they may be called a network structure, or a network.[40] An example would be a coalition of firms jointly working on the application of a fuel cell (technological rules), guided by a set of problem-solving routines and supported by a subsidy programme (institutional rules). Likewise, industry associations, research communities, policy networks, user-supplier relations etc. are all examples of networks; see Carlsson and Stankiewicz (1991) (p. 103) for a brief overview of the literature on industrial networks.

Network structures are crucial as forms of organisation that facilitate the exchange of knowledge and, based on this, an interactive process of learning. According to Carlsson and Stankiewicz:

'The fundamental uncertainty involved in innovation leads to a process of search, experimentation, and satisficing behaviour – in short, a learning process. The information requirements [of actors] are often unpredictable or unknown, and furthermore it may not be known whether the required information exists at all. […] There must be room for both positive and negative serendipity (unexpected discoveries) thus, the organisation surrounding the search for information has to be flexible. This is where the notion of networks enters in.' Carlsson and Stankiewicz (1991) (p. 103).

Networks enable a form of coordination that lies between the flexible indirectedness of markets and the controllable rigidness of a hierarchy (within firms, for instance) (Carlsson and Stankiewicz, 1991).[41] It also presumes a balance between trust and competition among dependent actors with possibly diverging interests. Keeping this balance is important in an environment where the development of an emerging technology depends on the recombination of knowledge, both conceptually and practically, from different 'worlds'.

Networks are of crucial importance for the development of a TIS.[42] As Carlsson and Stankiewicz put it: 'Such networks can be transformed into development blocks, i.e. synergistic clusters of firms

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[40] Many scholars have conceptualised networks as being structural elements. I chose not to use the term 'elements' since it suggests that networks exist on the same ontological level as actors and institutions, whereas clearly they do not.

[41] According to Carlsson and Stankiewicz: 'Networks are an intermediate form of organisation between hierarchies (internal organisation within entities such as firms) and markets. Their essential function is the exchange of information. Other resources may be transferred as well, but the more commodity-like the physical resources being transferred are, the more efficient is the market mechanism. When the important resource transfer involves complex information (or know-how), the market does not function well, and other arrangements have to be made.' (Carlsson and Stankiewicz, 1991) (p. 103).

[42] See, for example, the work of Carlsson, Jacobsson, Bergek and, more recently, Negro (Carlsson et al., 2002a; Carlsson and Jacobsson, 1994; Carlsson and Jacobsson, 1997; Carlsson et al., 2002b; Jacobsson and Bergek, 2004; Negro, 2007).

and technologies within an industry or a group of industries' (Carlsson and Stankiewicz, 1991) (p. 111). The dynamics within a TIS arise from a combination of structural tensions (conflicts between actors, institutions and technologies) and synergies (complementarities) that are constituted by the various relationships within and between networks.

2.2.5 System configuration

On a higher level, all the structural factors combined may be considered to form one big network[43] that, provided that it is a more or less coherent whole, constitutes a system configuration. One may also speak of a seamless web (Hughes, 1987), however, the idea of a seamless web does not help the analyst very much. It will be more useful to apply a perspective that binds elements together and summarises them, in analytical terms, on the system level. This can be done by discerning five system components, or subsystems, that make up any TIS; the government structure, the supply-side structure, the demand-side structure, the knowledge structure and the intermediary structure (Alkemade et al., 2007; Smits and Kuhlmann, 2004; Van Alphen et al., 2008a); see Figure 2.1.

- The supply-side covers all structures involved in the production and supply of technological artefacts and technological knowledge. This typically includes industries but also research institutes. Examples of important institutions are search routines, quality standards but also widely shared visions of a future market.

- The demand-side relates to the use of technology. In terms of actors this includes end consumers but also firms and governments. An example of an institution operating within this subsystem could be a tax law stimulating the demand for a particular application of technology.

- The knowledge structure comprises all actors, institutions and technologies that support the other subsystems by generating, assessing, and transferring knowledge, for example universities and other organisations within the educational system.

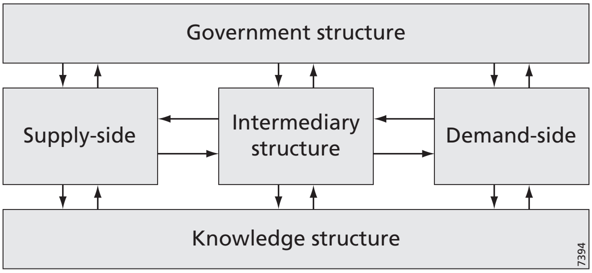

Figure 2.1 Five system components of a TIS.

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[43] This follows from the definition of Carlsson and Stankiewicz, which refers to the TIS as a 'network of agents' (Carlsson and Stankiewicz, 1991) (p. 93).

- The governmental subsystem involves structural factors related to the policy domain. In terms of actors this involves ministries and other governmental organisations, but also provinces and municipalities. Examples of institutions are laws and regulations issued by the government.

- Finally, the intermediary structure involves structural factors that support the relations and interactions between all the subsystems. In terms of actors, an example would be a knowledge broker or a standardisation institute. Examples of important institutions are policy programmes directed at stimulating collaborations, for example between researchers and firms or between governments and firms.

Note that each system component consists of a combination of particular actors, institutions and technologies; some may be part of more than one component. Moreover, it is expected that they contain networks. These are even more likely to stretch across system components.

The performance of the system configuration is determined by how well developed each of the components is and by the strength of the relations between components. A component is well developed if it contains a sufficient number and diversity of actors, institutions, technologies (and networks) that contribute to the diffusion and use of the emerging technology in focus (Alkemade et al., 2007). It is expected that an analysis of structures provides insights that shed a light on the propensity of a TIS to generate cumulative dynamics. A structural analysis typically results in the identification of drivers and barriers, both on the level of individual structural factors (firm strategies, institutions, technological features) and on the level of system components. An example of a structural barrier would be a poorly developed intermediary structure (system level) or the poor reliability of a technological application (factor level).

Obviously a TIS is characterised by a large set of drivers and barriers. Interventions are to be designed to overcome structural barriers and, where possible, to reinforce structural drivers.[44] For a literature overview, and a typology, of structural drivers and barriers, see Klein Woolthuis et al. (2005).[45]

2.3 Dynamics of technological innovation systems

A TIS approach can uncover structures and processes that determine the shaping of an emerging technology (Jacobsson et al., 2004). Since the purpose of this book is to analyse TIS dynamics, the focus will be on processes, or system functions.

2.3.1 Functions of innovation systems

A structural TIS analysis yields insight into systemic features – complementarities and conflicts – that constitute drivers and barriers for technology diffusion at a certain moment or within a given

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[44] The system failure approach to evaluating TISs is biased towards identifying and removing bottlenecks, or barriers. By taking a more dynamic perspective on the system failure problem, drivers will be put in a much more central position. In fact, structural drivers in one part of the TIS will prove, in the long run, to be the key to removing weaknesses in another part.

[45] Jacobsson and Bergek refer to drivers and barriers as inducement and blocking mechanisms (Bergek et al., 2008a).

period in time. However, there are important shortcomings to a structural approach, especially when the purpose of the analysis is to provide insight into the build-up of a TIS.

Firstly, an analysis of structures does not incorporate the dynamics that underlie the build-up of structures (Carlsson et al., 2002b). In the formative stage of TIS development, institutions and actors are bound to come and go as the innovation process unfolds. A study of TIS build-up should conceive of structures as endogenous variables, i.e., as 'moving parts', not as exogenous variables or constants.

A second problem is the fact that structural configurations of TISs may differ across nations, sectors and technologies, whereas they might be comparable in terms of innovative performance (Bergek, 2002; Jacobsson et al., 2004). Therefore, a structural analysis does not easily yield generalisable results. Clearly, this is problematic, both from a theoretical and from a practical perspective.

Even more problematic is the fact that a structural analysis does not provide a clear indication of TIS performance. After all, whether a structural configuration 'works' can only be determined if its influence on the innovation process is taken into account (Bergek et al., 2008a). A TIS may then be evaluated in terms of technology diffusion rates or market shares, for example by comparing such output figures across nations, but in the formative stage output figures are typically lacking or, in any case, unreliable as a basis for evaluation (Jacobsson and Bergek, 2004).

These shortcomings are addressed by focusing on system functions *in addition* to structures. The idea behind the so-called Functions of Innovation System Approach is to consider, more seriously, the TIS, or any IS for that matter, as being a system with a purpose which is to be served through the fulfilment of a set of system functions. As Bergek puts it:

'Inherent in a systems view is a notion that all [structural factors] contribute to the 'goal' of the system or they would not be considered part of that system. The contribution of a [structural factor] or a set of [structural factors] to the goal is what is here called a function.' Bergek (2002) (p. 21).[46]

The prime goal of an IS is to induce innovation processes (Bergek, 2002; Edquist, 2004). All activities that contribute to the development, diffusion, and use of innovations are considered system functions (Bergek, 2002), or key activities, as Edquist prefers to call them (Edquist, 2004). Examples, to be discussed in detail below, are *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion* and *Market Formation*. The system functions are considered to be processes that are necessary for TIS build-up. Bergek even suggests, based on an extended analysis of the literature, that system functions are the key determinants of innovative performance, not just for TISs but for ISs in general (Bergek, 2002). System functions are system-level variables. Therefore they should be understood as types of activities, or sets of activities, that contribute to the overall innovation process of a system.[47]

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[46] Bergek uses the term 'system components' to refer to what I have called structural factors.

[47] Note that this does not follow from Bergek's definition given above, which suggests that any contribution is, in itself, a function. Nevertheless, from the work of Bergek, Edquist, Jacobsson and others, it follows that system

In this respect, it is important to mention that system functions can be fulfilled in various ways as they relate to a variety of activities, all related to the same purpose. With this conceptualisation it is also possible to consider negative contributions to system functions as part of the same categories. Obviously, these negative contributions imply a (partial) breakdown of the TIS.

There are two main reasons for adopting the *Functions of Innovation Systems Approach*. The most fundamental reason is that an analysis in terms of system functions allows for a focus on dynamics. A functional analysis consists of mapping activities within a TIS over time. In other words, it focuses on the *flows* within a system rather than on its *stocks* (see Section 2.4.2) As a TIS develops, the intensity and variety of activities is expected to change. Also, system functions are expected to interact with each other (Bergek, 2002; Edquist, 2004; Hekkert et al., 2007; Jacobsson and Bergek, 2004). For example, *Market Formation* may induce *Entrepreneurial Activities*, which in turn may affect *Knowledge Development*. Interdependencies between system functions may even result in positive feedback, thereby inducing a dynamic of cumulative causation.[48] This refers to the core objective of this book: to gain insight into the dynamics of technological trajectories. Indeed, if such dynamics of cumulative causation were understood better, this could point out how a TIS is to be directed through its formative stage into a stage of market expansion (Jacobsson and Bergek, 2004).

The second reason for adopting a functional perspective is that it points to a notion of performance that incorporates variables other than diffusion rates. Jacobsson and Bergek suggest that system functions provide an intermediate level of understanding between the level of structural factors and the level of 'total performance', for example technology diffusion or market share. In this sense, each key activity is to be considered a separate dimension of TIS performance (Jacobsson and Bergek, 2004). This way, system functions serve as a basis for comparing structurally different TISs in terms of performance, without falling prey to an overly simplistic and misplaced comparison of output figures.

In the remainder of this section, the *Functions of Innovation Systems Approach* will be presented in detail, covering the set of system functions, definitions and an elaborate account of the concept of cumulative causation. However, before elaborating, a historical overview is given which serves as a background to understand where the *Functions of Innovation Systems Approach*, including various lists of functions, comes from.

2.3.2 Functions in literature

In the earlier IS literature, the term function tends to be used loosely, sometimes in relation to the workings of particular institutions (Edquist and Johnson, 1997; Galli and Teubal, 1997), sometimes in relation to the system as a whole (Carlsson and Stankiewicz, 1991; Lundvall, 1992). Few works apply the idea of IS functioning to conceptualise and measure system dynamics. Nevertheless, the *Functions of Innovation Systems Approach* builds upon a large number of IS studies. This section provides a short overview of this tradition in the literature. This overview is based on Hekkert et al. (2007).

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functions are meant to denote categories rather than particulars (Bergek, 2002; Edquist, 2004; Jacobsson and Bergek, 2004).

[48] Bergek (2002) (p. 24) refers to the interactions between system functions as the 'internal dynamics' of a TIS.

The function most often referred to in 'traditional' IS studies is the activity of learning, or interactive learning. As stated above, this activity lies at the heart of any IS analysis (Lundvall, 1992) (p. 2). On the other hand, as was discussed within the context of Carlsson and Stankiewicz's notion of economic competence, the activity of learning is not a goal in itself. In order to understand IS dynamics better, learning activities should be related to a number of other activities in the system (Carlsson and Stankiewicz, 1991). On a more abstract level, Edquist and Johnson attempt to do just this (Edquist and Johnson, 1997). They mention three functions, all of which are related to the workings of institutions within an IS. As they put it, institutions (i) provide information, (ii) manage conflict and cooperation, and (iii) provide incentives for innovation. The first function relates to learning but the other two are clearly about other activities. It is also stated that the three activities all reduce the overall uncertainty within an IS. McKelvey (1997) also discerns three complementary functions of innovation systems: (i) generation of novelty leading to diversity, (ii) retention and transmission of information, and (iii) selection among alternatives. These three functions correspond with the basic principles of evolutionary economics discussed in Chapter 1.

The inclusion of various sets of activities suggests a more encompassing perspective on IS dynamics. However, in order to be useful for practitioners, the system functions need to be defined on a more concrete level. Galli and Teubal (1997) do so within the context of the analysis of the evolution and transition of NISs. They distinguish between hard and soft functions. Hard functions are: (i) R&D activities (public) and (ii) supply of scientific and technical services to third parties (business sector and public administration). Soft functions include: (i) diffusion of information, knowledge, and technology; (ii) policy making; (iii) design and implementation of institutions concerning patents, laws, standards, etc.; (iv) diffusion of scientific culture, and (v) professional coordination. Even though they state that it is important to make a distinction between structural factors and functions, the functions as provided here are a rather straightforward extrapolation of the structural components as presented above. It seems as if the reduced level of abstractness has compromised the idea of functions as system level variables (each of which can be fulfilled by a variety of structural factors within an IS).

This type of direct extrapolation from structural factors to system functions is also done by Liu and White (2001), who address what they call a fundamental weakness of NIS research, namely 'the lack of system-level explanatory factors'. They focus on the following five activities: (i) research (basic, development, engineering), (ii) implementation (manufacturing), (iii) end-use (customers of the product or process output), (iv) linkages (bringing together complementary knowledge), and (v) education.

The conceptualisation of functions as true system-level variables takes off with the work of Bergek (née Johnson) on various TISs in the Swedish renewable energy sector (Johnson and Jacobsson, 2001).[49] In her thesis, Bergek conducts a meta-analysis of IS literature with the specific goal of finding out whether there is a shared understanding of key activities that need to be present in any IS in order for it to develop positively (Bergek, 2002). Based on the analysis, she identifies eight functions:

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[49] Johnson is Bergek's maiden name.

1. Supply incentives for companies to engage in innovative work
2. Supply resources (capital and competence)
3. Guide the direction of search (influence the direction in which actors deploy resources)
4. Recognise the potential for growth (identifying technological possibilities and economic viability)
5. Facilitate the exchange of information and knowledge
6. Stimulate and/or create markets
7. Reduce social uncertainty (i.e., uncertainty about how others will act and react)
8. Counteract the resistance to change that may arise in society when an innovation is introduced (provide legitimacy for the innovation)

This set of system functions differs from the previous sets in important ways. Firstly, the activities are concrete enough to be of use for practical purposes, and yet they do not relate directly to structural factors. This way they provide a perspective on TIS dynamics, which takes seriously the assumption that system functions are likely to be fulfilled by a variety of actors, institutions and technologies. Also this list of system functions can be regarded as a checklist of key activities that need to be present in any TIS in order for it to develop positively. Indeed, they are formulated in an active sense, as prescriptive recommendations for practitioners, especially policy makers.

The work of Bergek in association with Jacobsson has provided a basis for numerous other studies to be conducted along similar lines (Bergek, 2002; Bergek et al., 2008a; Borrás, 2004; Carlsson and Jacobsson, 2004; Edquist, 2004; Hekkert et al., 2007; Hillman et al., 2008; Johnson, 2001; Negro, 2007; Negro et al., 2007; Negro et al., 2008; Rickne, 2000; Suurs and Hekkert, 2005; Suurs and Hekkert, 2008a; Suurs and Hekkert, 2008b; Van Alphen et al., 2008a; Van Alphen et al., 2008b). It is beyond the scope of this book to discuss this literature to its full extent. It should be noted, however, that various lists of system functions have been constructed as part of these studies. Even Bergek herself has developed multiple variants of her first list. This raises the question whether a set of system functions actually covers relevant processes and whether it is complete. A comparison of various lists shows that differences are mostly superficial and reside in the way that various activities are clustered. Nevertheless, knowledge of system functions is still provisional and will need to be adjusted as our insight grows (Edquist, 2004). Therefore the lists of system functions need to be confirmed (or rejected) by empirical evidence.

2.3.3 Seven system functions

This section provides the set of system functions employed in this book. The set is based on the work of Bergek and Jacobsson and has been specified during numerous discussions between researchers from Utrecht University and Chalmers University (Sweden) (Hekkert et al., 2007). More importantly, it has been subjected to empirical validation, for instance, in studies by Negro, Suurs, Alkemade and Van Alphen (Alkemade et al., 2007; Negro, 2007; Negro et al., 2007; Negro et al., 2008; Van Alphen et al., 2008a; Van Alphen et al., 2008b). All these studies supported the original assumption that the set of system functions as provided here corresponds well with the actual processes relevant in the field of sustainable innovation.

Function 1: Entrepreneurial Activities

Entrepreneurs are at the core of any TIS. The classic role of the entrepreneur is to translate knowledge into business opportunities, and eventually innovations. The entrepreneur does this by performing market-oriented experiments that establish change, both to the emerging technology and to the institutions that surround it. The *Entrepreneurial Activities* involve projects aimed to prove the usefulness of the emerging technology in a practical and/or commercial environment. Such projects typically take the form of experiments and demonstrations.

Entrepreneurial Activities are necessary to overcome the fundamental uncertainties associated with emerging technologies (Carlsson and Stankiewicz, 1991; Meijer, 2008). Such uncertainties reside not in a lack of information on particular features or events but in the impossibility of foreseeing all the consequences of actions within a complex environment. The typical misfit between the technology and the structures in which it is embedded makes the development of emerging technologies especially unpredictable but, through practical experimentation and adaptation, an emerging technology can gradually be shaped to fit its structural environment, and vice versa.

This process of convergence involves many other system functions – in fact it heavily depends on the other activities, especially *Guidance of the Search* – but *Entrepreneurial Activities* are expected to occur first. The importance of *Entrepreneurial Activities* was already discussed by Carlsson and Stankiewicz (1991) who stressed economic competences as a crucial factor in the development of an emerging technology. In fact, it can be argued that the presence of *Entrepreneurial Activities* is what distinguishes a TIS from an R&D system; cf. Markard and Truffer (2008). This also relates to Schumpeter's idea of the entrepreneur as the source of innovation and the driver of creative destruction.

An entrepreneur can be a new business entrant taking part in the shaping of a new market, or an incumbent company diversifying its business (and related R&D) strategy to shape or take advantage of new developments. However, entrepreneurs need not be private enterprises; they can be public actors as well, as long as their actions are directed at conducting market-oriented experiments with an emerging technology.

Function 2: Knowledge Development

The *Knowledge Development* function involves learning activities, mostly on the emerging technology, but also on markets, networks, users etc. There are various types of learning activities, the most important categories being learning-by-searching and learning-by-doing (Sagar and Zwaan, 2006). The former concerns R&D activities in basic science, whereas the latter involves learning activities in a practical context, for example in the form of laboratory experiments or adoption trials.

The *Knowledge Development* function is a prerequisite for the development of an emerging technology. It is existing knowledge which is to be recombined, by entrepreneurs, to form technological innovations. The importance of *Knowledge Development* as a basic factor was especially stressed by Lundvall, who goes so far to state that: 'The most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning' (Lundvall, 1992) (p. 1). In the literature on system functions, activities of learning have been mentioned by Galli and Teubal (1997), Johnson and Jacobsson (2001) and Liu and White (2001).

From an evolutionary perspective, the *Knowledge Development* function is associated with the creation of variety within a system (McKelvey, 1997). Within the context of TIS development this means that an increasing intensity of *Knowledge Development* implies an increasing number of options available within the system, in terms of technology and also in terms of its possible applications. This is why *Knowledge Development* in the forms discussed here has the tendency to generate variety, and thereby to cause fundamental uncertainty within the system to increase. Other system functions, especially *Guidance of the Search* in combination with *Entrepreneurial Activities*, serve to keep this variety in check.

The *Knowledge Development* function is typically fulfilled through universities or other research institutes, although contributions by entrepreneurs are also possible, especially where learning-by-doing is concerned.

Function 3: Knowledge Diffusion

The characteristic organisation structure of a TIS is that of the network (Carlsson and Stankiewicz, 1991). The primary function of networks is to facilitate the exchange of knowledge between all the actors involved in it. *Knowledge Diffusion* activities involve partnerships between actors, for example technology developers, but also meetings like workshops and conferences.

The important role of *Knowledge Diffusion* stems from Lundvall's notion of interactive learning as the *raison-d'être* of any IS. The IS approach stresses that innovation happens only where actors of different backgrounds interact. A special form of interactive learning is learning-by-using, which involves learning activities based on the experience of users of technological innovations, for example through user-producer interactions (Lundvall, 1988).

Knowledge Diffusion activities involve a broad variety of actors and networks. It is expected that actors within a community, for example technology developers, will exchange knowledge on a more frequent basis than actors from different communities. Nevertheless, for a TIS to prosper it is important that *Knowledge Diffusion* among heterogeneous actors occurs. Policy makers should communicate with technology developers and technology developers should communicate with scientists. Through such communication activities, a mutual understanding may evolve, which makes it more likely that institutions can gradually be adjusted to technologies and vice versa. Also, the expansion of the TIS depends on the inclusion of an increasing number of actors within networks.

Function 4: Guidance of the Search

The *Guidance of the Search* function refers to the activities within the TIS that shape the needs, requirements and expectations of actors with respect to their (further) support of the emerging technology. *Guidance of the Search* refers to individual choices related to the technology but it may also take the form of hard institutions, for example policy targets. It also refers to promises and expectations as expressed by various actors in the community; see the work of Bakker (2008) and Van Lente (1993; 1998).

Guidance of the Search can be positive or negative. A positive *Guidance of the Search* means a convergence of positive signals – expectations, promises, policy directives – in a particular direction of technology development. If negative, there will be a digression, or, even worse, a rejection of development altogether. This convergence is important since, usually, various technological options exist within an emerging technological field, all of which require investments in order to develop further. Since resources are usually limited, it is important that specific foci are chosen within a TIS. After all, without any focus there will be a dilution of resources, preventing all options from prospering. On the other hand, too much focus may result in the loss of variety. A healthy TIS will strike a balance between creating and reducing variety.

The *Guidance of the Search* affects not only actors within the TIS but also actors not yet part of the TIS. This means that *Guidance of the Search* is especially important as a determinant of new entries into the TIS.

When *Knowledge Development* is regarded as a source of technological variety, the *Guidance of the Search* function represents the selection process. Selection is not only important with respect to the allocation of resources, but also in terms of translating broad visions of sustainable development into more concrete manifestations of technological desirability and feasibility as connected to the emerging technology. Without a concrete sense of direction, the activities of *Knowledge Development*, *Knowledge Diffusion* and *Entrepreneurial Activities* are bound to lead nowhere.

The *Guidance of the Search* function can be fulfilled through industries or governments, either within or outside the context of a market. In fact, it is bound to be an interactive process which involves governments, technology producers, technology users and NGOs, all exchanging promises and expectations of the emerging technology. The state of technology and its fit to the existing institutional structure will influence this process.

Function 5: Market Formation

Emerging technologies cannot be expected to compete with incumbent technologies (Rosenberg, 1976). In order to stimulate innovation, it is usually necessary to create artificial (niche) markets. The *Market Formation* function involves activities that contribute to the creation of a demand for the emerging technology, for example by financially supporting the use of the emerging technology, or by taxing the use of competing technologies.

Market Formation is especially important in the field of sustainable energy technologies, since, in this case, there usually is a strong normative legitimation for the intervention in market dynamics. This is especially the case in the energy sector, where the external costs of fossil fuel-based technologies are often unaccounted for. A distinction can be made between commercial markets, which are small commercial domains in which an emerging technology is subject to unusual selection criteria, and ‘protected spaces’ or nursing markets, which involve non-commercial domains that are dependent on specific government measures (Jacobsson and Bergek, 2004; Levinthal, 1998). The idea of supporting an emerging technology by means of market support policies has been made central in the literature on Strategic Niche Management (Hoogma, 2000; Raven, 2005; Schot et al., 1994).

In the literature on evolutionary economics, markets are considered to be the ultimate selection environment of a technology. In that sense, *Market Formation* activities can be regarded as a very special type of *Guidance of the Search*. The important difference is that markets involve the inclusion of actual users that generate a positive demand for the emerging technology.

In regular economies, *Market Formation* is an activity which is taken up by firms, for example through a marketing campaign providing a temporary discount. Such campaigns are typically set up when a commercially viable product has been developed. In case of sustainable innovations, there is usually no commercial product except when the institutional framework is adjusted to account for external costs. Therefore, in this case, the system function is typically fulfilled by governments, through the setting up of formal institutions.

Function 6: Resource Mobilisation

Resource Mobilisation refers to the allocation of financial, material and human capital. The access to such capital factors is necessary for all TIS developments. Typical activities involved in this system function are investments and subsidies. They can also involve the deployment of generic infrastructures such as educational systems, large R&D facilities or refuelling infrastructures. In some cases, the mobilisation of natural resources, such as biomass, oil or natural gas is important as well.

The *Resource Mobilisation* function represents a basic economic variable. Its importance is obvious: an emerging technology cannot be supported in any way if there are no financial or natural means, or if there are no actors present with the right skills and competences (Carlsson and Stankiewicz, 1991).

Resource Mobilisation may be fulfilled by all kinds of actors, industries and governments alike. It is expected that, in more mature TISs, more private actors will contribute to this system function.

Function 7: Support from Advocacy Coalitions

The rise of an emerging technology often leads to resistance from actors with interests in the incumbent energy system. In order for a TIS to develop, other actors must counteract this inertia. This can be done by urging authorities to reorganise the institutional configuration of the TIS. The *Support from Advocacy Coalitions* function involves political lobbies and advice activities on behalf of interest groups.

This system function may be regarded as a special form of *Guidance of the Search*. After all, lobbies and advices are pleas in favour of particular technologies. The essential feature which sets this category apart is that advocacy coalitions do not have the power, like for example governments, to change formal institutions directly. Instead, they employ the power of persuasion. The notion of the advocacy coalition is based on the work of Sabatier, who introduced the idea within the context of political science (Sabatier, 1988; Sabatier, 1998). The concept stresses the idea that structural change within a system is the outcome of competing interest groups, each representing a separate system of values and ideas. The outcome is determined by political power.

This system function is most typically fulfilled by private actors such as NGOs or industries, usually organised in networks, but public actors may also contribute. This is, for instance, the case when regional governments urge national governments to adjust regulations, or when intermediary organisations, such as planning agencies, advise regional governments to develop support policies for the emerging technology. Note that in all these examples, actors convince other actors to take particular actions that they cannot conduct themselves. This is what distinguishes the activities from plain *Guidance of the Search* activities which involve actions that can be taken directly.

2.3.4 Functions and cumulative causation

System functions are expected to reinforce each other over time. Indeed, a positive interaction between system functions is considered necessary for TIS build-up to occur. According to Jacobsson and Bergek (2004), the fulfilment of system functions could result in a virtuous cycle, constituted by positive feedback loops. For example, the successful realisation of a research project, contributing to *Knowledge Development* [F2], may result in high expectations, contributing to *Guidance of the Search* [F4] among policy makers, which may, subsequently, trigger the start-up of a subsidy programme, contributing to *Resource Mobilisation* [F6], which induces even more research activities that contribute to *Knowledge Development* [F2], *Guidance of the Search* [F4], etc. Thus, interaction between system functions results in a positive feedback loop within the TIS; see Figure 2.2.

Note that positive feedback implies a reinforcement of causes. This does not necessary mean a build-up process. System functions may also reinforce each other 'downwards'. In that case a sequence may result in conflicting developments or a standstill within a TIS, or even in a vicious cycle. An example of a vicious cycle would be that research projects (*Knowledge Development*) deliver negative results, thereby reducing confidence in the emerging technology among policy makers and investors (*Guidance of the Search*). This could then lead them to stop financing the technology altogether (*Resource Mobilisation*) meaning that the chances of successful research in the future are reduced (*Knowledge Development*, *Guidance of the Search*, etc). In this example the vicious cycle has the same form as the virtuous cycle presented above: it is characterised by a positive feedback loop of the same sequence of system functions. The difference is that system functions now reinforce each other to form a downward spiral. With each step of the cycle, key activities are reduced and/or counteracted, implying a rapid breakdown of the system.

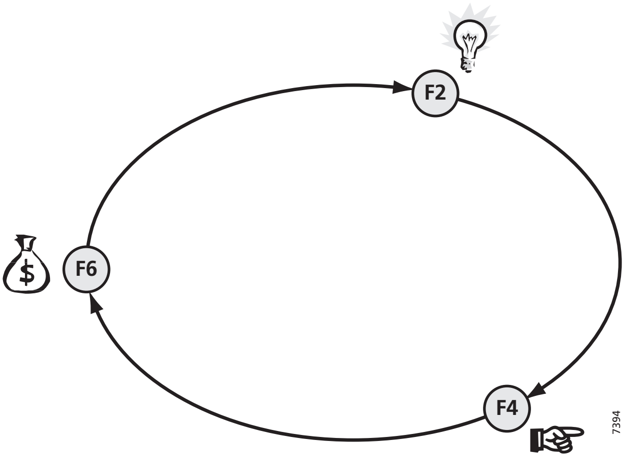

Figure 2.2 A positive feedback loop of system functions.

Negative feedback loops are conceivable as well. These involve homeostatic mechanisms that secure the stability of a system. For example, when a high demand for resources results in those resources becoming scarcer, this is translated into high prices; this in turn leads to a decreasing demand for those resources and lowering prices. The eventual effect is a stabilisation (or oscillation) of the structures that organise supply and demand, unless, of course, positive feedbacks disturb the system. Homeostatic cycles are expected to become dominant only after a technology has taken off. In the formative stage of a TIS, developments are expected to be determined by positive feedback loops that enforce virtuous or vicious cycles (Arthur, 1989; Arthur, 1994; Unruh, 2000).

This brings me to an important implication of Myrdal's concept of cumulative causation. Namely, that a dynamic of cumulative causation relates not merely to the activities within the cycle but also to the context in which the cycle arises (Myrdal, 1957; Skott, 1994). This means that the structural conditions from which a virtuous or vicious cycle emerges are affected by its dynamics. For TIS dynamics this means that with every turn of the cycle, the structural configuration – actors, institutions, technologies in the case of a TIS – will shift to reinforce the activities that constitute the cycle. For a virtuous cycle this would imply an accelerated build-up of TIS structures. Vice versa, the presence of a vicious cycle in a TIS would mean a rapid breakdown of TIS structures.

In order to develop an understanding of TIS build-up it is important to know under which conditions virtuous or vicious cycles occur. After all such dynamics point out a rationality that lies behind the occurrence of separate events. In this sense, it provides a system-level explanation of why a TIS is developing as it is.[50] Moreover, such dynamics have important implications for intervention strategies. An ambitious goal would be to shape a virtuous cycle and to support it, thereby inducing a dynamic so powerful that it will, eventually, undermine the incumbent TIS. This may be impossible to pull off as a single entrepreneur or even as a government. On the other hand, the concept suggests that once a cycle emerges, targeting any one of the activities involved in the cycle will affect all the others, thereby amplifying interventions throughout the TIS (Skott, 1994).

Note that the dynamics that unfold through cumulative causation, are primarily related to system functions, which are by definition internal to the TIS. However, the influence of external factors should not be neglected. This has been stressed by Myrdal who states that 'the main scientific task is (…) to analyse the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes' (Myrdal, 1957) (p. 18). In the extreme situation, TIS dynamics may be entirely coupled to 'outside pushes and pulls' abroad or in separate TISs. In that case a TIS could develop, but probably not according to an internal dynamic. In relation to this, it is important to understand that there is the possibility that a TIS does not develop any virtuous or vicious cycles.

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[50] It should be stressed that the occurrence of virtuous or vicious cycles does not imply that structural factors on the level of actors, institutions and technologies are not important as determinants of change. As will be discussed in detail, these are the subject of everything that happens on the system level. What the occurrence of a virtuous cycle does suggest is that there is a strong degree of coherence across important parts of the TIS configuration. In fact this is what makes cumulative causation possible.

2.4 Theoretical contributions

This book takes the position that a better understanding of virtuous and vicious cycles in TISs would contribute to the useful knowledge on emerging sustainable energy technologies. In this section I explain how a better understanding of these processes may be achieved. The section is structured according to the three main contributions presented in Chapter 1.

2.4.1 Motors of innovation

The idea of studying interactions between system functions is not new. Scholars such as Bergek, Jacobsson and Negro have studied the dynamics of TISs by focussing on identifying system functions and their interactions (Bergek, 2002; Jacobsson and Bergek, 2004; Negro, 2007). Moreover, they relate these to particular drivers and barriers internal and external to the TIS configuration. However, so far, no attempt has been made to generalise such findings in order to establish a more theoretical understanding of TIS dynamics. With respect to the energy transition challenge, it is extremely important to do so because there is never just one TIS which needs support; there are many. I attempt to map TIS dynamics across a variety of TISs in order to come up with insights that hold in general.

The assumption behind this objective is that multiple forms of cumulative causation may occur. So far only simple examples have been given but it is expected that in reality, more complex forms of cumulative causation exist, forms that involve more system functions and that may incorporate multiple feedback loops. Indeed, given that there are as many as seven system functions, and considering that there is no limit to the length of a cycle, they could be infinite. However, since not all sequences make equal sense, it is to be expected that there is a limit to the number of patterns that will occur historically. If this is indeed the case, then it makes sense to construct a typology of these forms of cumulative causation that may occur in a TIS in the formative stage.

On this account it is insightful to refer to the notion of a motor as employed by Poole et al. (2000) (p. 65-71). Based on a review of the literature on process theories, they present a typology of four fundamental explanations, each of which is based on a specific generative mechanism, or motor. Poole et al. (2000) suggest that all change processes can be explained by referring to one of the four motors, or a combination of them. These motors reside on all levels of organisational change; from the level of individual psychology to the development of a company, to the workings of an industrial infrastructure. An overview is given in Table 2.1. The motors are defined by Poole et al. (2000) on a meta-theoretical level which does not suit the purpose of this book. Nevertheless, I consider the idea of construing a typology of motors, based on generative mechanisms, useful for characterising TIS dynamics.

The main contribution of this book is to develop such generative mechanisms adapted to fit a TIS in the formative stage. These motors of sustainable innovation should help to explain TIS build-up around sustainable energy technologies. Obviously the motor concept needs to be specified to fit the context of a TIS, i.e., they are to be framed in terms of system functions. In order to construct motors, in the vein of Poole et al., it is important to employ a particular worldview, based on a so-called process approach (Poole et al., 2000) (p. 35-47). This worldview can be summarised according to the following fundamental assumptions:

- The world is made of entities that perpetually participate in events. These entities may change over time. With respect to the TIS, this means that structural factors are to be considered as subjects of change.

- A second assumption is that the world can be understood as a development process in which these events form one or more sequences. To understand a development process is to understand the logic of a sequence of events. This means that the development of system functions can be understood in terms of event sequences.

- The logic of event sequences is the logic of a narrative or a plot. Events that are part of a plot are not (only) related to each other by an efficient causality (the simple logic of mechanics or efficient causality) but (also) by final and formal causality. Final causality relates to the goal directedness of agents, whereas formal causality refers to the intangible forces that shape actions, like routines, regulations, markets and technologies. The narrative logic assumes that event sequences can be understood as a series of causal influences, sometimes operating at multiple levels, in time.

The process approach comes with a set of methodologies fit to derive theoretical insights from narratives. These methodologies recognise the complexity and variety of causal factors at play in development processes but nevertheless provide a basis for deriving general insights. As Poole et al. state:

'A defining feature of narratives is their inherent complexity. The events that comprise them are complicated. Narratives with the same 'plot' often differ considerably in specific sequences due to the particular conjunction of causes and contextual factors operating in specific cases [...].' Poole (2000) (p. 43).

Table 2.1 Generative mechanisms of change as recognised by Poole and colleagues.

Motors	Rationale/Generative mechanism
Life-cycle motor	A system progresses through a sequence of stages. The content of these stages is prescribed or regulated by an institutional, natural, or logical programme prefigured at the beginning of the cycle.
Teleological motor	A system progresses through a cycle of goal formulation, implementation, evaluation, and modification of actions or goals based on what was learned or intended by/ within the system. This sequence emerges through the purposeful enactment or social construction of an envisioned 'end state' among individuals within the system.
Dialectical motor	Within a system conflicts emerge between individuals or groups of individuals espousing two poles: a thesis and an anti-thesis. The conflict may result in a synthesis wherein opposite poles are resolved; this synthesis then in turn becomes a thesis as a new conflict emerges. A conflict may also result in stagnation or in the destruction of one pole of the conflict.
Evolutionary motor	The system is constituted by numerous individuals that compete for scarce resources. Development consists of shifts in the composition of the population as individuals experiment with more or less successful strategies for sustaining themselves over time. Success is determined by a selection environment.

Source: Poole et al. (2000).

‘The challenges for process researchers are to create theories versatile enough to discover common narrative forms and to elucidate generative mechanisms applicable to a broad range of complex and disparate cases that share a common developmental process.’ Poole (2000) (p. 43-44).

The main implication for the TIS analyses carried out in this book is that system functions do not represent variables in the traditional sense. Instead system functions are to be understood as categories of interpretation. In line with this, motors of innovation are to be understood as event sequences that correspond to a meaningful ‘plot’.[51] The process approach opens up a lot of possibilities for research on TIS dynamics. This will be further discussed in Chapter 3.

2.4.2 The relation between structure and function

The notion of cumulative causation points out that the dynamics of a TIS cannot be regarded independently of its structural features. Virtuous and vicious cycles emerge from a configuration of structural factors and, in turn, they rearrange that configuration. There exists a mutual relation between the structure of a TIS and the system functions which are realised in it. So far TIS studies have not extensively conceptualised and analysed this relation. An important contribution of this book is to integrate structural and functional TIS concepts in such a way as to make it possible to study this mutual relation.

All things are in flux

Structural factors have so far been put forward as the elements that actually make up the TIS at any given moment in time, whereas system functions have been presented as dynamic elements, the key activities that develop within the TIS over time. Intuitively, this distinction seems to work well enough, but it remains unclear as to how they relate precisely.

Earlier I have used the analogy of stocks and flows. In the language of system dynamics, stocks represent a pool of resources at a certain moment in time, whereas a flow is defined as a rate of change over time. According to this analogy, structures represent *states* of the TIS which are subject to change; system functions then represent this *change*. The system dynamics metaphor suggests that system functions and structures are not entirely separate things but, instead, are two sides of the same coin: a system always exists in time and its structural configuration is merely a snapshot of an ongoing change process.

This analogy is a crude one.[52] Yet, it serves to illustrate the idea that system functions, by definition, involve (changing) structures. Indeed, in a dynamic analysis it makes sense to adopt a worldview in which the world is not made of things but of processes, a reality which presumes that all things are always in flux. In this respect it makes sense to consider the actors, technologies

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[51] In this sense, the process approach is an alternative to the more familiar variance approach which regards the world as consisting of a set of independent variables. According to this view, processes can be explained in terms of independent variables without considering the time-ordering of these variables as an explanatory basis.

[52] The analogy does not work when considering the matter in detail. For one thing, stock variables consist of addable data, whereas a TIS structure is an amalgam of heterogeneous parts, all interrelated. Another problem is that a flow is defined as a ‘rate of change’ of a specific stock (for example, $/year as related to a yearly R&D budget), whereas a system function may very well relate to a range of structural factors.

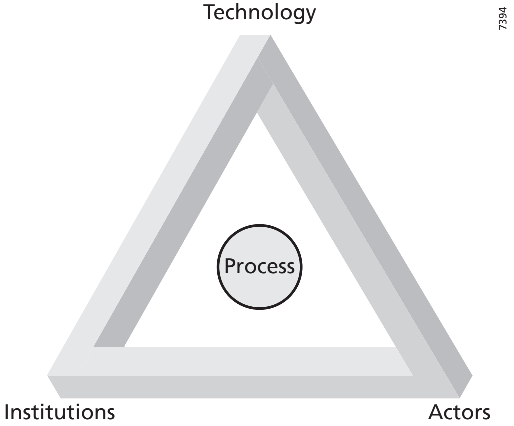

Figure 2.3 Structural factors as aspects of a process.

and institutions of a TIS as interrelated aspects of an ongoing development process; see Figure 2.3. Note that this underlines the assumptions of the process approach, which states that structural factors are subject to events and are thereby part of a change process.

If everything is considered part of a process, then what are these structural factors and how do they differ from events? To explain this, it is important to understand that stability is a relative notion which depends on the time window considered by an observer, in this case the researcher. Compare this to the phenomenon of how the shutter speed of a camera – i.e., the time window in which the film is exposed to light – determines whether a moving object is pictured as a still image or as an 'action blur'. A small time window will capture only structures (still images). Conversely, a large time window will capture anything that moves as events ('action blurs') possibly against a background of still images.

For all the studies in this book, the time window considered is typically 15-20 years. Therefore it makes sense to consider changes which take place within an interval of, say, a few days, as events. Every change which typically takes years to unfold may be considered a structural factor. For example, when within a year a large number of businesses is started, this will strike the observer of the TIS as a series of events. But when a business is present and gradually developing over a long period of time, it is considered (part of) a structural configuration. Likewise, if a number of trials is conducted that contribute to technological knowledge, these are considered events. But the stock of knowledge of that technology, and the technology itself, changes gradually and is therefore considered part of a structure. Similarly, the endowment of a subsidy by a government is considered to be an event, whereas the institutions, typically in place for many years, which make this possible, are structural factors.

According to this logic, actors, institutions and technologies are structural factors. This is especially true when they are considered on an aggregate level, as system components (see Section 2.2.5); after all, a network develops more slowly than its constituents. At the same time, actors, institutions and technologies are involved in rapid changes, for example when an institution is put in place by a government or when a technological application is first tested by a firm.

In the remainder of this book, I will adopt the view that structural factors are slow changes and that events are rapid changes. I will consider the structural configuration of a TIS as the background of slow changes against which events can be perceived as a foreground of rapid changes. The events are the conceptual basis for identifying system functions. As will be pointed out in the next chapter, the distinction between slow change and rapid change works well methodologically.

Co-evolution of structures and system functions

As considered here, rapid changes are embedded within slow changes (Poole et al., 2000) (p. 46-47).[53] This means that structural factors are always related to events, and therefore to system functions. This relation works in two directions. For example, a university that conducts a number of studies should be considered a structural factor (actor) that causes a series of events that contribute to the *Knowledge Development* function. The other way around, a strong *Knowledge Development* function implies that a large number of such events which will gradually affect the reliability of a technology, thereby strengthening the TIS structure.

Structural factors are expected to determine, for a large part, the fulfilment and interplay of system functions. Therefore the build-up of motors of innovation can only be understood if they are related to the TIS configuration (and external factors). These involve enactors and selectors being present, institutions present and the nature of technologies. And most importantly, the overall combination of these factors, as related to the five system components; supply-side, demand-side, government structure, etc. (see Section 2.2.5). What combination results in the emergence of motors is hard to predict, and in fact, to find out is one of the aims of my empirical studies. Finding out about this relation is an important contribution to the structural TIS approach. After all, it provides a basis for understanding how and why particular structural drivers and barriers contribute to the performance of a TIS.

Motors may impact TIS structures in turn. This way, they feed back into the TIS configuration that made it possible for them to emerge in the first place. These impacts may be a combination of new (types of) enactors or selectors drawn in, the setting up or adjustment of institutions, and improvements made to technologies.

Motors may also 'run into the ground'. The explanation for this is bound to be in the structural configuration (and external factors) as well. It may even be that a motor negatively affects the conditions required for its existence. All these possibilities will be kept in mind during the analyses.

2.4.3 Evaluating a TIS in the formative stage

The evaluation of a TIS in its formative stage is far from trivial. As Schumpeter states:

'[S]ince we are dealing with a process [of creative destruction] whose every element takes considerable time in revealing its true features and ultimate effects, there is no point in appraising

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[53] Poole et al. (2000) (p.131) suggest that 'events may differ in temporal and spatial scope […]. Events may be embedded within other, different types of events of larger scope'. Poole et al. would regard structural factors as events with a long duration. In this sense their terminology is different from mine.

the performance of that process ex visu of a given point of time; we must judge its performance over time, as it unfolds through decades or centuries.' (Schumpeter, 1942) (p. 83).[54]

Based on the theoretical notions discussed above, at least three approaches to 'appraising' a system's performance may be considered:

Output performance
The output performance of a TIS is primarily defined in terms of technology diffusion. Moreover, within the context of sustainable energy technologies, the contribution of the TIS to various dimension of sustainability (CO_2 reduction for example) may also be regarded as a performance indicator. The precise indicators depend on the TIS in focus and on the objectives held by policy makers and/or other actors involved. In the formative stage, such external performance indicators should not be valued too highly but eventually, considered over a long time, output is the main criterion for the evaluation of TIS. In the studies presented in this book, the output performance of the TIS is only incidentally mentioned.

Performance based on system functions
In the formative stage, technology diffusion has hardly taken place and thus it is important to take into consideration intermediate criteria of system performance. It is expected that as actors, institutions, and technologies are successfully arranged to increase their ongoing contribution to system functions, the chances of (eventual) technology diffusion will increase; see also Bergek (2008a). Therefore, system functions make suitable 'intermediate performance criteria'. As Bergek suggests: 'System performance may be evaluated in terms of the "functionality" of a particular innovation system, i.e. in terms of how well the functions are served within the system' (Bergek, 2002) (p. 24).

There is no gold standard for appraising the performance of each individual system function in terms of some kind of threshold that needs to be surpassed. Due to the historical nature of TIS development, the definition of success or failure cannot be specified in advance. Instead, success or failure will be determined on the basis of expert opinions.

The method to be used is to follow the enactors and selectors of a TIS as they themselves determine what are successes and failures (considering other actors, projects, rules, artefacts, trends, etc.). This way, evaluation will emerge as a socially constructed judgement that arises from within a TIS. The researcher has the task of collecting all these value judgements, making an overview of them and integrating them into a historical narrative. It is the task of the researcher to relate the successes and failures, via events, to the seven system functions. This way, the set of system functions provides a framework for the evaluation of a formative TIS, in terms of activities that contribute to its build-up (or breakdown).[55]

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[54] Part II, Chapter VII.

[55] This procedure may result in ambiguous ideas on what is a success and what is a failure, but this will then be a realistic ambiguity, one existing within the TIS, and hence one to be discussed rather than to be defined away.

Note that if this perspective is taken, the contribution of a technology to 'sustainability', or its desirability in general, is not considered as an objective outcome but as a search process with various intermediate outcomes.

Performance based on cumulative causation

The most important approach to evaluation will be to appraise cumulative performance. This notion of performance relates to the concept of motors of innovation. An evaluation in terms of motors is based on the appraisal of virtuous (or vicious) cycles. More specifically, it is expected that each motor of innovation has its characteristic strengths and weaknesses. My main contribution to the TIS literature and to the emerging theoretical work on transitions will be to provide evaluative insights into the workings of various motors of innovation, insights with respect to the structural drivers and barriers that underlie typical virtuous (or vicious) cycles. These insights will provide a basis for strategic intervention, by policy makers and entrepreneurs, based on an appraisal of technological change in the Schumpeterian sense of creative destruction.

Strategic lessons

Based on a combination of these evaluative approaches it will be possible to formulate strategies for policy makers and other practitioners that aspire to understand and influence emerging energy technologies. These strategies will be directed at strengthening system functions and at supporting motors of sustainable innovation. The focus will be on the latter; this means that the aim of policies and strategies may be stated in terms of improvements of a particular motor (or the shift to another).

The strategic lessons will be aimed, as much as possible, towards strengthening or overcoming the structural drivers and barriers (respectively) underlying system functions and/or motors of innovation.

3 The method of event history analysis

In the previous chapter I have indicated that in order to identify system functions and motors of innovation it is sensible to take the process approach as a starting point. The worldview employed in this approach is one characterised by events and sequences of events. In this chapter I will show how structures, as well as system functions, can be identified and measured in terms of events. This method is known as an event history analysis.

3.1 Introduction to event history analysis

The event history analysis has most been used in a series of studies oriented towards firm-level innovation trajectories (Boon, 2008; Chappin, 2008; Poole et al., 2000; Van de Ven, 1993; Van de Ven et al., 1999). With a focus on the micro-level, these studies typically monitor day-to-day events, often in real-time, within a firm, for example by systematically studying (minutes of) meetings and company reports. By employing quantitative as well as qualitative techniques, they distilled dynamic patterns, resulting in a number of theoretical insights, especially on the nature of organisational learning. Another important contribution of these studies was the development of statistical tests which could distinguish between a variety of organisational dynamics.

The event history analysis offers the possibility of operationalising and measuring system functions by relating them to events. However, studying a TIS implies a much broader research focus than a single firm, therefore the approach cannot be followed precisely. For one thing, change processes in a TIS typically take more time (in the order of decades rather than years), implying that an ex-post analysis is more suitable. Also, the size and heterogeneity of a TIS make it difficult to come up, a priori, with aggregate variables to be of use for statistical testing. Nevertheless, as Van de Ven has shown, the event history analysis can be adapted to fit the ex-post analysis of large systems as well; see Van de Ven (1993). The data collection is, in this case, not focused on tracking events of importance to individual actors and projects within the system, but on events that are important to the system itself, i.e., events that contribute to system functions. Also, the analysis is based on the construction of narratives (and analysis thereof), rather than on the identification of quantitative relations.

What remains is the basic unit of analysis: the event. Within the context of a TIS analysis, an event can be defined as an instance of rapid change with respect to actors, institutions and/or technology, which is the work of one or more actors and which carries some public importance with respect to the TIS under investigation. Examples of such events are studies carried out, conferences organised, plants constructed, policy measures issued etc.

Note that this definition of an event carries a dual meaning which makes it suitable as an indicator of system functions. The event refers to the world of concrete facts, capturing what is actually happening within the TIS on the level of structural factors. On the other hand, the event also refers to the world of concepts, connecting to how the TIS, as a whole, is functioning.

3.2 The construction of a narrative

The basis of the event history analysis in this study is the construction of a narrative, in other words a plot or storyline, consisting of sequences of events. The construction and analysis of a narrative will be the backbone for each of the case studies in this book. The following procedure explains how to establish such a narrative, i.e., how to distil meaningful event sequences.

3.2.1 Operationalisation

The operationalisation of system functions is based on the systematic collection, analysis and synthesis of event data. This section provides an overview of the steps that were taken during the course of each case study.

Collect data from literature

For each case study, a variety of literature was collected, including professional journals, newspapers, periodicals, reports, websites. The selection criterion was that the texts needed to cover topics related to the emerging technology. An important aid was the *Lexus Nexus* database in which a large number of news papers and popular journals are made digitally available. This enabled the use of search terms, which is a powerful way to sample a collection of articles within a journal systematically without having to browse through the volumes of the journal. For each case study a different collection of literature was used.

Construct a database

A database was constructed containing events in chronological order. This was done by reading through the literature and separating, throughout each text, the events reported. The identification of events in a text was an inductive exercise during which the conceptual framework of system functions was used as a heuristic, in the sense that with the definitions of system functions in mind it became easier to interpret particular reports as events. After all, events had to correspond to system functions. In this respect the events should be considered constructs of the researcher. They make up an intermediate level of representation that lies between the concrete literature reports and the abstract concepts.

Mapping events to system functions

The database provided an overview of the content of events and the time of their occurrence. Based on this overview, the events were clustered into types that corresponded to the system functions. The outcome, based on the studies presented in this book, is presented in Table 3.1. Note that each event type is mapped on a particular system function. This way events serve as indicators of system functions.

It is conceivable that an event contributes to multiple system functions. For example, setting up industry associations may be considered to contribute to *Knowledge Diffusion*, *Guidance of the Search* and *Support from Advocacy Coalitions*. In my studies I tried to avoid this ambiguity by explicitly distinguishing and mentioning the various actions of this structure. For example, I classified the creation of the branch organisation itself as contributing to *Knowledge Diffusion*,

Table 3.1 Event types as indicators of system functions.

System function	Event types
F1. Entrepreneurial Activities	Projects with a commercial aim, demonstrations, portfolio expansions
F2. Knowledge Development	Studies, laboratory trials, pilots, prototypes developed
F3. Knowledge Diffusion	Conferences, workshops, alliances between actors, joint ventures, setting up of platforms/branch organisations
F4. Guidance of the Search	Expectations, promises, policy targets, standards, research outcomes
F5. Market Formation	Regulations supporting niche markets, generic tax exemptions, 'obligatory use'
F6. Resource Mobilisation	Subsidies, investments, infrastructure developments
F7. Support from Advocacy Coalitions	Lobbies, advice

the promises it makes to *Guidance of the Search* and the lobbying it undertakes to *Support from Advocacy Coalitions*.

Events can contribute to system functions either positively or negatively. Therefore, the events in the database were categorised as either positive or negative. For example, events that were categorised as *Guidance of the Search* were rated positive/negative when they expressed a positive/negative opinion regarding the technology under investigation. Likewise, within the category of *Support from Advocacy Coalitions*, there were positive lobbies and negative lobbies.

Note that a negative contribution to a system function is not necessarily a bad thing in the long run. For example, negative expectations may be the result of important technological disadvantages that turn out to be impossible to overcome. This way, a negative *Guidance of the Search* signifies the exclusion of a badly performing technology. Nevertheless, the immediate consequence is a (partial) breakdown of the TIS.

It should be stressed here that the operationalisation of system functions in this way is the cumulative result of multiple case studies. The first studies resulted in a scheme that was loose and incomplete, for example, because infrastructure developments were not yet part of that TIS and therefore could not be mapped, or because the distinction between niche markets and mass markets was not clearly observed before a market expansion actually occurred within a studied TIS. With each case study, the event analysis resulted in a more developed operationalisation scheme.

In this respect, it is also important to remark that the system functions guided the interpretation of the literature but did not force it. The flexibility of the approach made it possible to check the construct validity of the seven system functions. When important events could not be allocated to either one of the seven functions, this would have been an indication of an incomplete set of system functions. Also, if for a specific system function only a small number of events would have been found without a clear indication of bad system performance, this system function would have been considered as irrelevant (unless explanations could be mobilised to account for it).

The first empirical studies on the dynamics of TISs using an event history analysis (around biomass digestion, biomass gasification and biomass combustion), by Negro (2007), have pointed out that the set of system functions as employed in this book corresponds well to empirical data in the field of sustainable energy technologies. Indeed, the studies presented in this book have not resulted in a substantial reorganisation of the set of system functions either.

3.2.2 Pattern recognition

The construction of a scheme of event types that connect well to system functions is the first step of the event history analysis. The next step is to analyse the event data. Based on the ideas of Poole et al. (2000) and Abell (1987), event data were subjected to two types of analysis. Both are based on the recognition of patterns in event data; trend patterns and interaction patterns. The first technique aims to derive trends from aggregated data over a period of time. The second technique aims to track causal chains of events based on the sequence in which they occur. Both techniques are means to develop a plot, and thereby to construct a meaningful narrative that captures the development of a TIS.

Trend patterns

Trend patterns indicate the fulfilment of individual system functions over time. They can be constructed quantitatively by plotting the aggregated number of events for each year per system function. The slope of the graph then represents the increase or decrease in number of events per system function. Positive and negative events can be plotted separately thereby pointing out support as well as resistance to the emerging technology. This representation gives a crude insight into the major turning points of TIS development such as, for instance, a sudden decline in the intensity of the *Guidance of the Search* function. If the available event data allows for it, a more disaggregated insight can be obtained as well. For example, the analysis could show a shift in the nature of events, indicating, for example, the participation of particular actors or the involvement of specific technological (sub)options.

For every system function, a separate graph may be drawn. Together these graphs provide an overview of how the various system functions develop in time. This way, they may indicate the effect of a motor of innovation. More importantly, based on such trends, characteristic episodes may be identified which deserve a more detailed analysis. For example, a sudden decline in the fulfilment of a system function may require an explanation in terms of structural factors. Such an explanation may involve a particular policy measure, the rise of a technological option, the entry of a particular actor or a combination of such events.

Trend patterns are not necessarily based on a quantitative analysis. The basic idea is to point out important developments in the overall flow of events. A qualitative analysis may yield such insights as well but in that case the information from the database is interpreted more in terms of content and impact.[56] The relative contribution of system functions is then measured, through interpretation, in terms of the impact of events as considered by the actors involved in a TIS.

In fact the qualitative measurement of trends in system function fulfilment is crucial as a complement to any quantitative pattern. After all, without such interpretations it is impossible to

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[56] A quantitative analysis is based on the occurrence of (types of) events, not on their content, or impact.

develop a normative idea on how well the TIS is actually developing. In other words, a qualitative insight is necessary in order to consider whether a certain 'threshold' of quality has been achieved. This touches upon the evaluation of a TIS in terms of process performance. Trend patterns for each system function can be regarded as intermediate outcomes of TIS development in the formative stage.

Interaction patterns

If trend patterns represent outcomes of TIS development, then interaction patterns offer a possible explanation for these outcomes. Before clarifying this, it is important to understand that the advantage of using events as indicators is that they can be connected through 'leads-to' relations, to form a sequence; cf. Abell (1987).[57] Many events refer to other events; these references can be tracked by checking the content of all the events in the database. For example, a promise to support the construction of a biofuels plant may be followed by the construction of that plant. Also, a positive lobby may result in the award of subsidies or the adjustment of institutions.

The overview of event references enables us to construct a narrative in which event sequences serve to construct storyline(s). By interpreting events as indicators of system functions, according to Table 3.1, it becomes possible to identify the role that particular system functions play within the event sequences. If particular system functions recur in an ordered sequence, this could imply a cyclic mechanism, a motor of innovation. This way it becomes possible to indicate whether system functions interact with each other. The event sequence indicates a virtuous cycle if it forms a repetitive loop of system functions reinforcing each other. The example of the virtuous cycle presented in Section 2.3.4 was already formulated in terms of events; the successful realisation of a research project (*Knowledge Development*) results in high expectations (*Guidance of the Search*) among policy makers, which subsequently triggers the start-up of a subsidy programme (*Resource Mobilisation*) which induces even more research activities. A vicious cycle would involve a cascade of negative events.

It is impossible to integrate all the events collected in a database into sequences. The challenge is to select those events that form motors of innovation (Poole et al., 2000). Note that event sequences may diverge, as one event may lead to multiple other events, or converge, as multiple events may be necessary before they can lead to one other event. I will attempt to reduce this complexity by summarising such leads-to relations on the level of system functions. For example, by stating that an important policy measure (*Guidance of the Search*) results in an increase of firm entry (*Entrepreneurial Activities*).

The recognition of interaction patterns benefits from the insights derived from trend patterns. Vice versa, the recognition of trend patterns benefits from the insights derived from interaction patterns. Both analyses mutually strengthen each other. The trend patterns can be used to identify

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[57] The term 'leads-to' is used to avoid an unnecessarily complicated discussion on various forms of causality. The point is that events are related in various ways. These relations may be based on such diverse elements as intention, strategy, necessity, etc. The storyline will have to reveal which of these elements is dominant in connecting the events to form a sequence. The general reasoning behind this approach is hermeneutic rather than physical-statistical.

particular periods that require special attention, whereas the interaction patterns help explain the occurrence of particular trend patterns.

Episodes

Based on the trend patterns and interaction patterns it will be possible to distinguish episodes within the development of a TIS. A particular episode may be characterised by important trends in system function fulfilment, by occurrence of particular motors of innovation or by considering important (external) background factors involved in the TIS dynamics in a particular period of time. For example, if the late 1970s were characterised by the aftermath of two oil crises and economic turmoil, then it makes sense to frame these years as an episode in the narrative. Episodes should be considered as the chapters of the narrative. They serve as a guide to the reader.

3.2.3 Structures and system functions

I have already explained how system functions are related to structural factors: as a foreground of rapid changes to a background of slow changes. This background generally consists of institutions, actors and technologies that form a structural configuration, whereas the foreground is a perpetual flow of events. How does this mutual relation come back into the event history analysis?

In the event history analysis, structural factors are indeed background factors in the sense that they are not directly measured. On the other hand, there exists (by definition) no event which is not related to (the networks of) actors, institutions and technologies that make up the TIS. This means that structural factors are always traceable in the content of events. Each event can be 'unpacked' to identify which structural factors 'participated' in it.

This way the event data offers the information necessary to identify structural drivers and barriers that are involved in the events that trigger or sustain a particular motor of innovation. Vice versa, it is also possible to identify the effect of motors of innovation on TIS structures.

3.2.4 Evaluation and triangulation

The outcome of the event history analysis is a narrative, in some cases underpinned by quantitative representations of how the development of system functions changes over time. The construction of the narrative is done as objectively as possible but the interpretation of the researcher is a crucial factor in this. To minimise personal bias, the narrative is verified, i.e., triangulated, and if necessary reconstructed, by including opinions based on interviews. This way, the interpretation of events is based on a combination of (personal) background knowledge, public opinion and the judgement of multiple experts. In the final stage of the research the narrative itself should be verified by means of interviews.[58]

The triangulation serves two interrelated causes. One is to develop a narrative that connects as closely as possible to the build-up of a TIS in terms of events that are meaningful to the actors which participate in it. The other is to develop, or co-develop, a normative stance towards this

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[58] The number of interviews and the affiliation of the interviewees is different for each case study. The details are provided in Chapters 4-8.

development. After all, system functions are evaluation criteria and a part of the narrative should capture the appraisal of system functions by the actors themselves.

3.2.5 A Synthesis of results from multiple case studies

As was stated in Chapter 1, there are four case studies for which narratives will be constructed. Each case study will reveal particular motors of innovation, along with a set of structural factors that relate to it. In order to provide general insights into how motors of innovation generally come about, it is necessary to combine results from multiple cases, thereby strengthening the results through replication.

Part II
Case Studies

Interlude A

The following chapter contains the results of a case study on the development of Dutch biomass gasification technologies. This study involved the first real test of the event history analysis. The focus of the chapter is therefore still very much on identifying system functions and on relating them to specific structural drivers and barriers – here called inducement and blocking mechanisms – within (and outside) the system. At the time of writing, the concept of a motor had not been developed; instead the text speaks of virtuous and vicious cycles.

The chapter was originally published as: Negro, S.O., Suurs, R.A.A. and Hekkert, M.P., 2008. The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. Technological Forecasting and Social Change, 75(1): 57-77.

4 The biomass gasification TIS (NL)

4.1 Introduction

In this chapter we analyse the development and diffusion of biomass gasification technology. The reason for this choice is that gasification technology is generally considered to be a promising technology to convert biomass into useful products. First, the conversion efficiency of biomass into electricity is much higher than for biomass combustion and digestion. Second, by means of gasification, biomass – as well as being used to generate electricity – can also be converted into feedstock for the chemical industry and for the production of liquid biofuels. Logically, the expectations around this technology are quite high and many actors see it as *the* technology to achieve a breakthrough for biomass as a modern energy source. However, despite the high expectations, high efficiency, and wide range of applications, biomass gasification has not been successfully developed, diffused and implemented in the Netherlands so far.

By analysing the Biomass Gasification Technology Innovation System (BGTIS) in the Netherlands, the inducement and blocking mechanisms may be identified which explain the failure of this technology. The research question is:

RQ: What are the inducement and blocking mechanisms that determined the evolution of the BGTIS in the Netherlands from 1990 to 2005?

The same theory and methodology as described in Chapters 2 and 3 are applied to this case study. In the historical analysis the key processes, more in particular the (lack of) virtuous and vicious cycles, that took place within the BGTIS are highlighted. The symbols [F1] – [F7] refer to the seven system functions as described in Chapter 2.4. The analysis was validated by checking the results through interviews with various actors in the field.[59]

In this case study the focus lies on biomass gasification plants where only biomass is gasified. Combined gasification of coal and biomass is not included, since in combined gasification coal is the major feedstock used and the biomass share is only marginal, resulting in other technical properties than full biomass gasification. We are aware of an experimental project on coal and biomass co-gasification in the large-scale (205 MW) coal gasification plant called 'Buggenum', but for the above mentioned reason we will not include the trajectory of this project. In addition, we focus on the use of biomass gasification for electricity production. Biomass gasification as for the production of automotive fuels (e.g. Fischer-Tropsch fuels) is developed in quite a different

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[59] Dr Andre Faaij, Associate Professor, Department of Science, Technology and Society, Utrecht University (2005); Professor Cees Daey Ouwens, initiator of the North-Holland project (2005); Dr Wim Willeboer, Senior project manager of the biomass gasification project of the Amer plant (2005). Additional interviews were included that have been carried out as part of the Master's thesis of Anouk Florentinus (2004): Ir. Kees Kwant, programme leader for EZ and VROM at Novem (2003); Ir. H.E.M Stassen, founder of BTG (2003); Dr Andre Faaij, (2004); Professor Cees Daey Ouwens, (2003); Dr Wim Willeboer, (2004).

Box 4.1 Introduction to biomass gasification technology.

The traditional way to convert biomass into electricity is through biomass combustion. The hot exhaust gases of the combustion process are subsequently used to produce steam that is processed through a steam turbine to generate electricity. An innovative and more efficient method is gasification of biomass. In this case biomass is combusted in an oxygen-starved environment, where the end products are CO and H_2 gases (so-called product gas or synthesis gas (syngas)). In contrast to solid biomass, this syngas can be fed into a gas turbine to produce electricity at a much higher efficiency (35-40%) than combustion (25-30%) (Faaij et al., 1997; Morris et al., 2005; Williams and Larson, 1996). Biomass gasification is a flexible technology, since syngas can be used not only to produce electricity but also feedstock for chemical processes (Morris et al., 2005). However, there are some fundamental requirements that limit the flexibility and efficiency of biomass gasification technology. The first is that a constant and sufficient supply of biomass has to be guaranteed for an installation to be able to run efficiently. Also, there is a need to ensure the quality and type of biomass. The cleaner the biomass, the lesser the costs that are involved in complex cleaning processes. Furthermore, dry biomass is more efficient than wet biomass, since no additional drying is needed. Finally, the type of gasifier used also determines the size of the installation. For small-scale applications (<5 MW), fixed-bed gasifiers are more efficient, whereas fluidised-bed gasifiers are more efficient for large-scale applications (>5 MW) (Faaij, 1997; Faaij et al., 1998; Williams and Larson, 1996).

innovation system. Therefore, it is not analysed in detail but briefly sketched in order to illustrate the dependencies between both innovation systems.

A short introduction into the technological features of biomass gasification technology is provided in Box 4.1.

4.2 The event history of the BGTIS

4.2.1 The hype of biomass gasification (1990-1998)

In the early 1990s biomass gasification starts to gain attention in the Netherlands. In the previous period, the Dutch government mainly stimulates research on alternative energy sources by publishing formal policy documents (1982 – White Paper on Renewable Energy; 1989 – National Environmental Plan (NMP); 1990 – White Paper on Energy Saving). However, these official documents are not backed up by other policy initiatives, which results in low funds for research on renewable energy; the engagement of implementation remains on general terms and on a voluntary basis (Verbong et al., 2001; DE, 1985; NE&S, 1982).

At the beginning of the 1990s, two urgent problems are identified. The Netherlands lacks sufficient landfill space for waste disposal, resulting in several R&D programmes, set up by Novem[60], to

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[60] Novem is an agency of the Dutch Ministry of Economic Affairs focusing on energy and environment.

reduce the amount of final waste by converting waste into useful energy (1989 – EWA programme; 1990 – NOH programme, 1992 – EWAB programme) (DE, 1992b). In addition, the awareness of the negative consequences of using fossil fuels increases, causing the need to develop and implement alternative energy conversion technologies to become more urgent (Lysen et al., 1992). These two problems guide the search towards new technologies that could solve these problems [F4].

The idea for large-scale biomass gasification until this point is still rooted in Dutch research on coal gasification and the development activities of small-scale biomass gasification units for developing countries. However, positive results obtained abroad inspire the idea to use biomass gasification as an alternative conversion technology for waste surplus in the Netherlands [F2] (Carpentieri et al., 1993; Williams and Larson, 1993). In addition, the province of North Holland[61] develops policies to provide a clean, sustainable and affordable energy supply by combining wind energy and biomass gasification [F4] (see the next section for a detailed description of the North-Holland project) (SN, 2005a). This triggers the commission of an inventory study for gasification of wet biomass waste-streams for electricity production. It is found that these biomass streams can also be used for gasification and that they reduce costs due to their negative value (Faaij et al., 1992). In addition a study trip to biomass gasification projects in Sweden[62,63] and Finland[64] is organised by the Dutch ‘Biomass Technology Group’ (BTG), to obtain more knowledge about the high potential of biomass gasification technology and the possibility of setting up gasification plants in the Netherlands (Kwant and Knoef, 2004; MT, 1993b). During the same period, Novem publishes a report which demonstrates that biomass gasification of energy crops like poplar and miscanthus for electricity production can also be quite profitable. The report states that electricity production is preferred to biofuels production from conventional agricultural crops (Lysen et al., 1992). This report has a major impact and shifts the direction in the BGTIS away from the use of biomass for automotive fuels towards the use of biomass for electricity by means of gasification [F4].

The report triggers more research [F2]. Desktop studies show that biomass gasification has a higher energy efficiency than biomass combustion (37-40% vs 25-30%) and that production costs can be reduced by using biomass waste streams instead of energy crops (Faaij et al., 1992; DE, 1992a; DE, 1992b; DE, 1992d). Due to these positive characteristics, the sustainable energy sector

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[61] Provincial Council of the province of Noord-Holland (North Holland).

[62] Since 1986 there have been nine small-to-medium scale (5-10 MWth) ‘Bioneer’ fixed bed gasifiers operating in Sweden and Finland (Kwant and Knoef, 2004; Morris et al., 2005).

[63] In the late 1990s, pressurised gasification technology is successfully demonstrated in the world’s first complete BIG-CC power plant in Värnamo, Sweden. The plant aims at demonstrating the complete integration of a gasification plant and a combined-cycle plant, fuelled by biomass; the basic idea is to demonstrate the technology rather than to run a fully optimised plant. Between 1996 and 2000 a demonstration programme is run to verify the status and future potential of BIG-CC from a technical and economic point of view, but after the demonstration programme is concluded, the plant is mothballed in 2000 since it is not economical to operate the plant given the low electricity prices in Sweden (Kwant and Knoef, 2004; Morris et al., 2005).

[64] In 1998 the commercial demonstration of the Lathi gasifier (60 MWth) is realised and is still operational today. In 2002 a similar plant (50 MWth) to that at Lahti comes into operation in Ruien, Belgium (Kwant and Knoef, 2004; Morris et al., 2005).

expresses high expectations of biomass gasification [F4] (DE, 1993c; DE, 1994b; MT, 1994). In addition the EU 'Thermie' programme[65] is started and several projects receive financial support from it [F6] (e.g. Zeltweg, Austria; Lathi, Finland; Amer-plant, the Netherlands; Arbre project, UK) (Morris et al., 2005). Also, Shell shows interest and invests in a biomass gasification project in Brazil, however, the project is not realised (Carpentieri et al., 1993). As a result, and in a very short time, biomass gasification is considered to be equally useful as other competing renewable energy technologies. This is illustrated by the following quote:

'The contribution of biomass to the energy supply is gaining more and more importance. The most realistic routes that can be used for the production of electricity are either gasification or co-combustion of biomass in existing installations (EPON-project), combined-heat-and-power (CHP) application and the conversion of biomass into biogas.' DE (1993a) (p. 35).

The high expectations of biomass gasification in this period are also reflected in the short development time that is expected for commercialisation of the technology, and in the plans to invest in technology development. For instance:

'In the coming years, more emphasis will be put on gasification, since this technology has the potential to be cost-effective and to convert waste and biomass with a high energy efficiency. Lots of efforts are expected to be necessary to achieve these expectations, since in 2000 it will be evaluated whether gasification can be implemented on a large scale.' Braber, Kwant and Smakman in DE (1993b) (p. 14-15).

The result is that studies are carried out [F2], which show that wet biomass (organic waste, sludge etc.), only thought suitable for digestion or fermentation, can also be used for gasification, providing additional biomass resources for gasification and higher energy output than for digestion [F6] (DE, 1992c; MT, 1993a). In addition, technological problems are not considered to be a major obstacle, as the next fragment shows:

'The gasification of organic household waste is researched by the Department of Science, Technology and Society at Utrecht University. Since no compost is being produced during gasification and due to its lower conversion costs, this conversion system has chances to become a realistic option. The practical problems, cleaning the syngas from alkali- and heavy metals, do not form any unsolvable problems.' DE (1992d) (p. 27-29).

These expectations result in a specific research programme, the 'National Biomass Gasification Research Programme'[66] by Novem, aiming to demonstrate biomass gasification technology in a number of projects [F4]. These projects not only lead to R&D [F2] and more financial resources [F6]; they also induce positive expectations of this technology [F4]. The aim of the programme is the following:

'Special emphasis will be put on the set-up of a circulating fluidised bed gasifier for the gasification of biomass waste. The aim is to demonstrate the techno-economic feasibility and to provide long-

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[65] Thermie Non-Nuclear Energy Programme, 1990-1994.

[66] In Dutch: Nationaal Onderzoek Biomassa programma (NOB).

term perspectives for this technology on the large-scale conversion of waste and biomass.' Braber, Kwant and Smakman in DE (1993b) (p. 14-15).

To recapitulate, positive results from abroad and a high impact study (Novem) puts biomass gasification on the agenda and quickly results in the rise of expectations for biomass gasification in the early 1990s. This, in turn, triggers a series of activities that can be classified as *Knowledge Development*, *Guidance of the Search*, and *Mobilisation of Resources*. The rise of a virtuous cycle is observed, since positive results from research lead to high expectations of biomass gasification [F2, F4], which in turn result in the setting up of research programmes in the context of which demonstration projects are set up [F2, F4, F6].

However, not all system functions in the BGTIS receive attention in that first period. In addition, there are several critical voices that warn against following the hype without first solving technical problems and obtaining consistent support from the government. One of the leading figures in this field expresses it as follows:

'There is no clear-cut national programme about biomass in the Netherlands. Some projects are being prepared, but mainly for the co-combustion of biomass in coal plants.' Daey Ouwens in DE (1993d) (p. 10-13).

An additional problem is the lack of market creation policies [F5] by the Dutch government. To attract more research funds [F6] and to get entrepreneurs interested [F1], a clear vision of the future market for these types of technologies is necessary [F4]. At this time, there are no subsidies, feed-in tariffs, or launching customer activities by the government. A spokesperson from an energy distribution company states the following:

'There are possibilities to set up gasification plants in the Netherlands, since there is enough hay and verge grass that could be used as short-term options. However, who is going to pay for it?' E&M (1993b) (p. 14).

Finally, there are some critical voices that warn against rushing the setting up of large-scale plants (due to high expectations and promises and ignoring technical problems [F4]), while the technology has not been proven, as expressed by Mr Smakman, project leader of the EWAB programme:

'… A long-term development is needed before gasification will be established in the Netherlands and the future of gasification is difficult to predict, since there is no experience and expertise in the Netherlands for this technology. Additionally, practice is unmanageable, so the new technology has to be 'proven' first, before it will be accepted.' E&M (1993b) (p. 14).

In this period, two projects aiming to realise large-scale application of biomass gasification dominate the dynamics of the BGTIS. Both projects receive much attention in the Dutch energy system and they trigger many other processes in the BGTIS, as we will see in the following sections.

4.2.2 The North Holland project (1993-1998)

In 1993, the Province of Noord-Holland, the coordinator of the national energy companies (SEP)[67], several energy companies (UNA and PEN) and researchers from ECN[68], design plans for the first large-scale gasification project in the Netherlands [F1] (DE, 1994a; DE, 1995b; E&M, 1995a). Several feasibility studies are carried out over the years to assess the location, scale, and biomass streams [F2] (DE, 1994a; E&M, 1993a; E&M, 1995a; E&M, 1995b). At the end of 1994, the preliminary studies are completed and the decision is taken to gasify waste wood, thinnings and other residues in a 30 MW installation linked to a combined heat and power (CHP) system in the region of North Holland. The expectations are high and it is predicted that the plant will be constructed at the beginning of 1998, run for a few years on a trial basis, and subsequently be sold to a user, for example UNA [F4] (E&M, 1993a).

During the project, several established actors in the Dutch energy system express serious interest in this technology, which results in the formation of an advocacy coalition [F7]. This, in turn, leads to increased funding [F6] (1.5 million € for the complete project) and more research to reduce the initial technical and economic uncertainties [F2]. The entire initiative can be regarded as the creation of a niche market for gasification technology [F5], since the national government – backed up by the consortium of private parties involved – indirectly stimulates the potential returns by encouraging provinces to incorporate renewable energy into their energy mix (Daey Ouwens, 2005). The first phase of the North-Holland project therefore boosts several system functions in the BGTIS.

Negotiations continue until 1997. However, one year before the construction is supposed to start, experiments demonstrate that the economics of the project are disappointing, in contrast with previously favourable forecasts, and that the North Holland project is not economically profitable [F4] (E&M, 1997b; Faaij et al., 1998). In addition, there are uncertainties about the wood supply [F6]. No suitable company is found for delivering the wood that provides the required long-term contracts (of ten years), due to the uncertainty of wood prices (Daey Ouwens, 2005). In addition, the time spent before building begins stretches in such a way that the liberalisation of the energy market starts to interfere with plans for the project. This national liberalisation movement (which starts in 1998 and embraces the entire electricity sector) turns out to have dramatic consequences for this project, one of which is the growing fear that SEP, one of the project partners, will be discontinued (DE, 2001; Daey Ouwens, 2005). Furthermore, energy companies become reluctant to invest in high-risk projects. The fact that biomass gasification is an unproven technology results in insurmountable technological uncertainties [F4] (DE, 2001; Daey Ouwens, 2005). The following quote underlines this point:

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[67] From 1948 until 1998, the SEP was an agency coordinating the national energy companies.

[68] ECN is the Energy Research Centre of the Netherlands. From 1994 on ECN carries out several feasibility studies, among others for the North Holland project, on various biomass streams (organic waste, wood, paper etc) and on the economical and technical potential of integration of a gasifier and a gas turbine. In 1996 a circulating fluidised bed, BIVKIN, is set up, with the aim to collect information about the gasification process and properties of different biomass streams. In a short period of time the gasifier becomes a reliable installation due to the collaboration of ECN, Stork, HoSt, Afvalzorg and Novem. In 1999 the gasifier is equipped with a gas cleaner developed by HoSt and plans are made to apply the technology commercially (E&M, 1995b) (p. 10).

'The delays for realisation of biomass units is not only due to technical aspects, but due to the energy world, which is reluctant to take high risks in the continuously proceeding liberalisation, and due to the reduction of oil prices. Expensive and risky projects are not realised without problems by the free market anymore.' DE (1997a) (p. 38).

Finally, the Province of Noord-Holland and the energy company ENW (successor of PEN) decide to abort their ambitious gasification project in 1998 [F1] (AV, 1998; BV, 1998; DE, 1998c). The final decision is caused by a build-up of disappointments in the technology and growing disagreement between the parties involved with respect to various technical and economical aspects, i.e., the unreliability of the technology, high costs and high risks [F4] (DE, 2001).

4.2.3 The Amer-Plant (1996-ongoing)

The second large-scale project is started in 1996, three years after the initiation of the North Holland project, by a consortium of PNEM[69], NUON, EPZ[70] and BFI[71] [F1, F3]. The size of the plant is planned to be 30 MW with an atmospheric circulating fluidised bed (ACFB) gasifier for co-firing, where the combustible gas from the gasifier will be co-combusted in the nearby coal-fired power plant 'Amer-plant', operating with a CHP unit, delivering 600 MWe of electrical power as well as up to 350 MWth of district heating (DE, 1996b; E&M, 1996b; EssentEnergieBV, 2001; MT, 1996). Once again, the expectations are high. It is promised that the plant will be operational in 1998, as indicated by the following quote [F4] (DE, 1996b):

'This plant will convert construction- and demolition wood into combustible gas, which can be co-combusted in the Amer-plant. There are several advantages of wood gasification: 46.000t coal will be saved, 115.000t CO_2 emission reductions will be achieved and 100.000t less wood waste will be dumped. From a feasibility study it is evident that such a plant will be profitable. If the construction starts by the end of 1996, then the plant will be operational in 1998.' DE (1996b) (p. 8).

However, shortly afterwards, the consortium aborts the project because the use of waste wood proves to be economically unfeasible for this application [F6]. It turns out that it is more profitable to export the cleaned demolition wood to Sweden, than to use it for biomass gasification in the Amer-plant. This results in a lack of biomass resources to run the plant (DE, 1996f). However, expectations of biomass gasification technology are still high and, in 1997, EPZ restarts this project [F1, F4]. This time, however, a different wood delivery company is engaged (DE, 1997b). The preparations pass off quickly and plans are that the plant will be operational in two and a half years:

'The plans for constructing a wood gasification plant on the site of the Amer-plant in Geertruidenberg by the electricity company EPZ is in an advanced stage. (…) The internal publication of EPZ writes that 'this is about a world premier'. The technology is new and has not been applied on commercial scale in combination with an electricity plant.' DE (1997b) (p. 26).

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[69] Dutch energy companies.

[70] NUON and EPZ are energy production companies.

[71] Waste processing company, now called SITA.

In 1998, subsidies are received from the European Union [F6] (Thermie programme, 5 million €) and the Dutch government (CO_2-emission reduction plan, 6 million €) and in 1999 the construction of the gasification plant enters the final phase, with completion due by the end of the year (DE, 2000a). In 2000, the construction is completed and the installation should be operational. The project receives much exposure in the (renewable) energy system of the Netherlands, as shown in the following quote [F4]:

'There are high expectations for the Amer-plant, where the gasified biomass is blown into the nearby coal plant. This project is just starting and any positive experiences could mean the long awaited breakthrough.' DE (2000b) (p. 36).

However, positive experiences fail to occur. Technical problems hamper a smooth running of the gasifier, making modifications necessary [F4]. The major problems are the gas cooling (from 900 °C to 220 °C) and gas cleaning. The contractor, Lurgi[72], has no experience with waste wood but only with coal, whereas the behaviour of the waste wood ash is different, clogging up the exhaust and causing congestion (Morris et al., 2005; EssentEnergieBV, 2001). In 2001, a temporary modification is carried out, marking a second phase of operation, in which numerous other, more structural, modifications are carried out. Both the gas cleaner and gas cooler are rebuilt to accommodate the properties of the ashes [F2]. Finally, in 2003, the plant is operational nearly full-time, as most of the problems – especially the gas cooling problem – have been solved due to the modifications [F4] (Willeboer, 2005). From 2004 onwards, the contract with Lurgi is discontinued and Essent takes over the maintenance and operation of the gasification unit, since enough knowledge and experience have been built up over the years. Finally, on 1 September 2005, after seven wearisome years (during which few kilowatt-hours of electricity have actually been produced), the modifications of the plant are finalised (Willeboer, 2005).

The story of the Amer-plant shows that the high expectations of biomass gasification were just too optimistic and turned out to be counter-productive. Note that, in 1992, the gas-cleaning problem was considered to be a technical problem, which could easily be resolved. However, it turned out to be one of the main problems, postponing the smooth functioning of the Amer-plant for seven years. Part of the reason for this problem is that the contractor did not have the necessary experience and expertise to foresee and resolve technical problems that would occur during biomass gasification. These problems might have been avoided if an experienced contractor had been involved.

4.2.4 The breakdown of expectations (1998-2002)

Now that we have described two projects in detail, we will return to describing the developments at a system level.

In 1998, the energy market is liberalised and the waste market deregulated. Despite the high expectations in the previous period, biomass gasification has failed to prove itself as a reliable, economically attractive, and efficient technology. The North Holland project is aborted in this

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[72] Lurgi: a German technology company operating worldwide in the fields of process engineering and plant contracting. The Lurgi process is one of the original developers of conventional gasification processes.

year, and it is still unclear how the Amer-plant will perform. The main industrial parties in the liberalised market choose not to use biomass gasification technology:

‘Energy companies have not embraced biomass gasification yet; partly it is still in demonstration phase and not a proven technology yet (…). Furthermore, the liberalisation of the energy market makes energy companies reluctant to take risks. Companies prefer proven technologies rather than doing innovative things.’ DE (2004) (p. 40).

As a result, hardly any research and development on biomass gasification for electricity production occurs in the following two years [F1, F2]. The hype of gasification clearly ends here [F4] (DE, 2000b).

In 2000, the government antagonises all further developments related to biomass gasification, by formulating a strict emission regime based on current coal combustion plants. The few initiatives for small-scale biomass gasification plants[73] are immediately unprofitable under the new rules, since now additional gas cleaning is needed to comply with these rules [F4] (DE, 2000a). As a consequence, no further research and exploration activities are carried out [F1, F2], bringing the development of biomass gasification for electricity production to a halt. In this period, a vicious cycle becomes dominant, since there is no more policy support [F4], resulting in a lack of demand and expectations [F4], causing no more projects to be funded [F6] and carried out [F1, F2].

4.2.5 A possible revival of biomass gasification (2002-2004)

However, in the period 2002-2004, a revival of biomass gasification seems to occur. The drive for this revival comes from a different direction. The European Union stimulates its member states to substitute part of their consumption of fossil-based automotive fuels by biofuels. In the Netherlands, so-called ‘second generation’ (2G) biofuels – partly based on gasification technology – are preferred over the so-called ‘first generation’ (1G), which can be associated with conventional technologies (NRC, 2004; ST, 2002b). This results in publicly-financed research programmes to develop the conversion technologies necessary for the production of these fuels, e.g. most notably the NECST/NEO programme in 2001 and the GAVE subsidy programmes in 2001 and 2002 [F2, F4] (SN, 2001; ST, 2003b). From 2001 on, a large number of entrepreneurs and research institutes, including Shell and ECN, conduct fruitful R&D on gasification processes for the production of Fischer-Tropsch Diesel and hydrogen. As a consequence, this period is characterised by renewed promises on behalf of the national government [F4] and R&D activities by entrepreneurs and researchers [F1, F2] (DE, 1993d).

‘The chances for a large-scale application of biomass in the Netherlands are high. Also the use of biomass for biofuel production is expected to increase to 10% in Europe, this could be achieved from linseed or rapeseed or by gasification of biomass.’ DE (2003b) (p. 34).

However, when the pressure of the EU to comply with the biofuels directive increases in 2003-2004, the 2G biofuels technologies are still not ready for market introduction. As a result, the support for the 2G biofuels trajectory shifts to the background as the conventional fuels become

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[73] Between 1993 and 2000 several small-to-medium-scale (100kW to 8MW) gasification projects are planned and some are set up by BTG, TNO, ECN, Goor, HoSt, Edon, Stork, Kara etc. (DE, 1998b).

more popular (Suurs and Hekkert, 2005). History seems to (partly) repeat itself as technological optimism turns into disappointment within a very short period of time.

4.3 Functional Patterns

In this section, the trend patterns of system functions are described by using graphic representations; the number of events per system function per year is plotted over time. The patterns observed are explained by referring to specific events within the storylines given above.

All the figures show a remarkable absence of activity before the 1990s (see Figures 4.1 to 4.5). In the 1990s things change; the main driving force within the BGTIS is now the search for alternative energy technologies to replace fossil fuels. As a result, several research programmes are set up to assess the application of gasification technology for energy production (F4, see Figure 4.4 peak in 1992). Experimentation and research provide positive results (F2, see the increase in *Knowledge Development* activities from 1991 to 1998 in Figure 4.2). Expectations grow as biomass gasification is increasingly mentioned as the solution to a sustainable energy production (F4, see Figure 4.4 peak in 1995 and 1997-1998). This sequence of events corresponds with a positive interaction between the system functions: the more research is done (F2, Figure 4.2), the more positive results are obtained and publicised (F3, Figure 4.3), the more resources are allocated to the technology

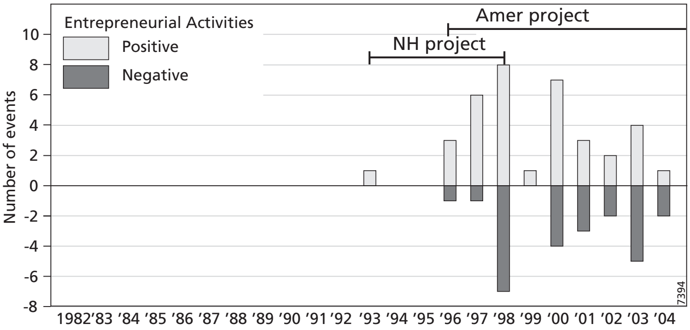

Figure 4.1 Trend pattern of system function 1: Entrepreneurial Activities.

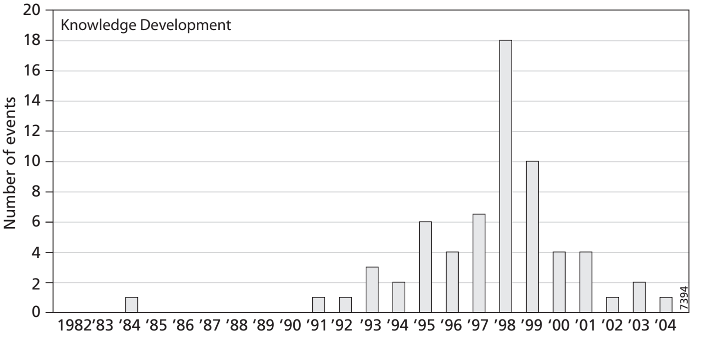

Figure 4.2 Trend pattern of system function 2: Knowledge Development.

(F6, Figure 4.5), ensuring further development of biomass gasification (F2, Figure 4.2). This, in turn, stimulates entrepreneurs to take their chances and set up two large-scale plants for biomass gasification (F1, Figure 4.1). Throughout those years, other small-scale plants are set up as well (F1, Figure 4.1 shows a peak in 1998). Thus, between 1992 and 1998, different system functions are fulfilled, driven by high expectations, resulting in the build-up of a virtuous cycle.

At the same time actors express their disappointment and reveal system flaws (see Figure 4.6 and the quotes in the gasification story line). Some system functions are not fulfilled or even have negative results. For example, actors express their disappointment; their main concern is the fact that the national government does not provide uniform, consistent, and long-term regulations throughout the years (see Figure 4.6, negative opinions about the system). In this figure, the actors' opinions are counted over the years; the representation shows that there are more negative opinions about the system than positive ones (only one in 2002). Thus, we see that the technology itself is perceived as positive, but the BGTIS is criticised heavily. In addition, some actors are sceptical about the hype around biomass gasification technology; they warn entrepreneurs not to be carried away without proving the technology first (see Figure 4.6, negative opinions about biomass (BM) gasification). In retrospect, these voices seem to have made an accurate analysis. Furthermore, there are expressions about the lack of resources (see Figure 4.5 negative line) and the lack of *Support from Advocacy Coalitions* (F7, no graphical representation due to unavailability of data). Nonetheless, in the period from 1992 to 1998, it seems that these negative or lacking system functions are outweighed by the positive build-up of activities, due to the hype and high expectations that dominate that period.

However, as the energy market is liberalised in 1998, the high expectations are shattered quickly. Unsolved technical problems and a poor economic performance ensure that biomass gasification is not ready for introduction in a turbulent market environment. This results in the discontinuation of the North Holland project (Figure 4.1, see markings in the graph) and the

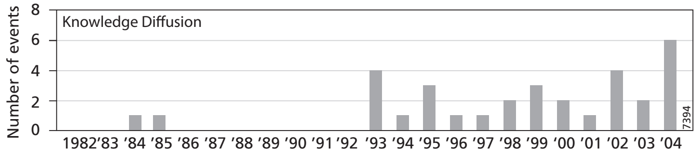

Figure 4.3 Trend pattern of system function 3: Knowledge Diffusion.

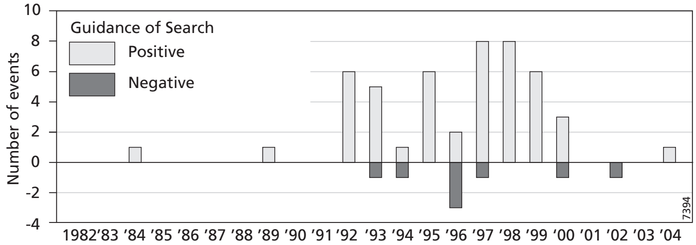

Figure 4.4 Trend pattern of system function 4: Guidance of the Search.

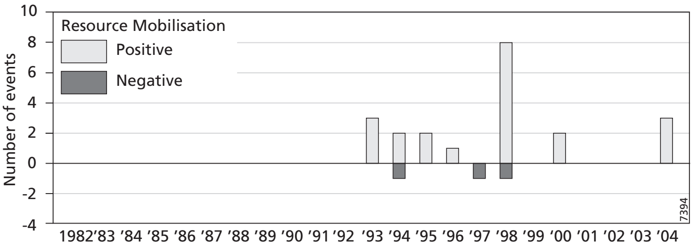

Figure 4.5 Trend pattern of system function 6: Resource Mobilisation.

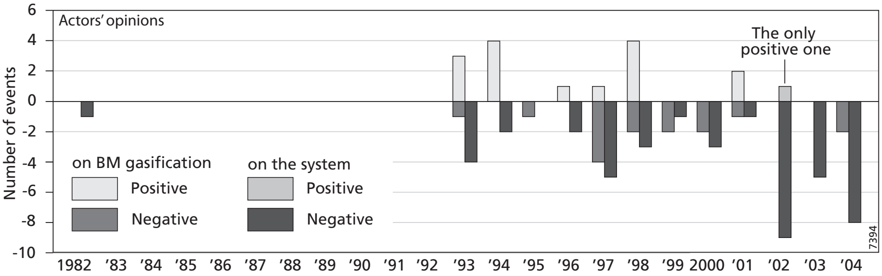

Figure 4.6 Trend patterns of actors' opinions about the BGTIS.

closure of several other small-scale plants that have been set up in previous years (Figure 4.1, see negative peak of projects aborted in 1998). In addition, most of the other activities in the BGTIS are discontinued as well; entrepreneurs and energy companies are reluctant to take high risks within the context of a liberalised market. No more research or studies are carried out (Figure 4.2, drop of positive line after 1998), and allocation of resources (F6, see Figure 4.5, drastic drop of positive line in 1998) and specific guidance (F4, Figure 4.4, drop after 1998) for biomass gasification are discontinued. In addition stricter emission regulations are introduced in 2000, which result in the shutdown of several small-scale plants (see Figure 4.1, negative line between 1999 and 2004 representing the shut-down of small-scale plants). Thus, the sequence of events after 1998 results in the collapse of the previous virtuous cycle.

The revival of biofuels seems to bring biomass gasification technology back onto the political agenda as a key technology for 2G biofuels, however, no increase of other activities occurs then. The critics on the TIS remain negative, due to inconsistent government policy that fails to provide consistent long-term support for biomass gasification technologies (see Figure 4.6, negative opinions about system).

4.4 Conclusions

Despite the promises of high energy conversion efficiency and the wide variety of applications, biomass gasification technology has not been successfully developed and implemented in the Netherlands. We applied the *Functions of Innovation Systems Approach* to obtain more insight into the dynamics of the BGTIS and the factors that induced or blocked its development. The most important insights gained are highlighted below.

The main inducement factors for the evolution of the BGTIS – in the period studied – are the high expectations and optimism about biomass gasification being an efficient and profitable energy production technology. This results in the initial hype where the build-up of the BGTIS becomes a reality; system functions such as *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search* and *Resource Mobilisation* mutually reinforce each other in this period. This virtuous cycle lasts for a period of six years (1992-1998).

One of the important blocking mechanisms arises when two drastic changes occur in the institutional system within which biomass gasification technology develops. Firstly, when the energy market is liberalised in 1998, and, secondly, when the emission regulations are changed, biomass gasification technology has not reported enough positive results to be accepted as a proven technology. Many actors become reluctant to give further support to biomass gasification, which results in the abortion of various initiatives and activities. This is reflected in the decline of function fulfilment, i.e., no more *Entrepreneurial Activities*, decreasing *Knowledge Development*, no more specific positive *Guidance of the Search*, and no more *Mobilisation of Resources* to biomass gasification technologies.

The main blocking factor throughout the entire period is the absence of the national government with respect to a clear and consistent policy support for biomass gasification technologies. Over the years, the opinions of actors within the BGTIS show that there is an absence of available public resources, guidance, and other forms of support for biomass gasification.

From our case it seems reasonable to assume that gasification technology still needed a protective environment to be able to develop further. Instead, the abovementioned events forced the entrepreneurs to move to a free market environment and either to accept or completely reject the technology. When a new technology is served-off like this, two opposite conclusions may be drawn. The first is that the BGTIS was successful in screening out unfit technologies; the second is that the BGTIS did not function well enough to protect the emerging technology from a harsh market environment. In this case, clearly the second conclusion needs to be drawn, since, for a technology to be declared incompatible, many experiments should be carried out first that show that the technical problems (which are inevitable) cannot be solved. In the Netherlands, though, only one project was realised and, after several years, the technical problems were solved. For an emerging technology to have any impact, it has to go through a lengthy, uncertain and painful process of trial and error. However, in this case, only one project went through this process, all other projects were already dismissed before the first trial phase.

The general conclusion that can be drawn from this is that a structural misalignment occurred between the institutional framework within which the technology was developing, on the one hand, and the technical requirements on the other. Here, the government should have intervened by creating the right conditions, for instance, by stimulating niche markets and/or by providing long-term R&D support for the emerging biomass gasification technology.

Interlude B

The following chapter contains a case study on the development of biofuel technologies in the Netherlands. A specific feature of this study is the analysis of different technology groups (1G and 2G) within a single TIS.

The focus of the analysis is on the identification of motors of innovation, and the underlying structural drivers and barriers. The chapter does not systematically pay attention to the development of TIS structures.

The chapter is written in article form. It is largely based on an article that has been submitted for publication and is currently under review. Parts of the chapter are also taken from: Suurs, R.A.A. and Hekkert, M.P., 2008a. Competition between first and second generation technologies: Lessons from the formation of a biofuels innovation system in the Netherlands (forthcoming in Energy).

5 The biofuels TIS (NL)

5.1 Introduction

The literature on innovation systems stresses the importance of path dependency, positive feedback and cumulative causation for understanding technological change and long-term economic growth (Andersen et al., 2002; Carlsson et al., 2002b; Carlsson and Stankiewicz, 1991; Lundvall, 1992). Our insight into what more generally could be called system dynamics is still limited, however (Hekkert et al., 2007; Jacobsson and Bergek, 2004). The majority of innovation system studies conducted so far start from the aggregated perspective of a national or sectoral economy. The scope and complexity of such systems make a thorough analysis of dynamics difficult, or even unfeasible, and as a result of this, most empirical studies aim at making static comparisons. Our understanding of innovation system dynamics is especially lacking for systems that are only just emerging (Jacobsson and Bergek, 2004; Lundvall, 2007). This is crucial in this area, however, since it is these innovation systems that can still be shaped and influenced; cf. Collingridge (1980).

The conscious shaping of an innovation system becomes especially relevant when one considers that technological change plays a crucial role in the transition to a sustainable energy system. However, with the fluidity of emerging innovation systems, the task of supporting sustainable energy technologies remains difficult. This is illustrated by their exceptionally low market shares, despite efforts by many European governments to support the development of renewable technologies (IEA, 2004c). Currently, renewables are locked-out of the energy system (Unruh, 2000) which not only implies the absence of a well-functioning market for renewables but also an immature supply system and poor – or unfit – supporting infrastructures, in terms of technology, policy, knowledge bases, finance, user communities etc.

Even if trust is placed in a particular emerging technology, it is still unclear how it should be supported (Coates et al., 2001). Therefore, the aim of this study is to contribute to insights into the innovation system dynamics that induce or block the successful development and diffusion of emerging technological trajectories in the context of sustainable energy innovation. We will do this by, theoretically and methodically, expanding on the Technological Innovation Systems (TIS) approach (Carlsson and Stankiewicz, 1991).[74] The TIS is a social network, constituted by actors and institutions, that is constructed around a specific technology.[75] Recent TIS literature particularly stresses that emerging technologies need to pass through a formative stage before they can be subjected to a market environment (Jacobsson and Bergek, 2004). During this formative stage, market diffusion is typically absent or insignificant, but actors are drawn in and technologies and

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[74] Carlsson and Stankiewicz actually use the term 'technological system' instead of 'technological innovation system', but this term usually refers to the notion of 'large technological system' (LTS) introduced by Hughes (Carlsson and Stankiewicz, 1991; Hughes, 1983). To avoid the confusion of concepts we choose to stick to the term that now has largely proliferated within the literature.

[75] A more precise definition will be given in the next section.

institutions are designed and adjusted. In short, structures are shaped that, positively or negatively, influence the emerging technological trajectory.

In many studies on innovation systems, these system structures are regarded as static, rendering them unfit to deal with the dynamics of emerging technological trajectories (Jacobsson and Bergek, 2004). Alternatively, following Rickne, Liu and White, Edquist, Bergek and Jacobsson, the build-up, or breakdown, of innovation system structures can be conceptualised in terms of key activities, or system functions (Bergek, 2002; Edquist, 2004; Jacobsson and Bergek, 2004; Liu and White, 2001; Rickne, 2000). Examples of such system functions are *Entrepreneurial Activities*, *Knowledge Development*, and *Resource Mobilisation* (Hekkert et al., 2007). The core of our analysis is to point out occurrences of positive feedback, or cumulative causation. Recent TIS studies suggest that cumulative causation can be captured by pointing out interactions between system functions (Bergek, 2002; Hekkert et al., 2007; Jacobsson and Bergek, 2004). This helps to explain successes and failures in the development of a TIS.

These efforts reveal that progress has been made with conceptualising dynamics. This direction of research is supported by Edquist (2004), who states in his overview of innovation systems literature that there remains a conceptual diffuseness to most studies. One reason for this is that empirical studies relate only superficially to the 'theory', and vice versa. Edquist suggests that one way to increase theoretical depth is to provide a clear description of system functions (activities) (Edquist, 2004). Another important recommendation is to integrate conceptual work more with in-depth empirical studies. We need insights into the particular dynamics of specific, historically-embedded technological trajectories.

In this study we take up this recommendation through analysing an empirical case and by introducing a new method for operationalising cumulative causation in innovation systems: an event history analysis (Poole et al., 2000). This approach takes 'events' as elementary units of analysis. This means that the unfolding of system functions over time is mapped in terms of events and sequences of events. Based on the sequences, we identify forms of cumulative causation, and indicate how these influenced the historical formation of an emerging TIS.

Our empirical focus is on the developments around biofuels in the Dutch automotive sector. The automotive sector is an interesting domain since, in order to reduce oil dependency and to meet (post-)Kyoto climate targets, the automotive sector is a crucial, and yet until recently highly neglected, target for innovation policy (Blok, 2005). We will analyse eighteen years of system dynamics in biofuel innovation.

This brings us to the following research question:

RQ: How did innovation system dynamics influence the formation of a Dutch biofuels innovation system from 1990 to 2005?

Section 5.2 describes our theoretical approach. In Section 5.3 the method of event history analysis is explained. Section 5.4 provides the application of theory and method in the case study on Dutch biofuels. Section 5.5 provides a reflection on the empirical results. Finally, in Section 5.6 we will conclude with arguing the value of our contribution to innovation systems research. Throughout the chapter, policy implications will be addressed.

5.2 Theory

From the 1980s onwards, innovation system studies have pointed out the influence of the social system on innovative performance. Different approaches exist – for an extended review, see Carlsson et al. (2002b), Lundvall et al. (2002) and Freeman (1995) – but all studies point to the structure of the innovation system as the explanatory basis. This idea has been well developed by Lundvall (1988; 1992), who stresses the importance of a broad selection of societal sub-systems, from R&D laboratories and production facilities to financial and educational systems, providing they contribute to the national innovation process.

Such a conception is highly relevant to understand macro-economic differences between modern states. However, as Carlsson and Stankiewicz (1991) argue, the national innovation systems approach fails to address the problem of how specific technological innovations are more or less successful. In this case the detailed characteristics of structures that constitute a technological field are more important determinants. These may persist just as well across as within national borders. A second point of criticism, which holds for innovation systems studies more generally, is its static perspective. Mapping the contours of innovation systems and analysing the (lack of) interaction between components does not explain how the system came into being. A dynamic framework is required, especially when one is interested in emerging technologies, such as sustainability innovations.

Many studies have provided conceptual and empirical evidence that supports the usefulness of the TIS approach for analysing emerging technologies, and in particular sustainability innovations (Bergek, 2002; Hekkert et al., 2007; Jacobsson and Johnson, 2000; Negro et al., 2007; Negro et al., 2008). We follow this strand of literature in defining the biofuels TIS as those structural elements (and their mutual relations) that directly support (or reject) the development and (eventually) the diffusion of biofuels in the Netherlands.[76] These consist of actors, institutions, and the network of relations through which they are connected (Carlsson et al., 2002b).[77] The general idea is that the configuration of structural elements influences the rate and direction of technology diffusion.

We propose to analyse the development of the biofuels TIS to explore its historical successes and failures. The difficulty is that, in this case, a TIS is only just beginning to emerge, providing little basis for evaluation. Carlsson et al. suggest that multiple dimensions should be addressed when assessing the development of emerging technologies, covering the generation, diffusion, and use of knowledge (Carlsson et al., 2002b). These dimensions should be measured by the indicators of scientific research input, societal embedding, and market penetration. Such an analysis is very

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[76] This is based on the following definition by Carlsson and Stankiewicz: 'A [TIS] may be defined as a network of agents interacting in the economic/industrial area under a particular institutional infrastructure (…) and involved in the generation, diffusion, and utilisation of technology.' (Carlsson and Stankiewicz, 1991, p. 93).

[77] The structure of the TIS is also affected by features of technological objects. By definition, these objects are exogenous to the innovation system, but their features could very well be considered part of it. See Sandén and Jonasson (2005) for an application of this idea.

Table 5.1 Functions of technological innovation systems.

F1. Entrepreneurial Activities	At the core of any innovation system are the entrepreneurs. These risk takers perform the innovative commercial experiments, seeing and exploiting business opportunities.
F2. Knowledge Development	Technology research and development (R&D) are prerequisites for innovation. R&D activities are often performed by researchers, but contributions from other actors are also possible.
F3. Knowledge Diffusion	The typical organisational structure of an emergent innovation system is the knowledge network, primarily facilitating information exchange.
F4. Guidance of the Search	This system function represents the selection process that is necessary to facilitate a convergence in development, involving, for example, policy targets, outcomes of technical or economic studies and expectations about technological options.
F5. Market Formation	New technologies often cannot outperform established ones. In order to stimulate innovation it is necessary to facilitate the creation of (niche) markets, where new technologies have a possibility to grow.
F6. Resource Mobilisation	Financial, material and human factors are necessary inputs for all innovation system developments, and can be enacted through, e.g., investments by venture capitalists or governmental support programmes.
F7. Support from Advocacy Coalitions	The emergence of a new technology often leads to resistance from established actors. In order for an innovation system to develop, actors need to raise a political lobby that counteracts this inertia, and supports the new technology.

useful, and in fact resembles, partly, what we will do in this chapter. Still, such an approach does not provide insight into cumulative causation. For that we also need insight into the historical interdependence of these dimensions.

Recently, scholars have made progress by suggesting how a TIS assessment can provide a dynamic perspective by keeping track of system functions as they unfold through time (Bergek, 2002; Edquist, 2004; Hekkert et al., 2007; Jacobsson and Bergek, 2004; Negro, 2007). These system functions are crucial processes, or key activities, that influence each other and foster the shaping and the diffusion of a technology. The premise is that a TIS should realise multiple system functions, each of which covers a particular aspect of technology development. Based on a review of innovation systems literature, a shortlist of seven system functions has been formulated (Hekkert et al., 2007); see Table 5.1 for definitions.

Various 'lists' of system functions have been constructed (Bergek, 2002; Borrás, 2004; Carlsson and Jacobsson, 2004; Edquist, 2004; Johnson, 2001; Liu and White, 2001; Rickne, 2000). Authors like Bergek et al. and Hekkert et al. give useful overviews (Bergek et al., 2008a; Hekkert et al., 2007). The general conclusion is that the lists show overlap, and that differences reside mostly in the particular way of clustering activities. However, we agree with Edquist that our knowledge is still provisional and will need to be adjusted as our insight grows. The list needs to be confirmed (or falsified) by empirical evidence (Edquist, 2004). For a large part such empirical validation has been provided, for instance, in studies by Negro, Alkemade and colleagues (Alkemade et al., 2007; Negro et al., 2007; Negro et al., 2008). These studies support our assumption that the set of system functions as given above corresponds well to the empirical data relevant in the field of sustainability innovations. Still, our methodology should leave room for adjusting the list, based on the (partly) unexpected outcomes of the empirical work.

The seven system functions are considered a suitable set of criteria for the assessment of a TIS in the formative stage. We expect that as actors, institutions, and networks are successfully arranged to bring about a fulfilment of system functions, the chances of technology diffusion will increase. To some extent, system functions need to be realised simultaneously, since they can complement each other. A TIS may very well break down due to the absence of a single system function. For example, Kamp (2002) shows that the Dutch wind energy innovation system was well developed in the 1980s but collapsed as the result of an important deficiency, namely the absence of *Knowledge Diffusion* between the emerging turbine industry and users, the latter being energy companies in particular.

As mentioned, a TIS does not come to its full realisation overnight. Therefore we are interested in the way system functions are built up. Being complementary processes, system functions will interact with each other (Hekkert et al., 2007; Jacobsson and Bergek, 2004). For instance, the successful realisation of a research project may result in high expectations and increased guidance activities among policy makers, which may, subsequently, trigger the start-up of a subsidy programme, to support even more research activities, etc. Thus, the interaction between system functions can result in the unfolding of a cumulative causation (Myrdal, 1957).

Multiple forms of cumulative causation may exist. In the ideal situation, the sequence of activities will form a virtuous cycle and trigger a take-off. Another possibility is that a sequence is less predictable, but still contributes to cumulative dynamics. Conversely, a sequence may also result in conflicts, a complete standstill, or even a vicious cycle. In short, multiple sequences are conceivable that result in a positive, or negative, development process. In this respect our approach reflects the opposition of the innovation systems approach to the linear model that states that technological trajectories are characterised by a fixed sequence of activities: R&D, prototype testing, niche market development, up-scaling; cf. Lundvall (1988). The identification of various forms of cumulative causation, or motors as they can be called (Van de Ven, 1993; Van de Ven et al., 1999), will be at the core of our analysis.

Note that the dynamics that unfold through the emergence of cumulative causation are primarily the result of factors (or events) internal to the TIS. However, they will be influenced by external factors as well, such as technical possibilities, historical shocks, and international trends. These will be mentioned in the analysis as background movements.

5.3 Method

The analysis of a TIS in a formative stage requires an empirical methodology that captures the microdynamics that contribute to its realisation. Traditional empirical methods fall short here. For example, bibliometric methodologies, as applied to publications or patents, are limited to the analysis of *Knowledge Development*, while social network analysis is limited in that it detects only network formation, i.e., *Knowledge Diffusion* or *Support from Advocacy Coalitions*. Similarly, firm data are well suited to analyse *Entrepreneurial Activities*, but are less suitable to construct indicators for other system functions. A more flexible, yet systematic, methodology to analyse the realisation of system functions is the event history analysis, as developed in the context of organisation studies; see Poole (2000). In the analysis as we apply it, events are the input data for two analyses that mutually support each other; one based on the qualitative reconstruction of a historical narrative, and one based on the quantitative identification of aggregate trends.

The starting point for both analyses is to construct a database in which events are clustered into types. The selection of events and their clustering is essentially an exercise of interpretation in which a large amount of data is surveyed and analysed.[78] Each instance of change with respect to actors, institutions and the technology, which is the work of one or more actors and which carries some collective importance with respect to the TIS under investigation, is considered an event. Besides events, context information is also retrieved from the documents. This provides the background for understanding the events and guides their positioning in a narrative.

The next step is to determine if and how the event types can be allocated to system functions. For instance, feasibility studies are regarded as contributing to *Knowledge Development* and the projects started contribute to *Entrepreneurial Activities*. This way the event types serve as empirical counterparts of system functions. The clustering of events into event types and the allocation of event types to system functions is checked by multiple researchers to avoid personal bias. Differences are discussed and resolved.

It may seem far-fetched to introduce the additional step of the construction of an event typology, but this is a necessary procedure to reduce the chances of ending up with a self-fulfilling prophecy where the theoretically defined system functions are the only processes visible to the researcher. For instance, we may end up with event types that are difficult to relate to any one of the system functions. This would be an indication that our list of system functions is incomplete. Thus, working iteratively from empirical material, guided by theory, towards an event typology makes sure that the system functions are not only measured, but also empirically validated. This way our approach strengthens the integration of empirical and theoretical work.

For our case, a literature search was carried out using Dutch periodicals in the period 1990-2005. The following keywords were used (translated from Dutch); bio(-)fuel, bio(-)ethanol, bio(-) diesel, dme (dimethylether), fischer-tropsch, htu (hydrothermal upgrading), pure plant oil, ppo (pure plant oil). See Table 5.2 for an overview of all sources used. In total about 1100 events were retrieved to form the basis of our analysis. All event types could be mapped on the current set of system functions, which is a (tentative) validation of the seven system functions used in this study. The allocation scheme resulting from our literature search is given in Table 5.3.

Note that some event types have a positive sign while others have a negative sign. This is an indication of whether the event type contributes positively or negatively to the development of the TIS. For example, negative expectations about the technology or policy decisions that are not in favour of the technology under investigation are labelled negative.

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[78] The clustering is based on similarities between the events.

Table 5.2 Literature sources.

Professional Journals

Agrarisch Dagblad
Boerderij
Duurzame Energie
Energie- en Milieuspectrum
GAVE Newsletter
Logistiek Krant
Stromen

Web Sites

Website and Publications ECN
Website NEO
Websites Senter, Novem, SenterNovem
Website VROM

National News

Algemeen Dagblad
ANP
De Telegraaf
De Volkskrant
Elsevier
NRC Handelsblad
Trouw

Financial News

AFX – NL
BIZZ
FEM Business
Het Financieele Dagblad

Regional News

BN/DeStem
Brabants Dagblad
Dagblad Flevoland
Dagblad Tubantia/Twentsche Courant
Dagblad van het Noorden
Dagblad voor Zuidwest-Nederland
De Dordtenaar
De Gelderlander
Deventer Dagblad
Eindhovens Dagblad
Gelders Dagblad
Goudsche Courant
Haagsche Courant
Het Parool
Leeuwarder Courant
Provinciale Zeeuwse Courant
Rijn en Gouwe
Rotterdams Dagblad
Utrechts Nieuwsblad
Veluws Dagblad
Zwolse Courant

Based on the ideas of Abell (1987) and Poole et al. (2000), the event data are subjected to two types of analysis. Both are based on recognition of patterns in the data: trend patterns and interaction patterns. The first technique involves a mostly quantitative approach and aims towards deriving trends from aggregated event data over a longer period of time. The second technique is primarily based on the construction of a narrative, and aims to find 'causal' chains between events.

Trend patterns indicate the fulfilment of individual system functions over time. Ideally, this is done quantitatively by plotting the aggregated number of events for each year per system function. The slope of the graph represents the increase or decrease in the activities per system function. This representation is useful as it gives insight into major turning points of the TIS development such as, for instance, a sudden decline in the intensity of the *Guidance of the Search* function. If the available data allows it, more detailed insight can be obtained into the way system functions are specifically fulfilled. For example, the analysis could show a shift in the share of activities conducted by particular actors (public or private). Alternatively, there may be shifts in the share of different technological varieties being developed (as, in our case, with respect to first-generation and a second-generation biofuels). It is the task of the researcher to anticipate important differentiations and to categorise the events accordingly.

If trend patterns represent the aggregate outcomes of TIS development, then interaction patterns offer a possible explanation for these outcomes on the micro-level. Before clarifying this, it is important to understand that the advantage of using events as indicators is that they can be connected through 'leads-to relations', to form a sequence. These relations can be traced in the database, as many events refer to past events. This feature enables us to construct a narrative in which the sequences serve to construct coherent storylines. By relating event sequences to system functions, again according to Table 5.3, we obtain insight into how system functions interact.

Table 5.3 Measurement scheme for mapping empirical events to system functions.

System function	Event type	Description	N	Sign
F1. Entrepreneurial Activities	Portfolio expansion	A (vested) actor explores activities without any previous experience.	11	+
	Project entry/Start	Technology is explored within a societal context and/or with a commercial goal.	95	+
	Project exit/Failure	Exploration activities are cancelled.	19	-
F2. Knowledge Development	Opinion	Actors' critical notes on institutions and/or past developments.	N/A	N/A
	Learning by exploring	Assessment research with no direct commercial orientation.	121	+
	Learning by doing	Practical research with no direct commercial orientation.	45	+
F3. Knowledge Diffusion	Network, Coalition	Co-operation between actors.	N/A	N/A
	Meeting	Workshops, conferences, etc.	61	+
F4. Guidance of the Search	Classification, Standard setting	-	3	+
	Doubt, Uncertainty	Expression of the technology's uncertain circumstances.	N/A	N/A
	Expectation positive	Expression of the technology's future expectations.	224	+
	Expectation negative	Negative expressions of the technology's future expectations	46	-
	Award	-	5	+
	Outcome study positive	Positive results of research and trials, often mentioned when reports are published.	81	+
	Outcome study negative	Negative results of research and trials.	32	-
	Promise or target positive	Promises by actors with the power to change institutions, complementing the technology.	171	+
	Promise or target negative	Promises by actors with the power to change institutions, hampering the technology.	22	-
	Technological guide, manual	Aid to support entrepreneurs.	10	+
F5. Market Formation	Tax exemption starts	-	N/A	N/A
	Tax exemption stops	-	N/A	N/A
	Niche market	Protected spaces where practical experiments can be conducted in a market environment.	N/A	N/A
F6. Resource Mobilisation	Feedstock	Content related to availability of biomass resources.	N/A	N/A
	Investment, Subsidy	Including dedicated subsidy programmes.	27	+
	Resource refusal	Rejection of financial support and cutbacks.	1	-
F7. Support from Advocacy Coalitions	Dissent	Conflicting interests around the technology.	N/A	N/A
	Lobby or advice pro	Pressure on actors in power to change institutions, complementing the technology.	138	+
	Lobby or advice contra	Pressure on actors in power to change institutions, hampering the technology.	20	-

Of the event types used for quantitative analysis, the number of events available is given, as well as whether its effect is positive or negative with respect to its contribution to the BFTIS (sign).

If system functions reinforce each other, we define this as cumulative causation. This may be a sequence of different system functions that positively reinforce each other, like mobilisation of public resources [F6], resulting in studies [F2] which deliver promising results, raising expectations [F4], and encouraging entrepreneurs to start businesses [F1] that result in more resources being allocated [F6] and more knowledge being developed [F2]. Ideally, a cumulative causation takes the form of a virtuous cycle: a sequence which repeats itself over time. If negative events reinforce each other, a system breakdown – i.e. a vicious cycle – may occur.

Note that event sequences may diverge, as one event may lead to multiple other events, or converge, as multiple events may be necessary before they can lead to one other event. As a shorthand, we will label various types of cumulative causation as motors, after Poole et al. (2000).

Insights from both analyses mutually strengthen each other. The trend patterns can be used to distinguish and characterise particular 'episodes' in the narrative. The interaction patterns unfolding within an episode may explain the occurrence of the trend patterns.

The construction of the event sequences and the narrative is done as 'objectively' as possible based on empirical sources. Still, the interpretation of the researcher is a crucial factor. To minimise personal bias, the narrative is verified, i.e., triangulated, and if necessary reconstructed, by including feedback from interviews with experts.[79]

In the next section, we reconstruct the development of the BioFuels TIS (BFTIS) and refer to the various system functions as F1, F2, F3 etc., following Table 5.1. The narrative is chronologically ordered and divided into six episodes. Motors will be identified for each episode, if present. The background movements of the BFTIS are covered as an introduction to each separate episode.

5.4 The event history of the BFTIS

Before starting the narrative, it is important to introduce a remarkable (technological) feature of the BFTIS, namely the existence of two distinct technology groups: first- generation (1G) and second-generation (2G) biofuels. Both technology groups connect to different knowledge bases and separate sectoral backgrounds. The 1G fuels are based on conventional technologies, mainly adopted by farmers' organisations. Agricultural crops are used, such as rapeseed or sugar beet, to produce biodiesel or bioethanol. The 2G biofuels originate from more science-based technologies (chemical and biotechnological) that are mostly advocated by research institutes and oil companies, but also by biotech industries and dedicated entrepreneurs. With the 2G technologies, woody biomass, consisting of waste wood or cultivated energy crops, is converted to 'biocrude', 'Fischer-Tropsch biodiesel' or 'cellulosic bioethanol' (all synthetic substances). The 2G biofuels are currently in a pre-commercial stage of development.

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[79] Seven interviews have been conducted with biofuels experts: entrepreneurs, senior policy makers and policy researchers. Also numerous informal conversations with researchers and policy experts have been used to check key insights.

It is currently expected that – in the long term – 2G biofuels offer the possibility for larger reductions in CO_2 emissions at lower costs than 1G fuels.[80] Another advantage of 2G biofuel technologies is that they can draw upon a wider variety of biomass resources, including waste materials. On the other hand, the 1G biofuels seem to offer a better perspective in terms of costs and implementation in the present and in the near future. As will be shown, the dynamics of the Dutch BFTIS largely revolve around a clash of these two technology groups.

With respect to utilisation in vehicles, biofuels may be used in their pure form but then significant vehicle changes are necessary. For blends, only minor changes are necessary. The exception to this is Fischer-Tropsch biodiesel, which can be used in regular diesel engines.

5.4.1 Emerging biofuel technologies (1990-1994)

During the early 1990s, there is no political urgency for a sustainable energy system. Oil prices are low and the climate issue is barely mentioned in (international) political arenas. The biofuels issue arises in Europe as an effect of a background movement: the decline of the agricultural sector. The European trade protectionism of the past decades has resulted in massive production surpluses and an unacceptable budgetary burden (NRC, 1991). In countries such as France and Germany, where (bulk) agriculture is relatively important, biofuels are first presented as a way out of this impasse. With the production of non-food crops, the sector could be aligned with a new market with new opportunities. In 1992, within the context of this 'agrification' idea, Europe proposes to financially support biofuels (NRC, 1992a) by proposing a scheme for generic tax exemptions. Furthermore, farmers are offered a premium for the cultivation of non-food crops. Environmental benefits are mentioned as the prime reason for these subsidies (EU, 1992; TRW, 1992).

In the Netherlands, this background movement is picked up by a group of entrepreneurs who start adopting biofuels [F1]. In the rural province of Groningen, a public transport company starts a trial [F2] with bioethanol in buses. A number of actors is involved, among them the alcohol producer Nedalco (AD, 1992c). Another trial [F2] is started in the city of Rotterdam, where buses are fuelled with biodiesel. Funding is provided by the companies themselves and through European subsidies [F6]. Figures 5.1 and 5.2 illustrate that these and other entrepreneurial experiments and trials [F1, F2], are the first signs of a Dutch BFTIS taking shape. The trials [F2] turn out to be technically successful [F4] despite the fact that the engines of the buses in Groningen incidentally catch fire (DG, 1995). A less positive outcome of the experiments is their low economic feasibility: under the present circumstances, biofuels cannot compete with fossil fuels [F4].

At this time biofuels fall under the same tax legislation as fossil fuels. Measures of national support are absent [F4, F5]. This relates to the emergence of a controversy around the use of biofuels. Illustrative of this is that, in 1992, the Dutch government agency for energy and environment (Novem) states that implementation of biofuels is too expensive compared with co-firing biomass in power plants [F4] (AD, 1992b; NRC, 1992b). Various assessment studies [F2] now set the tone for a 'debate' [F4] that will go on until today. Regional actors emphasise the strategic and environmental value of biofuels, whereas scientists and environmentalists stress their meagre performance. The Dutch government initially remains silent due to its internal division on

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[80] For a condensed technological overview of the different types of biofuels, see Schubert (2006).

the biofuels issue [F4]. In spring 1993, the Ministry of Agriculture takes a stance against public support [F4] (ANP, 1993a), whereas the advisory council on social-economic issues (SER) advises it to support the experiments [F7] (ANP, 1993b; TRW, 1993). Only a year later, in 1994, the Ministry of Agriculture decides to announce fiscal support of biofuels [F4], whereas the Ministry of the Environment expresses doubt [F4] (AD, 1992a).

Cumulative causation

In this first episode, the system functions are beginning to take shape; they are mainly driven by external factors. There is no indication of a cumulative causation internal to the BFTIS. An important trend pattern – one which will be very influential – is a slumbering turmoil with respect to the *Guidance of the Search*: see the negative peaks in Figure 5.3 offsetting the weaker positive ones.

5.4.2 The shaping of the BFTIS (1995-1997)

From 1995 onwards, a background movement is the gradual shift within the international energy domain; the climate issue is becoming a matter of political interest and the concept of biomass is becoming important in the energy sector (DE, 1995a; DE, 1996d).

In the Netherlands, a first series of projects is initiated which contributes to a sequence of further activities. It starts in 1995 in the rural province of Friesland, where two boating companies initiate adoption experiments with biodiesel [F1] (FD, 1995). An important reason is the increasing regulatory pressure with respect to the surface water quality [F4]. Biodiesel is biodegradable and poses only a limited threat to the water quality. The companies demand a national fuel tax exemption for the project [F7]; the provincial government and the district board of agriculture support the idea by forming an advocacy coalition towards the national government [F7]. They are successful and a first tax exemption is provided, for two years [F6] (FD, 1995). As the province decides to adopt biodiesel for its fleet of service boats, a virtuous cycle emerges. The adoption experiment improves existing knowledge [F2] and, most importantly, it serves as an example to others in the field [F4]. Several other boating projects start [F1] (see Figure 5.1) and once again tax exemptions are demanded [F7], and issued [F6]. Subsequently, the 1G technologies gain even more attention [F4], especially due to the positive outcome of the trials [F2].

A crucial barrier to these developments is that, meanwhile, various impact assessments [F2] yield contradictory or negative results for 1G fuels [F4]. Figure 5.3 shows the negative climax of this movement in 1996. The national government does not take a clear stance in the debate, as tax exemptions are issued on project-specific grounds [F6] instead of on the basis of a policy strategy. There is at this point in time no structural form of support [F4]. An issue that keeps coming up in this respect is the budgetary gap that would have to be filled if a generic fuel tax exemption was to be issued [F5] (MinVROM, 2006).

Around the same time, in 1995, Nedalco, an alcohol producer, starts to play an influential role in pressing the national government to change the tax scheme. Nedalco's business expansion [F1] starts with a trial production of bioethanol [F2] (FD, 1996a). Together with other companies, plans are made for a pilot plant [F3]; pressure is put on the government to issue a tax exemption [F7]. According to Nedalco, returns cannot cover the investments without a tax exemption (Nedalco, 2005). Nedalco succeeds in raising attention to the possible advantages of bioethanol [F4]; see

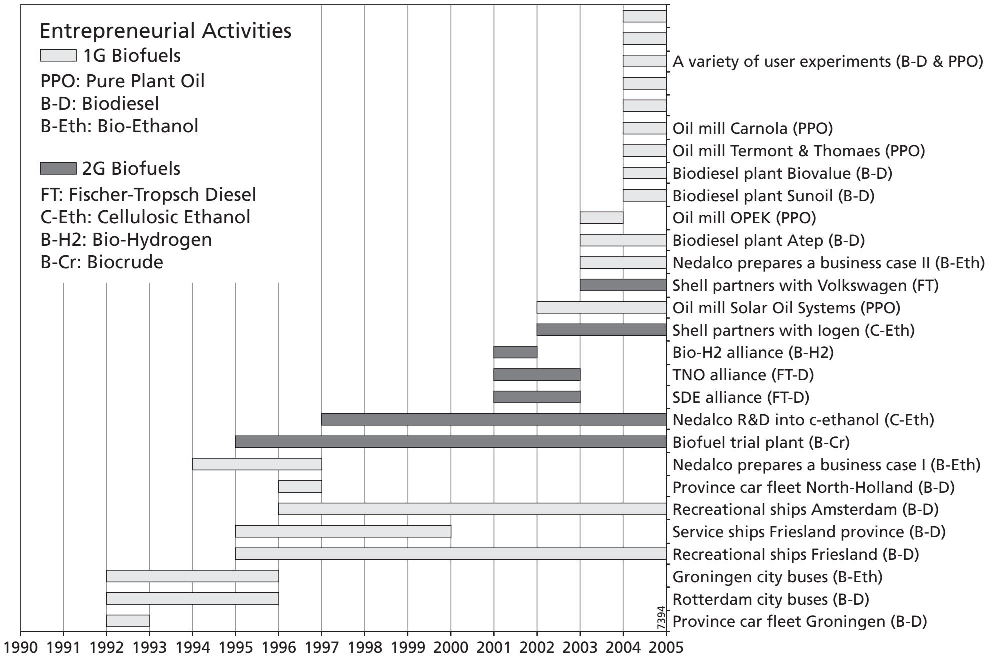

Figure 5.1 Key events related to Entrepreneurial Activities [F1].

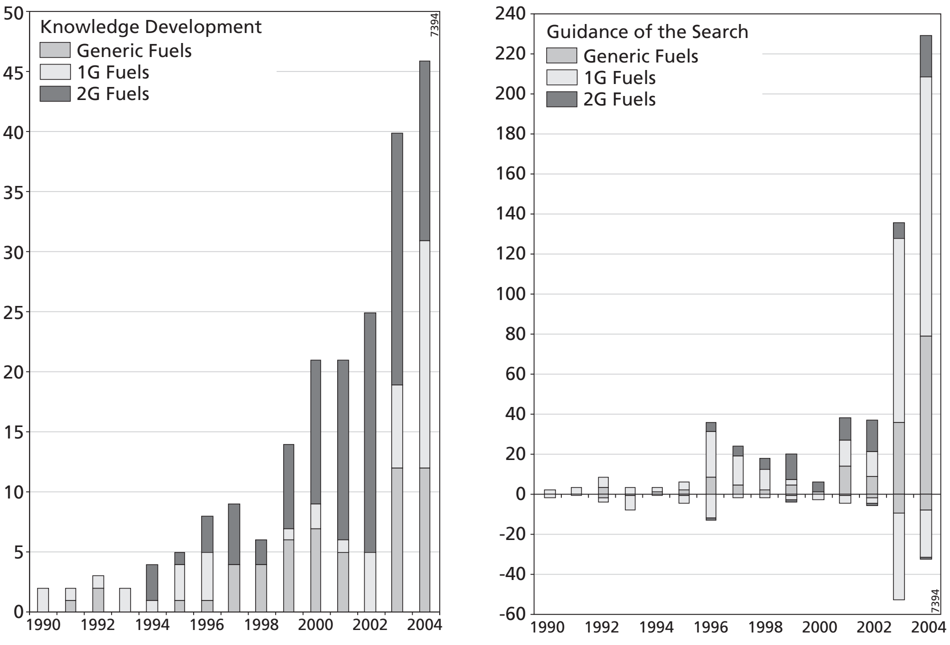

Figure 5.2 Knowledge Development [F2] (aggregated events/year).

Figure 5.3 Guidance of the Search [F4] (aggregated events/year).

the trend in Figure 5.3. Its political lobbies [F7] are complemented by positive announcements in the media [F4] and by the outcome of new assessment studies [F2], carried out under the supervision of Novem [F4], confirming the potential of its project (E&M, 1996a) [F4]. In the summer of 1997, Nedalco succeeds in persuading [F6] the national authorities to guarantee a ten-year tax exemption [F5] for the annual production of 30 million litres of bioethanol. Furthermore, a subsidy is promised for the expansion of Nedalco's activities [F6] (DS, 1998). However, the apparent success is undone by the fact that the tax exemption turns out to be insufficient to cover the investments (Nedalco, 2005).[81] As a result, the project is discontinued [F1] and the plans remain just a promise.

Nevertheless, Nedalco's project is successful in the sense that it takes a stance against the government's resistance to (1G) biofuels. A lasting effect of Nedalco's activities is the recognition in the field of 1G biofuels as a viable option. Figure 5.3 illustrates this trend, a rise to a high level of guidance (mainly expectations) around (all types of) biofuels by 1996.

So far, not a drop of biofuel has been produced within the Netherlands, although a first attempt to supply biofuels has been made. The episode is characterised by an increasing attention on biofuels and by the first real steps being taken by national government authorities to actually support biofuels. The tax scheme remains an important barrier, still not differentiating between fossil fuels and biofuels. Also, the government mainly follows the entrepreneurs instead of taking a strategic lead. This is about to change.

In 1996 the possibility of using 'solids to liquids' technology starts receiving media coverage [F4]. Academic researchers and environmentalists have mainly been calling attention to the negative properties of 1G fuels (DE, 1996a; DE, 1996c; DE, 1996e), thereby discrediting the biofuels option as a whole [F4]. However, their criticism now becomes more constructive as they propose an alternative in the form of 2G biofuels [F4]. Previously, the 2G technologies group had been developed in R&D settings [F2] but now a small company named Biofuel – a spin-off from Shell – joins forces with several industrial parties and starts working on the construction of a first pilot plant for the production of 'biocrude' [F1, F3] (E&M, 1997a). This R&D project is financed by both Shell and a national subsidy programme [F6] (Biofuel, 2005).

Cumulative causation

The event sequences observed indicate the emergence of a motor. The event sequence is characterised by contributions to *Entrepreneurial Activities*, *Knowledge Development* and *Knowledge Diffusion*. The role of *Guidance of the Search* (public opinion, press releases, Novem) and *Support from Advocacy Coalitions* (especially the lobbies) has become important as well. The pivot is a recurring lobby (to the government) for resources by regional entrepreneurs [F1-F7-F6-F1]. If successful, the entrepreneurs manage to realise their projects, thereby providing a basis for positive expectations and more projects [F1-F2/F3-F4-F1]. Note that the presence of local regulations, constituting a small niche-market [F5], has been an important success factor.

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[81] In particular, Nedalco's partners are unsatisfied with the limited volume of bioethanol qualified for a tax exemption (MinVROM, 2006).

Given the centrality of *Entrepreneurial Activities* in the interaction pattern, it makes sense to call this motor an *Entrepreneurial Motor*. The rise of *Knowledge Development* and *Entrepreneurial Activities* in the field of both 1G and 2G biofuels are typical for this episode; this is visible in Figures 5.1 and 5.2. Furthermore, Figures 5.3 and 5.4 show the shift of the *Guidance of the Search* and *Support from Advocacy Coalitions* patterns from 1995 to 1998 as a result of these developments. Figure 5.5 shows how *Knowledge Diffusion* – in the form of workshops and meetings on biomass energy – improves during this episode.

5.4.3 The separation of 1G and 2G Biofuels (1998-2000)

In 1998, the climate issue becomes an important background movement. A milestone is the signing of the Kyoto treaty by member states of the European Union in 1998. The European target is to realise more than 60% of the CO_2 reduction through the use of biomass (EU, 1997). In the Netherlands, this target is adopted by various government programmes (DE, 1998a; E&M, 1998b; E&M, 1998c). On top of this the automotive sector is increasingly considered an important target for energy policy (E&M, 1998a; E&M, 1998b).[82] A most significant event during this episode is the initiation by Novem of a national programme for the assessment and support of gaseous and liquid CO_2-neutral energy carriers – the GAVE programme (GAVE, 2005).

So far, the emerging BFTIS has received little government support. A troublesome factor with respect to the issue is the biofuels controversy. GAVE manages to establish a breakthrough in the status quo, by starting up a motor that triggers the following three trend patterns:

The first trend pattern is related to *Guidance of the Search*. Scarcity of biomass has been increasing as a result of growing demands for electricity production [F6] (ST, 1999), causing a dispute on the use of biomass streams for transport versus electricity purposes [F4] (MinVROM, 2006). However, an influential study [F2] authorised by GAVE (KEMA, 2000), designates that biofuel production could certainly be favourable, provided that production scales are sufficiently high [F4] (ST, 2001e). Moreover, a range of alternative energy sources already exists for electricity production, whereas little has been achieved for the mobility domain [F4]. With this argument, GAVE turns to the responsible government ministries and manages to put the issue on the national policy agenda [F7] (GAVE, 2005).

A second trend initiated by GAVE is *Knowledge Development* in the field of 2G biofuels. In 1999, GAVE's first move is to authorise a number of assessment studies [F2] aimed at removing the controversy around various biofuel options [F4]. A pre-study results in a shortlist of fuel chains to be analysed in more detail (GAVE, 1999); the results are based mainly on energy balances and cost figures [F2]. The advice is to support exclusively projects which guarantee a CO_2 reduction of at least 80% [F4] (GAVE, 2005). Subsequently, all 1G options are (de facto) excluded from further assessments. It is within this context that the term 2G biofuel is actually invented to distinguish the contested agricultural biofuels from technologically advanced options (GAVE, 2005). Figures 5.2 and 5.3 show this trend. From 1998 to 2000, the 2G biofuels attain dominance over 1G biofuels.

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[82] Before 1998 – all the way back to the post-oil crisis years – the issue of sustainable fuels for automotive purposes was largely disregarded in the Dutch political arena (MinVROM, 2006).

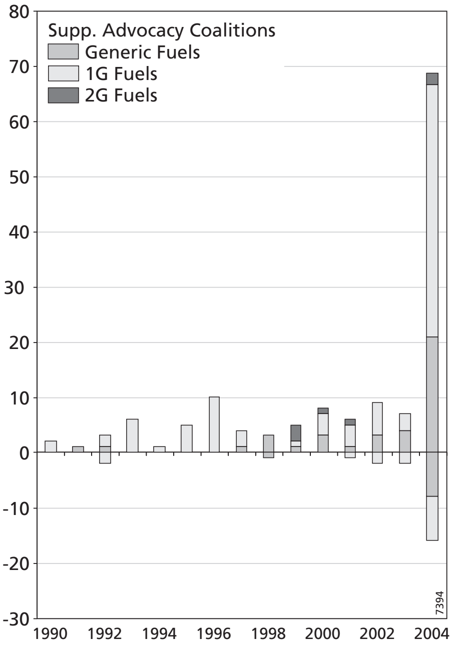

Figure 5.4 Supp. Advocacy Coalitions [F7] (aggregated events/year).

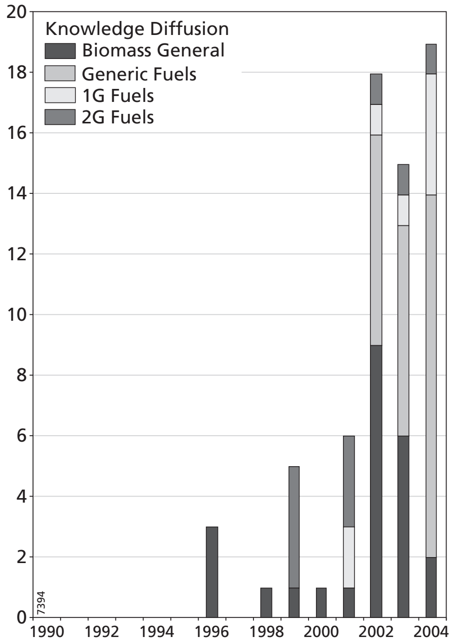

Figure 5.5 Knowledge Diffusion [F3] (aggregated events/year).

The programme creates a spin-off in the form of new undertakings of Nedalco and the Biofuel Company:

The Biofuel Company starts working on a pilot plant [F1] and manages to realise a proof of principle for the HTU process (DE, 1999). Originally, the R&D activities [F2] are not specifically aimed at producing automotive fuels; in fact, the possibility is barely mentioned [F4] (NRC, 1999). However, from 2000 onwards and triggered by GAVE, the Biofuel Company's technological progress is increasingly considered a contribution to the substitution of petrol-based resources [F4] (E&M, 2000; Novem, 2000; NRC, 1999).

Nedalco has also shifted its attention in response to the rise of 2G biofuels [F1]. With the original plan discontinued (as mentioned above), Nedalco now studies the possibility of using 2G biofuels [F2]. A highly innovative R&D project on the production of cellulose ethanol is initiated. Other organisations involved are Wageningen University, TNO[83], and Shell [F3]. The project is partly funded with government subsidies [F6] (Nedalco, 2005).

The third trend is GAVE's contribution to *Knowledge Diffusion*. As Figure 5.5 shows, there are no meetings specifically on biofuel [F3] in the period 1990-1998. From 1998 onwards, general biomass energy meetings become more important, yet, they are still mostly directed at the stationary use of

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[83] TNO is the Dutch Organisation for Applied Scientific Research. The network consists of TNO and a number of companies active in chemical engineering and energy distribution.

biomass.[84] Meetings specifically on biofuel (mainly 2G fuels) start occurring from 1999 onwards. Figure 5.3 shows the positive impact of GAVE on *Guidance of the Search*. From 1998 to 2000, the 2G biofuels attain dominance over 1G biofuels.

Cumulative causation

The main source of dynamics in this episode is the GAVE programme. The programme serves as a catalyst, bundling and connecting activities that, until now, had been developing in relative isolation. The interaction patterns indicates that a motor has emerged which is different from the one in the previous episode. The dominant system functions are now mainly *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search* and *Resource Mobilisation*. The *Support from Advocacy Coalitions* and *Entrepreneurial Activities* are less prominent than before. The dynamic involves positive expectations and/or research outcomes [F4] leading to the setting up of a government R&D programme [F4] and, directly linked to it, the allocation of financial resources [F6], resulting in a boost to 'scientific' activities in the form of feasibility studies [F2], some entrepreneurial experiments [F1] and also conferences, workshops and other meetings [F3]. Given the predominance of scientists and technology developers in developing 2G biofuels, and given that projects are mainly initiated through a government programme, it makes sense to label this form of cumulative causation a *Science and Technology Push (STP) Motor*. Note that the dynamics that characterise this motor are driven by promises of technology developers combined with the visibility, networks, and funding delivered by the policy programme.

The promise of 2G technologies triggers fruitful BFTIS dynamics, yet the negative aspects of 1G biofuels are now further stressed [F4]. Figures 5.1 and 5.2 show a stagnation in *Entrepreneurial Activities* and *Knowledge Development* around 1G in the late 1990s. The complete absence of a complementary policy environment for 1G fuels results in the exclusion of the entire technology group. Whether this will be fruitful in the long term remains to be seen. Government support now mainly focuses on R&D and on subsidies. This can be considered risky. Apart from the 'boating niche', there are no further market dynamics.

5.4.4 A tentative offer (2001-2002)

In the new millennium, the issue of sustainable mobility is put on the political agenda. Besides the climate issue, the issue of security of oil supply is becoming more urgent, especially since 9/11. In the Netherlands, these background movements are reflected in a variety of policy measures aimed at reducing fuel consumption in the mobility domain (MinVROM, 2001). Despite weak ministerial support, the work of GAVE continues (ST, 2001c). From 2001 to 2002, GAVE installs a subsidy programme [F6] aimed at guiding entrepreneurs towards the realisation of demonstration-scale fuel chains [F4] (GAVE, 2003; ST, 2001g; ST, 2002a). The programme consists of two tenders for a total budget of approximately 2 million €. The first step is to stimulate the formation of coalitions [F3] and to support assessment research [F2]. The 80% CO_2-reduction criterion still holds; the emphasis is on innovative fuel production. As a result, all new projects [F1] are exclusively directed at 2G biofuel technologies.

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[84] Since data collection was not specifically directed at these general events, one should not conclude that there were no other general biomass meetings in this period.

Two entrepreneurial experiments [F1], focusing on combining biomass gasification with Fischer-Tropsch synthesis, are characteristic for this episode. If successful, they could enable the production of biodiesel from practically any biomass source [F4]. The projects are set up by two alliances [F3]; the Shell-ECN network and the TNO-Nuon network, and various other actors, such as banks, a car company, and many others (GAVE, 2002b). The projects are successful [F4], particularly with respect to solving technological bottlenecks such as gas cleaning [F2] (Boerrigter et al., 2002).

The final purpose of the subsidy programme was to realise a commercial demonstration. By the end of 2002, possibilities are considered [F4], as both alliances are viable candidates and GAVE has a sum of 5 million € to offer [F6]. Unfortunately, both parties decide to discontinue [F1]. The main reason is that building a commercial-scale plant would cost far more than 10 million €, which would not be feasible without a flanking market stimulation programme, e.g. tax exemption measures [F5, F6] (GAVE, 2002a; GAVE, 2005). The subsidy programme stops [F6]; once again, the absence of sufficiently powerful (fiscal) market creation policies forms a critical barrier to the further development of the BFTIS [F5] (GAVE, 2005).

Towards the end of the episode, political pressure from the EU increases (ANP, 2001b; EU, 2001; ST, 2001b; ST, 2001d; TRW, 2001). In the Netherlands, this background movement results in a lobby from national parliament [F7] (ANP, 2001c), pressing the national government into issuing generic tax exemptions for experiments with automotive biofuels [F5] (FD, 2001; ST, 2001a; ST, 2001f).

Cumulative causation

The *STP Motor* has been running for two years now. From a technology perspective, this motor has resulted in important outcomes; see Figures 5.2 and 5.3. Still, a crucial system function – namely *Market Formation* – is left unaddressed; the exclusive orientation towards 2G biofuels will, as we shall see, result in the neglect of potentially powerful demand-side dynamics.

5.4.5 European intervention (2003-2005)

In 2003, the EU decides on a biofuel directive forcing its members to substitute a percentage of the supplied automotive fuels by biofuels (EU, 2003). This background movement has drastic consequences as the EU is more fond of 1G biofuels than the Dutch government.

With GAVE's subsidy programme terminated, and with a new national task of implementing the EU directive, a reorientation of government policy is imminent (ST, 2003a). Therefore GAVE is issued with a new priority task [F4]: the development of a generic market for biofuels. The 1G technologies are now increasingly perceived as a stepping stone towards future use of 2G fuels (GAVE, 2005; MinEZ, 2007).

In 2003, once again, Nedalco starts influencing the field. With the directive being taken up by national policy makers [F4], the alcohol company now works on a new business plan for the large-scale production of (1G) bioethanol [F1] (Nedalco, 2005). However, despite the policy shift [F4], concrete tax measures are still not in effect [F5]. Once again, Nedalco pleads for a long-term tax exemption [F7]. Within the context of this lobby, the promise of 2G technologies serves as important leverage, as in the intermediate period, Nedalco's venture in R&D on 2G ethanol has been extraordinary fruitful [F4] (GAVE, 2005; Nedalco, 2005). The national government shows interest, but does not readily respond [F4]. The project is halted [F1]; Nedalco restlessly awaits the disclosure of the future Dutch biofuels policy.[85]

Despite the absence of a clear and supportive national programme [F4], a variety of 1G initiatives commence from 2002 onwards [F1]; see Figure 5.1. One of the most influential endeavours is initiated by a company named Solar Oil Systems (SOS). This small business starts off adjusting conventional diesel engines to PPO fuel[86] [F1], but in 2002, SOS expands its activities by preparing the construction of an oil mill. The project is supported by more than 25 partners, among them farmers, farmers' associations and local government authorities [F3] who are made shareholders [F6]. The company's downstream activities are covered by promoting biofuels to potential users [F4]. In order for the project to be financially feasible, SOS demands a tax exemption [F7] (Bizz, 2002a; Bizz, 2002b); see Figure 5.4. The government eventually agrees with the company's terms [F6].

The SOS network makes sure that multiple system functions are realised simultaneously (Solar Oil Systems, 2005), which results in a positive spin-off. In March 2005, the first Dutch oil mill is completed; the oil is delivered mainly to fleet vehicles of the provincial government. This success triggers a large number of events: from 2002 onwards, entrepreneurial projects [F1] are initiated throughout the country, most specifically in rural areas; see Figure 5.1. The oil mill is often mentioned as an example [F4] (DvhN, 2004; DvhN, 2005a; LC, 2004; PZC, 2004).

Once again, it is the regional authorities and entrepreneurs – this time supported by a European directive – that drive the BFTIS forward. The rural developments are complemented by the initiation of the Energy Valley cluster [F3] (EV, 2006). This cluster strives for the alignment of public investments with local economic interests [F4, F7].

A remarkable trend that emerges is a counter movement formed by the oil industry, environmentalists, and academia (ANP, 2003b; DE, 2003a; DvhN, 2005a); see the negative peaks in Figure 5.3 and 5.4. The controversy around 1G and 2G seems to increase. However, at the same time there is a stronger *Guidance of the Search* for 1G biofuels than ever before. Moreover, there is an increasing support, both in terms of *Guidance of the Search* and in terms of *Support from Advocacy Coalitions*, for biofuels in general. The choice for 1G or 2G biofuels was first presented as a conflict of opposites, but now it seems that the BFTIS actually supports the co-existence of the technologies.

Cumulative causation

This episode is characterised by an increasing activity level for all system functions; Figures 5.1-5.6 all illustrate this trend. Multiple system functions are fulfilled, bottom-up, by a variety

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[85] Only recently did the national government respond to Nedalco's request; a factory was planned in 2008. Since this event did not occur within the time-span of our analysis, it is not included in the narrative.

[86] Pure Plant Oil (PPO) is unrefined oil extracted from rape seed. In order to use it in conventional diesel engines, a serious reconstruction is required. Regular biodiesel is usually produced from rape seed as well, but the oil is chemically refined to such an extent that it has similar characteristics as regular diesel and only marginal adjustments are necessary.

of actors that increasingly operate in networks. The perspective of a market for 1G biofuels -offered through the European directive – plays a crucial role in this. The renewed *Guidance of the Search* resulting from this initiates an interaction pattern which is, again, characterised by *Entrepreneurial Activities* inducing *Support from Advocacy Coalitions* and *Resource Mobilisation*. The entrepreneurs and their expectations play a pivotal role. It seems that the *STP Motor* of the previous episode has transformed into an *Entrepreneurial Motor*.

Note that these dynamics are largely the effect of the EU directive. It should be stressed that it is not until the summer of 2004 that developments take-off on the national policy level, with the release of the government's white paper on traffic emissions [F4]. This document contains a section on generic measures that need to be taken for the implementation of biofuels (MinVROM, 2004). The 2G fuels are still considered preferable, but 1G fuels are explicitly considered as a stepping stone option.

5.4.6 A Market in distress (2006-2007)

With oil prices rising, biofuels are becoming an ever more important subject of energy policies, not only in the EU but worldwide (Schubert, 2006). A drawback is that, with market diffusion of (1G) biofuels taking off globally, the resistance to biofuels is growing at the same time. The controversy becomes greater when studies show that the increased land use for energy crops – for 1G and 2G alike – results in rising food prices and in the deforestation of vulnerable natural areas like rainforests (SenterNovem, 2008a).

In the Netherlands the EU directive is translated into national policies [F4]. For 2006, a generic tax exemption is issued (as a temporary measure), which is replaced, in 2007, by a scheme of obligatory blending [F4, F5]. The scheme obliges oil companies to sell biofuels as an increasing share of their fossil-derived fuel sales; from 2% (on an energy basis) in 2007 to 5.75% in 2010 (DG, 2006b). In addition, to promote R&D on 2G biofuels a 60 million € subsidy programme, specifically directed at 2G biofuels production pilots (IBB), is introduced for 2006-2014; with 12 million € allocated for 2007 [F6] (MinTr, 2006).[87]

As the result of these supportive policies, the number of business start-ups increases [F1]. Biofuel plants (1G) and logistics facilities are being built in Rotterdam harbour (SenterNovem, 2008a). A positive effect of the biofuels market that has been created, is that entrepreneurs no longer have to lobby for subsidies [F7]. Instead, successful businesses breed even more start-ups without the need for specific government interventions [F4] (SenterNovem, 2008a).

An exception is formed by entrepreneurs aiming for the further development of 2G technologies. The 2G biofuels are, as yet, not developed far enough to be commercially available (Schubert, 2006). The support for R&D, and the anticipated market, induces a number of companies, like Shell and Nedalco, to invest resources [F6] in 2G technologies R&D [F1, F2]. Also, plans are made, most notably by Nedalco, for the construction of 2G pilot plants. These initiatives are, however, largely dependent on government funding, and the resources allocated are marginal [F6]. Indeed, they are comparable to what was available within GAVE and this turned out to be insufficient

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[87] Note that this way the oil companies act as a gate keeper of the biofuels market; they can determine whether to supply biofuels as blends, or as pure substances.

at the time. But now that there is a market, Nedalco continues its course of activities in much the same way as it began, by lobbying the government for a large subsidy [F7]. According to the latest information, the company was granted a subsidy for the building of a 2G pilot plant, but is currently (2008) uncertain whether these plan will be realised (SenterNovem, 2008a).

Despite the strong position in terms of *Knowledge Development*, entrepreneurs are generally hesitant to initiate *Entrepreneurial Activities*. The problem in general, for potential 2G biofuel producers, is the uncertainty of the biofuels market [F5]. After all, it remains to be seen whether 2G biofuels can eventually compete with 1G biofuels [F4]. This uncertainty is the more striking in the face of cheap imports from Brazil and Eastern Europe. In fact, even 1G biofuel producers have a hard time competing with the biofuel imports [F4, F5]. This is a reason for some entrepreneurs to call for protectionist policies in the biofuels trade, especially since some of the imported biofuels are deemed 'unsustainable' [F7] (SenterNovem, 2008a).

The latter point relates to a more stringent issue: a renewed rise of the biofuels controversy. With the increasing market diffusion, scientists and environmental organisations have continued to stress that biofuels are not a solution but a problem [F4, F7] (Fargione et al., 2008; Searchinger et al., 2008). Their distress calls are heard by politicians and the Dutch government picks up on this by falling back on the original distinction between 1G and 2G biofuels, although it is a more fine-grained distinction this time around. A system of sustainability criteria is developed that should allow policy makers to incorporate the CO_2-reduction potential and land-use of particular biofuel chains [F4] (ET, 2007). The most recent development is that a debate has started, on the EU level, about the question whether the biofuels directive should be adjusted to take into account such sustainability criteria. Dutch policy makers have a large say in this discussion since they have already started to develop sustainability criteria, as a response to the early rise of a biofuels controversy in the Netherlands [F4, F7] (SenterNovem, 2008a).

Cumulative causation

The dynamics within this episode suggest a segregation of the development of 1G biofuels and 2G biofuels. The event sequence related to 1G biofuels is characterised by the creation of a market environment [F5]. This has resulted in a guaranteed demand for biofuels, leading various firms [F1], encouraged by expectations [F4], to enter the TIS and start investing in the commercial production of 1G biofuels [F1, F6]. Where successful, this leads to even higher expectations [F4] and more entries and investments of firms [F1, F6]. This form of cumulative causation may be labelled a *Market Motor*.

The 2G biofuel technologies are still driven by an *Entrepreneurial Motor* as characterised in the previous section. The further development of this motor is currently uncertain due to the rapid expansion of 1G biofuels.

On top of this, the biofuels controversy rages on, undermining the long-term perspective for the development of biofuel technologies, 1G and 2G alike [F4]. It seems that the BFTIS is on a tipping point. Either, the BFTIS actors, including the international ones, manage to establish a consensus on what biofuel options are worthy of support, or else the BFTIS will dissolve and break down as the result of ever-increasing uncertainty.

5.5 Reflections

The event history analysis has allowed us to conceptualise the development of the BFTIS in terms of system functions. Occurrences of cumulative causation have been pointed out, in the form of three motors, and particular drivers and barriers related to these motors have been revealed. In this section we will answer the research question: *How did innovation system dynamics influence the formation of a Dutch biofuels innovation system from 1990-2005?* This section also outlines strategic implications for policy makers and entrepreneurs.

5.5.1 Lack of continuity

As we have seen, cumulative causation mostly emerged where entrepreneurs started deliberately to shape the BFTIS. Notable examples are the boating companies and an ethanol producer, initiating an *Entrepreneurial Motor*, and the recent successes around 1G biofuels, triggering a *Market Motor*. Furthermore, the GAVE programme initiated virtuous dynamics in the form of an *STP Motor*. However, our analysis has also shown that these motors often came to a halt. As a result, there has been little continuity in the development of the BFTIS. The absence of follow-ups to *Entrepreneurial Activities* played a key role. This was illustrated by the isolation of the early adoption experiments with public transport, the termination of Nedalco's expansion plans, and the failure of GAVE to realise demonstration projects. Recurring barriers were the absence of *Market Formation* and the general lack of a consistent *Guidance of the Search* by the national government, both of which could have been overcome with more dedicated policies. Also entrepreneurs could have made a stronger point for the support of virtuous dynamics, as will be discussed below.

In general, our case shows that the fulfilment of various system functions is important and that during the build-up of system function fulfilment, various forms of cumulative causation – motors of innovation – play a role. Ideally, these motors coexist, but more realistically, they will gradually emerge and follow up on each other to provide 'step by step' increases in functionality of the TIS. For instance, a motor exclusively driven by subsidised R&D may pave the way for a market-based motor phasing in later. The challenge for policy makers and entrepreneurs is to be aware of such possibilities, to facilitate the necessary underlying interactions, and to be flexible, yet enduring, in response to unexpected shifts.

5.5.2 The linear model of innovation

The strength of a systematic and consistent policy approach is shown by the main success of the Dutch biofuels policy: its impulse to R&D developments around 2G biofuels via the GAVE programme. The resulting technical successes were internationally appreciated. However, as soon as the national government decided that biofuels were to be supported, its strategy was to initiate exclusively *Knowledge Development* among incumbent industry networks. The orientation was on lab-scale *Knowledge Development* whereas *Market Formation* activities were absent. The failure of GAVE's demonstration projects can be ascribed to the absence of such complementary system functions, mostly *Guidance of the Search* and *Market Formation*. As a result, the 2G projects were a technical success, but turned out to be economically infeasible.

The general lesson to draw from this is that the linear model of innovation is still operational today. If the sole purpose of governments is to boost R&D, the other activities of the system are neglected, meaning that potentially powerful feedbacks remain absent.

5.5.3 A controversy

The absence of a broader scheme of national support can be related to the controversy on whether 1G biofuels have the potential to contribute significantly to a sustainable mobility domain. Environmental organisations, academic scientists, and oil companies have pressed officials on the national level to refrain from support, whereas entrepreneurs and farmers have stressed the opportunities for economic growth and environmental gain. As a result, the great variety within the BFTIS has become the driver of a conflict that continues today. This conflict is mirrored in the realisation of various system functions, mainly in *Guidance of the Search* and *Support from Advocacy Coalitions*. The conflict is largely caused by the fact that the national government has not taken a clear stance. On the one hand, project-specific tax exemptions were issued, thereby fostering the 1G biofuels, while, on the other hand, the government increasingly adhered to arguments of the counter lobby, promoting 2G fuels. The other side of the story is that entrepreneurs and scientists did not adhere to a joint cause, rendering a conflict almost impossible to avoid.

Perhaps excluding alternatives from support is sometimes justified. In the case of emerging technologies, however, it can be argued that such choices are unwise as technological performances are as yet uncertain. Moreover, the emergence of motors depends on the preservation of variety within the TIS. The implication for entrepreneurs is to bury the hatchet with respect to their mutual disagreements and to join forces. Only by 'running in packs' can entrepreneurs (and local governments) increase their chances of establishing a foothold within the incumbent mobility domain; cf. Van de Ven (1993). The challenge for policy makers is to refrain from selecting technologies altogether, and, instead, to build and facilitate an environment consisting of actors and institutions aiming for inclusion.

5.5.4 Levels of government authority

The development (and policy) of biofuels has largely been the result of European pressure. The Dutch government was – for numerous reasons – not particularly inclined to respond to European signals. A striking outcome of our analysis is that it was mainly small entrepreneurs, collaborating with farmers' associations, providers of public transport, and provincial fleet owners that picked up these incentives. Also the (regulatory) *Guidance of the Search*, *Resource Mobilisation*, *Market Formation*, and much of the *Knowledge Development* relevant for the entrepreneurs was provided by public authorities on the level of regions and provinces. Of the three motors identified, national policy only played an initiating role in one of them – the *STP Motor*. The other motors were generally hampered rather than supported by the national government.

This observation can be related to the more general discussion on globalisation, and the simultaneous regionalisation, of knowledge-based economies. Despite the importance of a nation as a politico-economic entity, one cannot deny the increasing importance of global and regional innovation processes. A theoretical implication is that a TIS analysis could better be delineated on the European level; this way factors that are now considered exogenous may appear as part of the endogenous dynamics. A practical implication is that the policy maker at the national level does not necessarily have to be a prime mover. In fact authorities and entrepreneurs at the local level could well take the initiative. A case in point is the fact that the more influential motors (the *Entrepreneurial Motor* and the *Market Motor*) both started off as 'Europe-driven' regional developments. National government could have backed up these developments by targeting the system functions that were yet poorly developed.

5.5.5 Summary

In short, the formation of a TIS requires that multiple system functions are increasingly fulfilled by a broad group of actors, consisting of governments and entrepreneurs alike. Within the Dutch BFTIS the conditions have not been very supportive for this to happen. With conflicting views by entrepreneurs, environmentalists and scientists, and with the national government hampering most system functions, the emerging motors have largely failed to develop. Only recently has the European biofuels directive resulted in the creation of a market for biofuels. This seems to have triggered virtuous dynamics within the BFTIS, both among entrepreneurs and policy makers, although the biofuels controversy still rages on and the future of the BFTIS seems more uncertain than ever.

5.6 Concluding remarks

We started this chapter by expressing the need for increased insight into the formative stage of innovation system development, particularly in order to be able to support sustainable energy innovations. We adopted the TIS framework and argued for a focus on system functions. By analysing and evaluating the development of biofuels in the Netherlands, we illustrated how the build-up of system functions can be conceptualised and measured over time. Our study empirically confirmed the importance of dynamics, and offered insights into the influence of various motors of innovation that contributed to the build-up of a TIS.

Our case study revealed three motors that supported biofuels development in the Netherlands; an *Entrepreneurial Motor*, a *Science and Technology Push (STP) Motor* and a (promising) *Market Motor*. The *STP Motor* involved research and development guided by a government programme. The *Entrepreneurial Motor* was initiated by entrepreneurs pushing government to support them. The promising *Market Motor* was driven by positive expectations and policies directed at the formation of a mass market.

What does this add to the existing innovation systems literature? First of all, our approach allows for a fruitful combination of quantitative and qualitative analysis, that is fit for recognising and interpreting historical patterns. In our case study we systematically pointed out how system functions developed and interacted. The motors and their effects, spanning a long period of time and covering a broad variety of activities, could not have been identified by using a more traditional approach, such as a patent analysis or a formal network study. Nor could such dynamics have been found by describing and comparing institutional setups for different innovation systems.

Second, our approach offers advantages with respect to the integration of empirical and conceptual work. With event history analysis, case studies can be conducted in a systematic way, with the list of system functions serving as a powerful heuristic framework. By focussing on events, clustering them in event types, and then (indirectly) attributing them to system functions, a 'self-fulfilling prophecy' bias is prevented. This is important as the system functions, as concepts, are still in the process of being validated. If more case studies are carried out in this way, then the dynamics of different TISs can be compared, leading to a more general insight into what system functions matter, and into the types of motors that (may) occur. This way, eventually, this empirical approach has the potential to make a strong contribution to a better theoretical understanding of innovation system dynamics.

Our approach provides a new perspective on energy and innovation policies. Instead of targeting mainly the supply-side (R&D programmes) or the demand-side (market creation policies) of the innovation chain, it stresses the systemic nature of technological change. In order to achieve this, policy instruments should contribute to the formation of new technological innovation systems, thereby increasing the success chances of new technologies. The set of system functions offers a heuristic model that indicates the most crucial policy targets. If a particular system function is lacking, attention should be paid to it. In more advanced policy designs, the presence of motors could be monitored, and policy may then be directed at supporting these forms of cumulative causation.

There are also implications for entrepreneurs active in an emerging technological field. Their chances of survival will improve when the innovation system develops further. Therefore they should be aware of innovation system dynamics and their pivotal role in contributing to motors. By running in packs, and organising themselves into alliances, they are likely to be more influential, and more successful in innovating.

Interlude C

In the following chapter the dynamics of the Dutch Biofuels TIS are compared with the dynamics of the Swedish biofuels TIS. This study was conducted in close collaboration with Karl Hillman from Chalmers University in Gothenburg (Sweden) who provided the data for the Swedish case based on the work of Sandén and Jonasson (Sandén and Jonasson, 2005).

The focus of the comparison is on the identification of forms of cumulative causation, i.e. motors of innovation, and the underlying structural drivers and barriers. Based on differences and similarities between the two countries, evaluative insights are formulated that are of relevance to policy makers and entrepreneurs. The chapter does not systematically pay attention to the development of TIS structures.

This chapter was originally published as: Hillman, K.M., Suurs, R.A.A., Hekkert, M.P. and Sandén, B.A., 2008. Cumulative causation in biofuels development: A critical comparison of the Netherlands and Sweden. TASM 20(5): 593-612.

6 Comparison of the biofuels TISs of the Netherlands and Sweden

6.1 Introduction

The problem of climate change as a result of greenhouse gas emissions is today (2008) seen as one of the most important environmental issues facing humankind. A major culprit is the transport sector, which has been growing for several decades (IEA, 2004a). Scenarios assume that this sector will continue to increase its share of world fuel use for many decades (EIA, 2003; IEA, 2007b). The emissions from the transport sector can be mitigated by a reduction in transport activity and more efficient vehicles, but there is also a need for new sources of energy that – on a net balance – do not (or barely) give rise to greenhouse gas emissions. Thus, strong arguments are made for public support of renewables (Sandén and Azar, 2005), and there is an increasing political willingness particularly to support biomass-based automotive fuels, i.e., biofuels (IEA, 2004a). In the European Union (EU), this has been acknowledged in a policy directive which presses the national governments to enforce the introduction of biofuels (EU, 2003).

Still, the task of supporting renewables is not trivial. The emergent technology will have to compete within the environment of a techno-institutional complex, a set of interlinked 'large technological systems and the public and private institutions that govern their diffusion and use' (Unruh, 2000) (p. 825-826). Over the past decades, this complex has evolved into an energy and transport system that continuously provides positive feedback – in the form of scale economies, cumulative learning, network externalities and the emergence of habitual routines – for the further development of fossil-fuel based technologies (Unruh, 2002). Hence, diffusion of emerging renewable technologies is hampered by the momentum of the energy and transport systems.

Nevertheless, change is possible. Studies by Suurs et al. (Suurs and Hekkert, 2005; Suurs and Hekkert, 2008a; Suurs and Hekkert, 2008b) and Sandén and Jonasson (2005) have investigated the recent history of biofuels in the Netherlands and Sweden, respectively. Both studies show how the technology passes through a formative stage characterised by weak institutions, little market demand and multiple technology designs. The returns on (private) investments are highly uncertain and only to be expected in the long run, in fact developments largely depend on public support.[88] However, in Sweden, entrepreneurial efforts and government policies linked up in a process of cumulative causation (as a result of positive feedback) (Myrdal, 1957) putting significant pressure on the transport energy system to adopt biofuels. The result was that utilisation increased, starting from the mid 1990s, to more than 2% of the total transport fuel supply in 2004 (Sandén and Jonasson, 2005). In the Netherlands, the government also supported biofuels, but at the time of writing market diffusion has barely taken off (Suurs and Hekkert, 2005; Suurs and Hekkert, 2008a; Suurs and Hekkert, 2008b). How can this difference be explained and what lessons can be learned?

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[88] For a more general account of the characteristics of the formative stage of technological systems, see Van de Ven (1993), Rip and Kemp (1998), Unruh (2000; 2002) and Jacobsson and Bergek (2004).

The purpose of this chapter is to point out the drivers and barriers of cumulative causation in the development of biofuels in both the Netherlands and Sweden (1990-2005). Questions to be answered are:

RQ1: What forms of cumulative causation occurred in the two countries?

RQ2: What caused cumulative causation to emerge or collapse?

RQ3: What lessons may be drawn for policy makers and entrepreneurs?

One important point to make is that in this chapter we are interested in dynamics and growth processes in a formative stage. We do not attempt to say anything about the desirability of introducing various types of biofuels. Obviously, the desirability as perceived by the actors in the system does play a role in our analysis as these positive and negative expectations are crucial to understanding innovation system dynamics. We also admit that, in later growth stages beyond the scope of this study, limitations of various kinds may very well hamper a sustained growth (as a result of negative feedback).

Studying the formative stage of technological trajectories demands an analytical framework that addresses not just the technical and economical dimensions of technological trajectories but also the broader processes of societal embedment (Bijker et al., 1987). Moreover, because the formative stage is characterised by rapid changes in the system surrounding and supporting the technology, the analysis needs to pay close attention to the dynamics of change within this system (Hekkert et al., 2007; Jacobsson et al., 2004). There are many partly related streams of literature that in different ways take these dimensions into account (Bijker et al., 1987; Van de Ven, 1993). In this study we choose to adopt the framework of Technological Innovation Systems (TISs). The TIS approach stresses the idea that innovation is a collective and context-specific process, wherein governments have a particular role of facilitating the introduction of emerging technologies (Jacobsson and Johnson, 2000). The recent TIS literature that we build upon explicitly tries to conceptualise the dynamics related to a technological field (Hekkert et al., 2007). Much attention has been given to systematic operationalisation of the concepts used (Hekkert et al., 2007), and the system metaphor opens the way for assessment of system performance and effectiveness of policy and entrepreneurial intervention.

The chapter is structured as follows. In Section 6.2, an overview of theoretical concepts is presented, together with a methodology for operationalising the concept of cumulative causation. Section 6.3 presents a background to the development of biofuels, and Sections 6.4 and 6.5 provide the analysis of the Dutch and Swedish TISs related to biofuels, here called BioFuels Innovation Systems (BFTISs). In Section 6.6, a comparison of the observed dynamics is given, resulting in strategic insights. Conclusions are formulated in Section 6.7.

6.2 Theory and method

Various innovation system approaches exist: from nationally-oriented approaches to those with a focus on regions or industrial sectors. In our case we apply the framework of Technological Innovation Systems (TISs). In terms of its boundaries a TIS can be regarded as ‘cross-cutting’ geographical and sectoral domains; the principal starting point is a technological field. As an additional delineation we focus on the national TISs of the Netherlands and of Sweden. In the greater part of the literature, the TIS is defined by the actors (organisations), networks of actors and institutions (regulations, norms, cultures) involved in the generation, diffusion, and utilisation of a technology.[89]

The TIS framework serves as a heuristic tool to point out the structural elements that are relevant for a strategic intervention in technology development (Jacobsson et al., 2004).[90] However, in the past, most innovation system studies have focused on just this and, as a result, have neglected the development process itself. See, for instance, how Freeman contrasts various National Innovation Systems – Japan vs. USSR in the 1970s, East Asia vs Latin America in the 1980s – in terms of R&D intensity, educational system, industrial structure, and many other factors (Freeman, 1995). Even if processes are being measured, such as yearly budgetary flows or patent outputs, then still no attention is paid to the interdependence of such processes in time.[91] Important contributions to the sectoral innovation systems approach also show a primary focus on the state of structures: technological regimes rather than historical mechanisms (Breschi and Malerba, 1997; Malerba, 2002). The TIS approach has been recognised by Carlsson et al. (2002b) to be the most dynamic of the innovation systems approaches and many scholars have used the TIS framework to conduct longitudinal studies that indicate the key historical drivers of a technological field.

A focus on static structure has some disadvantages: (i) as structural factors have been historically shaped, they will differ so much between contexts that a comparison between TISs is hard to make, and (ii) a static structural approach tends to disregard important explanatory factors behind cumulative causation dynamics (Hekkert et al., 2007). To overcome these shortcomings, recent studies have suggested augmenting the analysis of structures with an analysis of key processes, or system functions (Bergek, 2002; Bergek et al., 2008a; Carlsson et al., 2002b; Edquist, 2004; Hekkert et al., 2007; Jacobsson and Bergek, 2004). The literature presents different lists of such activities. In this chapter we will use the seven system functions listed in Table 6.1 (Bergek, 2002; Hekkert et al., 2007).

The system functions are defined as categories of 'actions taken by actors in the system' (events).[92] Since the system functions are defined on a more abstract level than the actions themselves, they are applicable to a wide variety of empirical observations. As a result, it becomes possible to compare different TISs in a systematic way. The system functions can be used to explain the endogenous dynamics of the system. However, any TIS is also embedded in a wider environment consisting of factors beyond the direct influence of the national TIS, for instance, oil price shocks and international policy.[93]

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[89] This definition is based on Carlsson and Stankiewicz (1991).

[90] For an argument on the applicability of the innovation systems approach to the issue of energy system innovation, see also Sagar and Holdren (2002).

[91] See also the more recent work by Balzat and Pyka (2006), who conduct a cluster analysis on the innovation system characteristics of OECD countries to classify different systems into groups.

[92] They thus differ slightly from the functions used by Bergek, Jacobsson and Sandén (2008b).

[93] By leaving these factors outside the TIS, we run the risk of missing out dynamics 'on a higher level'. In return, this makes possible a more detailed analysis of the factors included.

Table 6.1 Functions of technological innovation systems.

F1. Entrepreneurial Activities	At the core of any innovation system are the entrepreneurs. These risk takers perform the innovative commercial experiments, seeing and exploiting business opportunities.
F2. Knowledge Development	Technology research and development (R&D) are prerequisites for innovation. R&D activities are often performed by researchers, but contributions from other actors are also possible.
F3. Knowledge Diffusion	The typical organisational structure of an emergent innovation system is the knowledge network, primarily facilitating information exchange.
F4. Guidance of the Search	This system function represents the selection process that is necessary to facilitate a convergence in development, involving, for example, policy targets, outcomes of technical or economic studies and expectations about technological options.
F5. Market Formation	New technologies often cannot outperform established ones. In order to stimulate innovation it is necessary to facilitate the creation of (niche) markets, where new technologies have a possibility to grow.
F6. Resource Mobilisation	Financial, material and human factors are necessary inputs for all innovation system developments, and can be enacted through, e.g., investments by venture capitalists or governmental support programmes.
F7. Support from Advocacy Coalitions	The emergence of a new technology often leads to resistance from established actors. In order for an innovation system to develop, actors need to raise a political lobby that counteracts this inertia, and supports the new technology.

At the heart of the TIS approach is the idea that system functions can interact with each other (Bergek, 2002). For instance, the successful realisation of an important research project (*Knowledge Development*) may result in a rise of expectations among policy makers (*Guidance of the Search*), which may subsequently trigger the start-up of a subsidy programme (*Resource Mobilisation*, *Guidance of the Search*) to support even more research projects (*Knowledge Development*). This example illustrates how complementary effects can result in the unfolding of a pattern of cumulative causation (Myrdal, 1957)[94]: events driving other events driving even more other events. As an event sequence unfolds, it can branch out, eventually resulting in a richer realisation of system functions. Ideally, these dynamics may be cyclic, creating a loop of positive feedback, which may trigger a take-off from a formative to a growth stage of the TIS. However, such positive feedback may also be destructive, yielding a regression of the TIS. In the first case we speak of virtuous dynamics (a build-up sequence) and in the second case of vicious dynamics (a breakdown sequence).[95]

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[94] For a historical perspective on the concept, see Skott (1994).

[95] The idea of a virtuous or vicious cycle is rather abstract. As we will see, the actual dynamics of a TIS are often not exactly circular. Even in the presence of positive interactions between system functions, we will find that developments tend to be more chaotic than the ideal type of a recurring circle. Nevertheless the concept of a circle is useful as it provides a reference point to relate our findings to. We follow a rather narrow definition of what are virtuous and what are vicious dynamics; the division merely captures the dynamics of the TIS and does not (directly) relate to the desirability of the TIS or the technology it surrounds. Note that Myrdal's

Table 6.2 Event types as indicators of system functions.

System function	Event types
F1. Entrepreneurial Activities	Projects with a commercial aim, demonstrations, portfolio expansions
F2. Knowledge Development	Studies, laboratory trials, pilots, prototypes developed
F3. Knowledge Diffusion	Conferences, workshops, alliances between actors, joint ventures
F4. Guidance of the Search	Expectations, promises, policy targets, standards, research outcomes
F5. Market Formation	Market regulations, tax exemptions, events supporting niche markets
F6. Resource Mobilisation	Subsidies, investments, infrastructure development
F7. Support from Advocacy Coalitions	Lobbies, advice

The empirical basis for the analysis of TIS dynamics is a narrative consisting of events.[96] Each event is mapped on a system function; this way the events serve as the empirical counterparts of system functions; see Table 6.2. Patterns of events in the narrative can provide insight into the emergence of cumulative causation. The identification of patterns is based on qualitative techniques presented in Poole et al. (2000). Our focus is on interaction patterns, i.e., sequences of events. By relating event sequences to the abstract level of system functions, we can point out how system functions reinforce (or antagonise) each other through time. If this carries on for some time, this indicates the unfolding of a cumulative causation process.[97]

The narrative is organised in episodes arranged in chronological order; the episodes are characterised by different interaction patterns. When an event contributes to a system function, this is indicated within square brackets and numbering following Table 6.1 [Fx]. A negative contribution is indicated by a minus sign [-Fx]. Common background factors are introduced in the following section; exogenous factors that are case specific are only mentioned in the separate narratives.

6.3 Background to biofuels development

We identified five exogenous factors that drive or hamper the endogenous developments in both our cases: (i) oil supply, (ii) local air and water quality, (iii) EU agricultural policy, (iv) climate change, and (v) technological features. These factors are of both international and national origin, but are common to both countries. As will become clear from the analysis, their influence on BFTIS dynamics differed between the two systems studied.

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original concept of a vicious or virtuous cycle was applied to large social systems. As we are now dealing with a far more specific problem, the development of a TIS, it could very well be that the concept does not apply in the same way. This is the reason why our research results are theoretically relatively 'loose' and oriented towards close empirical observations. On the other hand, the concept has been applied with success in earlier studies; cf. Jacobsson and Bergek (2004).

[96] This study arises from two previous studies from the Netherlands and from Sweden, presented in Suurs and Hekkert (2005; 2008b), and Sandén and Jonasson (2005), respectively. Both studies were based on empirical material collected from articles in periodicals and newspapers, and reports from governmental agencies, academia and consultancy firms. Literary sources were supplemented by interviews with key persons involved, and the results found were checked through discussions with industry representatives.

[97] This has been empirically shown by Negro, Hekkert and Smits (2008) and Negro, Suurs and Hekkert (2008).

The first factor is the issue of the security of oil supply. The oil crises in the 1970s made the industrialised world aware of the vulnerability connected to oil dependence. Alternative energy sources were sought and increasingly biofuel technologies were being developed to utilise them. However, from the 1980s on, the oil price dropped and ceased to be a driver of change. Cheap fossil fuels then became an economic barrier for all renewables development. This changed towards the end of the period studied, as the oil price began to increase again.

The second factor concerns worries about local air and water quality. The issue arose on the political agenda throughout Europe from the 1980s onwards. In the transport sector this resulted in incremental innovations such as the catalytic converter and cleaner diesel engines. It also became an argument for implementing biofuels.

Third is EU agricultural policy. The issue at hand is a restructuring of the declining agricultural sector, reducing the agricultural surplus and exploiting new markets. In the 1990s, farmers received subsidies for keeping land fallow and for the cultivation of non-food crops. The climax was the biofuels directive of 2003, which set targets for the member states regarding the introduction of biofuels.[98] The directive was increasingly legitimated by referring to energy security and climate change.

Fourth, the debate on climate change especially gained attention in the 1990s. Because of the possible reduction of CO_2 emissions, biofuels were seen as an interesting option. A milestone was the signing of the Kyoto treaty by the EU member states in 1998. The European Commission recognised the utilisation of biomass resources as having a great potential to reduce CO_2 emissions (EU, 1997).

Finally, in addition to these factors, different technologies emerged of which the inherent features affected the events in our two cases. European policy has particularly supported biofuels based on agricultural products. This involves a rather conventional set of conversion technologies with limited performance in terms of costs and CO_2 reduction. An alternative exists: a second technology group with potentially lower costs and higher CO_2 reductions (Hamelinck and Faaij, 2006). The differences between this first generation (1G) and second generation (2G) of biofuels have played a central role.[99]

In the following section we will reconstruct the development of the Swedish and the Dutch BFTISs. For each country we will focus on that part of the technological domain where the most activities have taken place; 1G/2G biodiesel in the Netherlands and 1G/2G bioethanol in Sweden.[100]

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[98] The targets were 2% for 2005 and 5.75% for 2010, of the petrol and diesel used for transport purposes (EU, 2003).

[99] It may seem inappropriate to consider the technology dimension an exogenous factor, but this is a matter of delineation. Adhering to the tradition of innovation system studies, we choose to focus on the societal dynamics around technology development.

[100] There are also significant activities related to other biofuels. The accounts given here are for the large part based on more detailed event analyses; see Suurs and Hekkert (2005; 2008b), and Sandén and Jonasson (2005), for a more elaborate account.

6.4 The Dutch biofuels innovation system: the case of biodiesel

Developments of biofuels started around 1990. The case of diesel substitutes serves to illuminate the characteristic features of this development. Four episodes are distinguished.

6.4.1 European drivers of change

From 1990 on, small entrepreneurial experiments with the adoption of 1G biofuels were initiated [F1]. The projects received policy support and financing, partly from the EU (exogenous). Trials were performed [F2] and turned out to be technically successful [F4], but the economic returns were disappointing [-F4]. Regional governments played a guiding role during this early start [F4]. However, the national government stood back, as it doubted the importance of the small projects [-F4]. Moreover, a couple of influential assessment studies [F2] underlined the shortcomings of the agriculture-based 1G biofuels [-F4]. The argument was that they were expensive and offered no long term potential (AD, 1992a; AD, 1992b; NRC, 1992b).

Up to 1995 not much happened. In this first episode, developments were mainly driven by (the preparations of) EU policies (exogenous). The system functions were just beginning to take shape.

6.4.2 The shaping of a niche

The experiments with the adoption of agriculture-based fuels had limited success. A major drawback was the extreme scarcity of land, which pushed up the production costs of the energy crops (LEI, 2005). In contrast, another exogenous factor triggered a wave of new experiments, namely the increased stringency of regulation with respect to local water quality standards. Biofuels became a commercially feasible option for utilisation in ships, as they are biodegradable and therefore less polluting.

A small niche market emerged [F5]. Two (private) boating companies in the rural province of Friesland grasped the opportunity and initiated projects with 1G biodiesel [F1]. The companies started adoption trials [F2]; as they did this, they turned to government authorities, on the provincial and on the national level, to lobby for a tax exemption [F7]. The province and the district board of agriculture supported the idea and started to advocate biofuels as well [F7]. They were successful; a first tax exemption, for two years, was provided [F5, F6] (FD, 1995).

The adoption experiment [F1] contributed to knowledge and experience on the application of biofuels [F2] and most importantly it served as an example to others in the field [F4]. The province decided to adopt biodiesel itself as well, for its fleet of service boats [F1, F2]. Multiple other boating projects were started [F1]. Again tax exemptions were demanded [F7], and were in turn issued by the national government [F5, F6]. The 1G technologies gained more and more attention [F4]. Still, the experiments were only partly successful; technically everything seemed to work, but the boats caused a smell and there was a negative economic pay-off [-F4]. Nevertheless some of the experiments continued till 2002 [F1].

The entrepreneurial (boating) experiments contributed to a modest wave of cumulative causation, driven by coalitions of entrepreneurs, local governments and their continuous lobby for resources. This process was influenced by external conditions in the form of local water quality regulations.

Meanwhile, developments around 1G biofuels were heavily scrutinised by scientists, engineers, and most notably, by the environmentalist movement [-F4, -F7]. The national government remained divided, and as a result, entrepreneurs who performed adoption experiments [F1, F2] lacked the necessary support. Tax exemptions [F5, F6] were incidentally issued, though for a short time period. No policy strategies were formulated, and hence (potential) biodiesel entrepreneurs remained in the dark with respect to the future institutional support [-F4].

From 1997 the criticism of biofuels, aimed at 1G technologies, turned into a more positive movement as new options gained attention. From then on, the 2G technologies – which were being developed in the laboratories [F2] – became part of the public discussion [F4]. This was mainly the work of entrepreneurs who started attempts to bring 2G biofuels to the market [F1]. The Dutch government, mainly MinVROM[101], considered acquiring a stake in this promising emerging technology [F4] (MinVROM, 2006).

Thus 2G biofuels started to play a role during this episode as well, although this was largely limited to Knowledge Development. A downside was that the experiments with 1G biofuels were shaded by the promises of 2G biofuels. No new entrepreneurial experiments were initiated.

6.4.3 The GAVE Programme

In 1998 the climate issue became an important exogenous driver. As a response to the Kyoto protocol, the GAVE (*Gasvormige en Vloeibare Energiedragers*) platform was initiated in 1999 through Novem.[102] It was the first programmatic government attempt to support biofuels [F4]. The transport sector was originally not its specific orientation, but automotive fuels were quickly established as a priority (GAVE, 2005). GAVE's first move, during 1999, was to authorise a number of assessment studies [F4, F6] (GAVE, 1999; KEMA, 2000). The studies should clear up the controversy around various biofuel options. The result was a shortlist of fuel chains to be analysed in more detail, based mainly on energy balances and cost figures [F2]. GAVE's advice was to support exclusively the projects which guaranteed a CO_2 reduction of 80% [F4] (GAVE, 2005). All 1G options were (de facto) excluded from further assessments [-F4] (GAVE, 2003). It is within this context that the term 2G biofuel was actually introduced to distinguish the contested agricultural biofuels from more technologically advanced options (GAVE, 2005).

GAVE provided 2 million € [F6] to stimulate the formation of networks [F3] and to support assessment research [F2]. This would eventually lead to a demonstration for which a budget of 5 million € was reserved [F6]. The emphasis was on innovation in fuel production, where cooperation with downstream industrial parties and private investors was encouraged [F3]. The projects that started [F1] were all exclusively oriented towards 2G options [F4].

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[101] The Ministry of Housing, Spatial Planning and the Environment.

[102] GAVE (*Gasvormige en Vloeibare Energiedragers*): Platform for Gaseous and Liquid Fuels; Novem (*Nederlandse Onderneming voor Energie en Milieu*): Dutch Agency for Energy and the Environment. The agency is mainly responsible for executing government policy on energy, innovation and sustainability.

The projects were set up by two alliances – the Shell-ECN network[103] and the TNO network[104] – and other actors, among which were investors [F6], a car company and many others [F1, F3] (GAVE, 2002b). The projects were successful [F4], particularly with respect to solving important technical bottlenecks [F2] such as gas cleaning [F2] (Boerrigter et al., 2002). The programme served as a catalyst that bundled and guided R&D projects that until then had been going on in relative isolation [F3, F4]. As a consequence, multiple entrepreneurs [F1] started new biofuels projects during this episode, even outside GAVE.

The purpose of GAVE was to realise a demonstration plant. By the end of 2002 it turned out that the two networks were both viable candidates. Unfortunately both parties decided to abort the projects [-F1]. As a result, the programme was stopped [-F6]. The main reason was that the building of a commercial plant would cost far more than 10 million €; with the absence of a flanking market creation policy, the projects did not make a business case.

In this episode, a pattern of cumulative causation pivoted around *Entrepreneurial Activities* related to 2G technology, but especially around *Guidance of the Search*, *Knowledge Diffusion*, and *Resource Mobilisation*, mainly provided by GAVE. This has resulted in important successes. A knowledge base was developed and the issue of developing alternative automotive fuels was put on the political agenda, but still there was no commercial perspective for biofuels. In this light, the slow technological progress of 2G biofuels can be seen as an exogenous barrier.

6.4.4 An emerging market

Things changed in 2003 as the EU issued the biofuels directive (EU, 2003). This exogenous factor had drastic consequences, as, in contrast to the Dutch government, the EU was largely oriented towards 1G biofuels. With the subsidy programme terminated and with the new task of translating the EU directive into national policies, the national government changed its strategy (ST, 2003a).

From 2003 on, GAVE was given a new task [F4]: the development of a generic market for biofuels. The 1G technologies were increasingly perceived as a bridge towards 2G fuel implementation (GAVE, 2005; MinEZ, 2006). The 1G biodiesel options had so far been excluded from support by GAVE [-F4], with reference to arguments such as high costs and weak environmental performance, implying that market-oriented projects had been subdued. Up to 2002, not a single drop of biodiesel (1G or 2G) had been produced by Dutch companies.[105] By 2002-2003 this changed, as many regional entrepreneurs executed plans for the construction of small factories [F1]. The main driver was (again) the EU directive (exogenous).

These were the first commercial experiments that targeted the supply-side of the biofuels chain [F1]. The projects were supported by a large number of actors; among them farmers, farmers' associations and local government authorities [F3]. Many of these actors were made

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[103] A knowledge network, active in development of advanced bioenergy conversion technologies. The network consists of oil company Shell, ECN (Energy research Centre of the Netherlands), universities, technology institutes and energy companies.

[104] TNO is the Dutch Organisation for Applied Scientific Research. The network consists of TNO and a number of companies active in chemical engineering and energy distribution.

[105] The early adoption experiments are all linked to foreign supply.

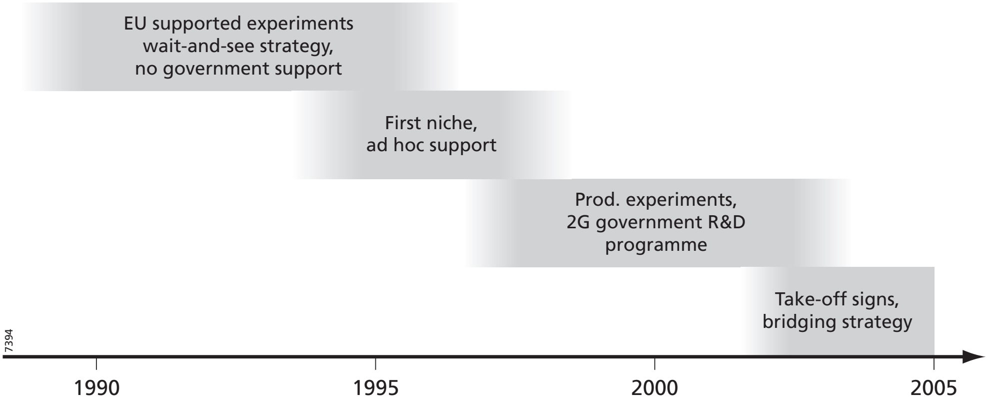

Figure 6.1 Four episodes of Dutch BFTIS development.

shareholders [F6]. Also, biofuels were promoted to potential users [F4]. For these projects to work out financially, tax exemptions were requested [F7], and issued on a project basis [F5, F6] (Bizz, 2002a; Bizz, 2002b). By 2005, the first (1G) biodiesel plant was built. This successful outcome [F4] triggered a new series of events, as from 2002 numerous projects [F1] started all over the country, especially in rural areas. The later developments were additionally driven by the advocacy and guidance from the Energy Valley cluster [F4, F7], a regional network of public-private partnerships. The first plant became an example for other projects [F4] (DvhN, 2004; DvhN, 2005b; LC, 2004; PZC, 2004). In 2004 numerous municipalities started to adopt biodiesel for their car fleets [F1] (RD, 2004b; ST, 2004).

In this period, multiple system functions were fulfilled, from the bottom up, by a range of collaborating actors. The promise of the (exogenous) EU directive was apparently more important in fostering this interaction pattern than the ad-hoc national support. Remarkably, it was again regional authorities and entrepreneurs that took the BFTIS forward. The perspective of a market, offered through the EU directive, played a pivotal role. Also national policy makers realised that their scheme for demonstrating fuel chains had failed because there was no market. In accordance with this, GAVE changed its role from an R&D catalyser into a facilitator of networks and markets. In the process, GAVE influenced *Guidance of the Search* by stressing the concept of bridging technologies from 1G to 2G. In summer 2004, the government released a White Paper on traffic emissions. The document contained a section on generic measures to be taken for the implementation of biofuels. The 1G fuels were now explicitly regarded as a bridging option. Whether this will turn out to be a watershed event, leading to a take-off, remains to be seen. See Figure 6.1 for an overview of the four episodes of Dutch BFTIS development.

6.5 The Swedish biofuels innovation system: the case of bioethanol

The development of alternative automotive fuels in Sweden began in the 1970s with the main focus on methanol produced from different resources. This was a response to drastic increases in the oil price, but interest faded as the price went down in the early 1980s. At this time, the first activities related to bioethanol surfaced. Through the years, this development would come to revolve around four parallel tracks that were more or less intertwined and in different ways contributed to the build-up of the BFTIS. These were the bus niche, the production of wheat ethanol (1G), the market for flexifuel cars and research into wood ethanol (2G). The Foundation for Swedish Ethanol Development (SSEU) was the central player in two of them, while partly influencing the other two. It was formed in 1983 by private and municipal companies around a plant processing ethanol as a by-product from the pulp and paper industry in Örnsköldsvik. After 1990, bioethanol became the dominating biofuel. It serves as an illustrative example of the development of biofuels in Sweden, in six episodes.

6.5.1 1980s pre-developments

After some lobbying efforts [F7], the Federation of Swedish Farmers (LRF) gained financial support from the government [F6] to run a pilot plant for 1G production during the first half of the 1980s [F1, F2]. In parallel, the existing production in Örnsköldsvik was supported by the government for reasons of national security – the supply of chemicals (exogenous). On top of this, new markets were sought for economic reasons [F1] (FSED, 2005). Inspired by international developments in the field (exogenous), the focus of SSEU was to promote the use of ethanol from biomass for transport [F7]. The diversity of actors involved in SSEU [F3] resulted in the vision of 1G bioethanol being a bridge to the more advanced 2G bioethanol [F4] (FSED, 2005). However, it was argued by some that it would be cheaper (and more efficient) to produce methanol instead of ethanol from wood [-F4].

During the second half of the 1980s, SSEU took the initiative for a field test with two ethanol buses in Örnsköldsvik [F1, F2], and then a larger fleet demonstration in Stockholm [F1, F2]. The Stockholm project was performed in co-operation with the bus manufacturer Scania and the municipal authority, Stockholm Public Transport [F3], but it was also financed by the government [F6]. Two exogenous driving forces were present in the project; air pollution, and a possible international market for Scania's ethanol buses (Protima AB, 2005).

In general, entrepreneurs and advocates played an important role in this early stage, where a first pattern of cumulative causation could be seen between *Support from Advocacy Coalitions*, *Resource Mobilisation*, *Entrepreneurial Activities* and *Knowledge Development*.

6.5.2 Bus Market Formation and 2G R&D

A government bill on energy policy (SG, 1991), the 'Three-Party Agreement', paved the way for further expansion [F4], and two R&D programmes followed from the agreement. The first was the Ethanol Research Programme [F4], which included financial support [F6] for R&D of production processes for 2G wood ethanol, and was mainly performed at universities [F2]. Second, the KFB (the Swedish Transport and Communications Research Board) Biofuels Programme [F4] funded projects between 1993 and 1997 [F6]. The aim was to test and demonstrate the use of ethanol as a transport fuel [F2], which implied that the ethanol bus projects were brought up to a national level [F3] and in parallel a market for ethanol city buses evolved in Swedish municipalities [F5]. The tests were performed by universities, companies and municipalities around Sweden [F1, F2], often as joint projects [F3]. The first projects of the Biofuels Programme came from a list prepared by SSEU [F7] (KFB, 1997).

The development was stimulated by exogenous factors – the growing interest in environmental issues in the municipalities and concerns for air quality.[106] In Stockholm and other larger cities, 'clean vehicle organisations' were formed to manage field tests of electric cars, an exogenous factor that later turned out to be useful for the diffusion of 'clean vehicles' in general, including those running on bioethanol.

This episode was strongly connected to the ongoing *Support from Advocacy Coalitions* from LRF and SSEU. Supplemented by *Guidance of the Search* and *Resource Mobilisation* in the form of government subsidies, the pattern of the previous episode was repeated in other municipalities. Fulfilment of system functions diverged gradually and a first (niche) market was established.

6.5.3 EU entrance and tax exemptions

Thus, when Sweden entered the EU in the middle of the 1990s, there were already some structures in place in the national BFTIS, both regarding supply and end-use technologies. The Federation of Swedish Farmers (LRF) had been planning to build a 1G bioethanol plant to market surplus production [F1] ever since the first pilot plant was closed down in the mid 1980s [-F1]. It lobbied for better economic conditions for bioethanol production [F7], which were finally rendered possible as the result of the Three-Party Agreement [F4]. However, the expansion of ethanol from agricultural crops was delayed owing to Sweden's entrance into the EU, an important exogenous event. The incentives for wheat-ethanol production decreased because of EU subsidies for export of agricultural surplus (exogenous). In addition, tax exemptions for biofuel pilot projects needed approval from the EU [-F4] (LRF, 2005). In 1997, an application [F7] for specific tax exemptions [F5, F6] for the planned 1G bioethanol plant was approved by the Swedish government [F4], and the following year it was approved as a pilot plant by the EU. A contract on low blending was arranged with the fuel distributors [F5, F6] and the plant was built by LRF [F1]. Production started in 2001.

The main connection to the previous episode came with *Guidance of the Search* from the Three-Party Agreement and the ongoing *Support from Advocacy Coalitions* by LRF. Also in this episode, the *Entrepreneurial Activities* were crucial in supporting *Guidance of the Search*, *Resource Mobilisation* and even *Market Formation*. An important hampering influence came (exogenously) from the EU.

6.5.4 Enlarging the BFTIS to include cars

For non-fleet vehicles (not belonging to a common depot), the problem was that no ethanol pumps would be installed as long as there were no ethanol cars, and no such cars would be sold if there were no pumps. Backed by SSEU,[107] the former leader of the ethanol bus project in Stockholm and a car retailer from Örnsköldsvik decided to tackle this 'chicken and egg' situation by importing flexifuel cars[108] from Ford in the USA [F1]. The project was gradually expanded from 3 to 300 vehicles [F1]; also the fuel distributor OK was increasingly involved [F6] (Protima AB, 2005). The introduction of flexi-fuel vehicles, which was partly funded by the KFB programme [F4, F6], was successful in demonstrating that it was possible to use ethanol for non-fleet vehicles

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[106] The interest was partly associated with the Agenda 21 framework after the Rio World Summit in 1992.

[107] About this time, SSEU was renamed BAFF (BioAlcohol Fuel Foundation).

[108] Flexi-fuel vehicles can run on any mix of petrol and E85, which consists of 85% ethanol and 15% petrol.

also [F2]. The cars were sold with mainly environmental arguments [F4]. In 1998, the flexifuel importers acquired the task from 'Clean Vehicles in Stockholm' and the Swedish Energy Agency of organising a larger purchase of a new generation of flexifuel car, resulting in the introduction of the Ford Focus flexifuel in 1999 [F4] (Protima AB, 2005).

This is perhaps the clearest example of how entrepreneurs set out to build up parts of the BFTIS that were lacking in previous episodes. The cumulative causation process originally related to biofuels applications in buses was now broadened to include cars as well; some of the original actors (SSEU, the City of Stockholm and KFB) were involved. This was the start of a trend of diffusion of 'clean vehicles' in Sweden.

6.5.5 R&D programmes and large-scale strategies

In 1996, the Prime Minister announced an ambition to create 'a green society' [F4]. After this, the ethanol research programme was followed up by a new one [F4], to be pursued during the period 1997-2004, including enlarged funding [F6] for 2G bioethanol R&D [F2] (SG, 1997). In addition, a programme co-funding environmentally-related investments was introduced by the Swedish Environmental Protection Agency [F4], contributing with funding for the later stages of the ethanol flexifuel introduction [F6] (Protima AB, 2005).

At the end of the 1990s, two exogenous factors became dominant; climate change and rising oil prices. As a consequence legitimacy increased for efficient large-scale solutions for transport fuels (e.g. gasification technology). This implied that 1G biofuels were being questioned [-F4]. Despite this controversy, there was co-operation between advocates of 1G bioethanol and advocates of R&D of 2G bioethanol production as they often lobbied for the support of bioethanol in general [F7].

In 2002, four governmental agencies (VINNOVA[109], Swedish Energy Agency, Swedish Environmental Protection Agency, and Swedish Road Administration) agreed on a common strategy for the introduction of biofuels. The production of 2G bioethanol was to be 'demonstrated by building a plant' [F4]. The blending of biofuels was generally preferred to the use of pure biofuels, which would have to be used where they were 'economically feasible' [F4] (VINNOVA, 2003).[110] Following this strategy, the two ethanol research programmes resulted in the production of a 2G pilot plant [F2, F4], built in Örnsköldsvik. It started production in 2004, and was mainly financed by the Swedish Energy Agency [F6].[111] Although it is a 1G technology, wheat ethanol also survived the discussion on large-scale solutions and was recommended for blending into petrol in the strategy document prepared by the four agencies [F4].

Cumulative causation was here mainly related to 2G bioethanol R&D. Building on previous episodes, *Guidance of the Search* was followed by *Resource Mobilisation* and *Knowledge Development*. In addition, despite strong criticism, 1G bioethanol technologies were still supported by a variety of system functions.

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[109] Swedish Agency for Innovation Systems.

[110] The strategy was mainly in support of gasification technology producing fuels other than ethanol.

[111] In parallel, pilot plants for gasification technology (i.e., not related to ethanol) were prepared.

6.5.6 Large-scale market stimulation

Despite the criticism of 1G biofuels, beginning around 2000, various economic incentives were introduced for biofuels and 'clean vehicles', such as reduced vehicle tax and lower benefit tax for privately-used company cars on the national level [F5], and parking fee subsidies on the local level [F5]. General exemptions from energy and CO_2 tax for biofuels were decided upon [F5], which contributed mainly to the 5% blending of bioethanol in petrol (SG, 2006). In parallel with the Swedish 1G production, the import of ethanol produced from sugar cane in Brazil rapidly increased (SBA, 2006).

The Swedish policies for market stimulation were further justified through the EU biofuels directive, and national targets were set [F4]. 'Clean vehicles' were exempted from the congestion tax in Stockholm during the trial [F5], and some national and local authorities were obliged to purchase certain shares of 'clean vehicles' [F5]. To guarantee the build-up of a refuelling infrastructure, there was a political agreement that an increasing number of refuelling stations would have to supply at least one renewable fuel; this would mainly imply bioethanol [F5] (SG, 2005). Together, the various measures contributed to a rapid expansion of the market for flexifuel cars and the introduction of several new models [F5].

This episode was characterised by a strengthening of the *Market Formation* function, but also, following from the economic incentives, *Guidance of the Search* and *Resource Mobilisation*. The emergence of these system functions was a result of the variety of system functions built up through cumulative causation processes during previous episodes. Most system functions were strong and a take-off was expected for domestic bioethanol production. See Figure 6.2 for an overview of the six episodes of Swedish BFTIS development.

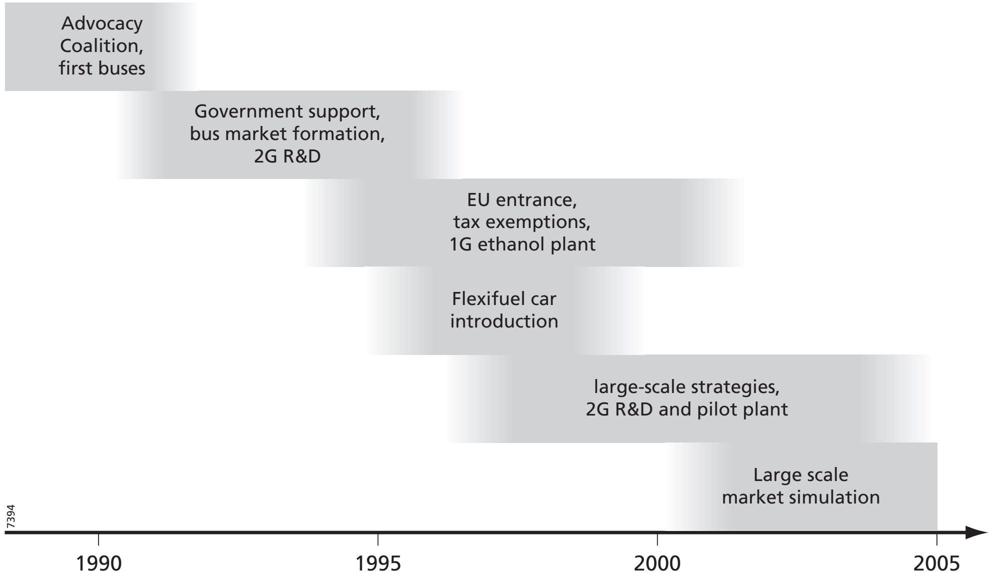

Figure 6.2 Six episodes of Swedish BFTIS development.

6.6 Comparing the Dutch and the Swedish cases

The historical analyses show that Sweden and the Netherlands differ significantly regarding the development of their BFTISs. The event sequences portrayed reveal that in the Dutch BFTIS, system functions were fulfilled more or less sporadically and that cumulative causation occurred only for short periods of time. It could be argued that since the 2003 EU directive this has been changing, as since then all system functions are present and seem increasingly to reinforce each other. In Sweden, signs of cumulative causation could be seen already at the onset of the 1990s. Since then most system functions have undergone a continuous positive development. So there are significant differences between the two countries, implying important lessons for BFTIS actors such as policy makers and entrepreneurs.

6.6.1 Addressing multiple system functions

As suggested by the TIS framework, our cases confirm the importance of addressing the whole range of system functions. Policy measures are more effective when designed to target all the BFTIS functions, but also entrepreneurs are most successful in bringing about change when actions are directed at facilitating multiple system functions at once. This is actually what makes cumulative causation processes possible. Our two cases clearly differ in this respect, especially with regard to policy.

The Dutch government has shown a rather linear orientation to the promotion of biofuels. From the moment that support of 2G biofuels was deemed desirable as a policy strategy, the government has been focusing on subsidising R&D (*Knowledge Development* and *Resource Mobilisation*) and the formation of networks (*Knowledge Diffusion*), but the market was left largely unaddressed. This was, at least partially, the reason for the discontinuation of *Entrepreneurial Activities*, in the form of a commercial demonstration of 2G biofuels. The possible advantage of a broader policy orientation is shown by the variety of actions taken by the Swedish national government. Besides *Guidance of the Search*, Swedish policies targeted *Knowledge Development*, but also, in a more parallel approach, the early *Entrepreneurial Activities* and (niche) markets around 1G biofuels. This was done by providing financial support but also by means of market stimulation. Influential initiatives are the bus projects supported by the KFB programme, tax exemptions for 1G bioethanol, and economic incentives related to vehicle purchase and ownership.

It should be stressed that the orientation of Swedish policy was as much a result as a cause of BFTIS dynamics, and was not completely intentional and strategic. *Entrepreneurial Activities* and the formation of *Advocacy Coalitions*, on behalf of entrepreneurs, had a significant impact on policy making as well.

6.6.2 The crucial role of entrepreneurs

The TIS framework recognises the importance of entrepreneurs through the existence of an explicit system function that captures their activities. Our analysis suggests that *Entrepreneurial Activities* played a crucial role in most interaction patterns. After all, the private and municipal entrepreneurs have been prime movers, contributing to the build-up of *Support from Advocacy Coalitions*, *Guidance of the Search* and other functions of the BFTIS.

In the Netherlands, cumulative causation has generally been short lasting, but where it occurred, it was driven by entrepreneurs. This is true, for instance, for the episode where Dutch boating companies started adoption experiments, raising expectations and lobbying for government support. Such activities drew in even more entrepreneurs. Also in Sweden, *Entrepreneurial Activities* around ethanol were often the start of a chain of interrelated activities. The first examples are the ethanol bus projects that started before 1990 in Örnsköldsvik and Stockholm, which opened up possibilities for further developments towards a market for city buses fuelled by ethanol. A few years later, similar projects were run in the car segment, partly by the same entrepreneurs. *Entrepreneurial Activities* (of LRF) were also a premise for the building of a 1G bioethanol plant.

6.6.3 Reducing long-term uncertainty

Entrepreneurial Activities play a central role in both countries, but these alone cannot provide enough momentum. As initial policy measures were made possible by *Entrepreneurial Activities*, the continuation of *Entrepreneurial Activities* was strongly related to the presence of policy support. Our cases show that follow-ups on *Entrepreneurial Activities* were strongly related to the presence of consistent government policy. Strong programmatic policy guidance, reducing long-term uncertainty, had a sustaining effect, while the absence thereof was a recurring barrier.

Especially in the Netherlands, the absence of clear policy guidelines made promising *Entrepreneurial Activities* too risky to continue (Shell, TNO). Policy makers certainly did make contributions to the fulfilment of other system functions, such as *Resource Mobilisation* (R&D subsidies) and incidental *Market Formation* (temporary tax exemptions), but these were not part of a general policy programme. A more positive example is the programmatic support by the national GAVE programme, which strongly influenced a variety of entrepreneurs, especially around 2G technologies. The importance of *Guidance of the Search* becomes even clearer from the Swedish case; here, an important decision was taken very early, through the Three-Party Agreement in 1991. Support for ethanol use was warranted, paving the way for R&D programmes and a scaled-up use of ethanol buses. The agreement also resolved the long-standing uncertainty for 1G bioethanol production. Another important example is the strategy document elaborated by four governmental agencies in 2002, where a demonstration plant for 2G bioethanol and blending of biofuels into petrol (and diesel) was recommended. Both these Swedish examples were strongly related to functions already present in the national BFTIS.

In both countries the influence of policy programmes – positive or negative – was crucial. When the government issued consistent policy guidelines, *Entrepreneurial Activities* were initiated that fostered further event sequences and cumulative causation in the BFTIS. The absence of a consistent policies resulted in destructive effects on the emerging BFTIS.[112]

6.6.4 Policy support at different levels

Our cases show that policy support can and should be provided at different government levels, i.e., the regional, the national and the EU level. In both countries the regional level has been important as a source of market-directed innovation. The earliest entrepreneurial experiments were, in

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[112] Note that the *Guidance of the Search* function need not necessarily be fulfilled by policy makers. In fact, entrepreneurs themselves can play an important role, for instance, by collaborating through the formation of *Advocacy Coalitions*. However, for the long-term perspective it turns out that government leadership is a requirement.

several cases, related to regional companies that were strongly linked up with the municipality or provincial government. As regional initiatives were connected, a knowledge-oriented industry cluster emerged, but most importantly also *Advocacy Coalitions* that pressed national government for policy measures and legislative change. In the Dutch case this became apparent through the coalition around 1G biofuels in the rural areas. In Sweden, the first two ethanol bus projects were started at the local level.

The response from the national government level to these regional dynamics has been very different in the two countries. The Swedish BFTIS was strengthened through a mostly facilitative orientation, fostering the regional developments and thereby contributing to the build-up of cumulative causation. In contrast, the Dutch government largely neglected support of all developments around 1G that were driven by regional interests.

An important difference also lies in the countries' relation to EU policy. In the Netherlands, national policy makers have been following EU incentives, though mostly they were lagging behind. As a result, regional projects were typically stimulated by EU policies, while hampered by (the lack of) national policies. Conversely, in Sweden, the national government took the initiative of providing guidance, while the *Entrepreneurial Activities* related to 1G fuels at the beginning of the 1990s were held back because of the EU entrance and the change in agricultural policy. The developments were eventually continued nonetheless, and years later, when the EU directive was launched, the introduction of biofuels had already started in Sweden.

This underlines the importance of support from different policy levels, but also that conflicting signals at different levels become a barrier for further developments. Where policy on the national level is lagging behind, coordinated incentives on the regional and the EU levels may stimulate national developments. Where national government shows higher ambitions, the EU policies can be troublesome.

6.6.5 Hard technological choice

Policy makers have been influential in framing the selection environment for biofuel technologies, both in a positive and negative sense. Our comparison shows how the more fruitful situations were those where national policy allowed for various technologies to develop in parallel, taking into account their respective stages of development. When hard technological choices were made by policy makers, important system functions were weakened.

Government authorities in the Netherlands have been closely involved in the discussion on the technology features themselves. The 2G technologies have been presented as the group worthy of (programmatic) support, while the 1G technologies were 'left to the market'. This way a large part of the emerging BFTIS was excluded already at an early stage of development. The idea of 1G biofuels being bridging technologies to 2G biofuels only comes with the implementation of the EU directive. In Sweden, there were advocates representing either 1G or 2G alternatives, or both, whose standpoints were taken up in the policy-making process. The potential controversy between 1G and 2G was not as severe because the governmental support was for a variety of alternatives all at different stages of development. Although this idea was not explicitly articulated by policy makers, the Swedish case suggests that cumulative causation was facilitated through activities related to the field of 1G bioethanol, where *Entrepreneurial Activities* were abundant. Also the most recent Dutch developments show that the technically less promising biofuels should not be underestimated with respect to their potential contribution to cumulative causation. A direct selection on behalf of the government towards (primary) technological features entails the risk of killing off a potential for the future.[113]

6.7 Conclusions

Our analysis partly confirms and explains results from earlier studies. However, applying the framework of Technological Innovation Systems (TISs) to the field of biofuels adds to the understanding of how emerging technologies develop under the influence of endogenous (and exogenous) forces of change. In addition, some specific lessons on biofuels can be drawn for policy makers and entrepreneurs from our comparison of two Biofuel Innovation Systems (BFTISs).

Taking a step back, looking at what we have learned, we can conclude that our analysis pointed out the crucial importance of dynamics when trying to understand innovation processes around emerging technologies. We adopted the TIS framework to determine the factors that influence such processes by analysing the build-up of system functions over time. This made it possible to pinpoint how system functions interact and lead to cumulative causation. The comparative perspective allowed us to show similarities and differences from which important lessons could be derived for influencing and improving such processes in the future.

We have shown how the Netherlands and Sweden differed in stimulating the build-up of a comprehensive set of system functions, necessary for the successful development of their respective Biofuels Innovation Systems (BFTIS). As a result of a continuity in the sequence of various entrepreneurial experiments and the emergence of cumulative causation, the Swedish BFTIS has reached market expansion and social implementation of biofuels, whereas the Dutch have so far established considerably less. The TIS framework can be valuable for policymakers and entrepreneurs. The results were translated into strategic lessons that may be used to accelerate the build-up of the BFTIS.

For instance, both in the Netherlands and Sweden, *Entrepreneurial Activities* proved to be a crucial system function for triggering cumulative causation. Our study suggests that to facilitate *Entrepreneurial Activities*, policy makers, at multiple government levels, should develop long-term support programmes. Governments should facilitate TIS development by targeting multiple system functions simultaneously and support multiple technologies in parallel. Entrepreneurs may contribute to the TIS by forming networks and cooperating, thereby strengthening *Knowledge Diffusion* and *Support from Advocacy Coalitions*. They should articulate what they believe is desirable or feasible and avoid or resolve mutual conflicts. The entrepreneurs may also benefit from directing their actions at a broad range of system functions.

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[113] The development of various technologies can only be stimulated through the use of several different policy instruments in parallel. See Sandén and Azar (2005) on the need for technology differentiated support. Of course, there is need for a balanced view, as too much focus on 1G technologies may lead to a dead end. See Hillman and Sandén (Hillman and Sandén, 2006). See also Suurs and Hekkert (2008a).

Some limitations should be expressed as well. Our approach uncovers particularly the dynamics that are endogenous to the technological field. Some macro-events are taken into account as exogenous forces of change. However, many differences at the macro-level between the two countries with regards to cultural, industrial and political structures and events have not been considered as possible alternative explanatory variables.

A second limitation concerns the methodology used. Since it is only in retrospect that we can acquire an insight into the consequences of particular (sequences of) events, it remains difficult to provide truly generalisable lessons. Still, this limitation is not unique to this approach but is an inherent feature of social science. We see our ambition to systematise narratives, or history, using the model of a system with functions, to be in line with Freeman and Louçã's plea for reasoned history (Freeman and Louçã, 2001). Hopefully, we contribute with insights and advice that are useful for policy makers and entrepreneurs in many technological fields.

Interlude D

In the foregoing chapters, I have applied the TIS approach in combination with an event history analysis, thereby providing insights into the various forms of cumulative causation – motors of sustainable innovation – that unfolded as the result of interactions between system functions. The main outcome from these case studies has been the identification of a number of motors of innovation, along with a set of specific structural drivers and barriers that drove or hampered them. In the following chapters I will continue the search for motors in order to increase knowledge of the processes that determine TIS build-up. These involve two additional case studies, one about the development of hydrogen and fuel cell technologies in the energy sector of the Netherlands and the other about the development of natural gas technologies in the mobility domain of the Netherlands.

The main goal of these two case studies is to strengthen and broaden current insight into the dynamics of TIS build-up. If different motors are found than in the previous cases, this will add to insight into the possible forms of cumulative causation. If similar motors are found, this will confirm the idea that motors are forms of cumulative causation that are of general relevance.

In the previous chapters the emphasis of the case studies was on the identification of motors. Structural drivers and barriers – blocking and inducement factors – were identified as well but this was not done in a systematic way. Also, the impact of the motors on TIS structures was not explicitly taken into account. Therefore, another goal of the following two case studies is to develop a better understanding of the drivers and barriers that cause motors of innovation to emerge, develop and (possibly) decline. The studies also aim to achieve insight into the influence of the motors, in turn, on these structural factors.

The previous chapters employed a rather loose conceptualisation of TIS structures (actors, institutions, networks and, to some extent, technologies). In the remainder of this book the structural factors are analysed more according to the theoretical notions presented in Chapter 2.2. This especially means that more attention is given to the actor concept (enactors-selectors) and to the system components (supply-side, demand-side, government structure, intermediary structure, knowledge structure). Also, more attention is paid to the role of technological factors as material artefacts.

7 The hydrogen and fuel cells TIS (NL)

7.1 Introduction

This chapter will analyse and evaluate the development of Hydrogen and Fuel cell (HyF) technologies in the Netherlands. At the core of the HyF Innovation System (HyFIS) is the hydrogen fuel cell, a device that converts hydrogen gas into electricity through an electrochemical reaction. It enables the clean and efficient conversion of hydrogen into electricity. Fuel cells can be utilised in zero-emission vehicles for the transport sector. Fuel cells can also be applied in power plants, as a means to produce heat and electricity in an efficient and clean way.

The fuel cell in combination with hydrogen is widely considered to play an important role in future sustainable energy systems, even to the extent that visions of a hydrogen-based economy have become dominant among policy makers, scientists and firms. According to this vision, hydrogen is the energy currency of the future to replace petrol, diesel, natural gas and electricity as energy carriers. In light of this, it is important to understand that hydrogen itself cannot be found in nature but needs to be produced. Currently it is produced from natural gas (Adamson, 2004) but the idea of a hydrogen-based energy system is based on the assumption that hydrogen will (someday) be produced from renewable energy sources (Adamson, 2004).[114]

Despite high expectations, HyF technologies are associated with persistent problems. Recurring technological, economic and societal barriers have held back the diffusion of HyF technologies. Also the whole point of a hydrogen-based energy system has been called into question.[115] In the face of this troublesome history, the HyF Innovation System (HyFIS) is an interesting example of a TIS in the formative stage. It has been developing for more than 50 years, and yet HyF technologies are still in an early stage of development. One reason to look more closely at the HyFIS is to find out how it could remain immature for so long without becoming subject to decline. A part of the answer lies in the fact that a lot has been achieved in those 50 years, and in fact, as will become clear in this study, the HyFIS, as well as the HyF technologies themselves, have changed and improved in multiple ways. Another part of the answer lies in the importance of promises and expectations. It is known from the energy literature that HyF technologies have been subject to multiple waves of expectations (Schaeffer, 1998). Nevertheless, the expected distance-to-market of HyF technologies has remained a rather constant 5-15 years, depending on the actors' perspective. It will be interesting to find out how a TIS manages to develop for such an incredibly long period of time without realising any significant technology diffusion.

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[114] For example, why not use electricity in combination with (improved) batteries as an energy carrier?

[115] We do not take a stance on this matter as it is not the purpose of the analysis to evaluate the desirability of a TIS.

The following research questions are central to this study:

RQ 1: What were the motors of innovation that constituted the development of the HyFIS (in the Netherlands) between 1980 and 2007?

RQ 2: What were the underlying structural drivers and barriers that explained the emergence of the various motors of innovation in the HyFIS?

RQ 3. How did the various motors of innovation in their turn influence HyFIS structures?

The history of the Dutch HyFIS goes back to the early 1950s but the analysis in this chapter is limited to the period from 1980 to 2007. This is because of practical limitations of time and availability of data (see below). Moreover, it was considered sensible to focus on the most 'recent' history, as results will then be more comparable to our other case studies and more applicable to practitioners active in today's energy system.

The outline of this chapter is as follows: Section 7.2 gives the research design of this case study, pointing out differences with the approach taken in previous case studies. Section 7.3 provides an empirical background on the HyF Technology and its history in the Netherlands, thereby setting the stage for an in-depth analysis in Section 7.4. Section 7.5 concludes by answering our research questions.

7.2 Research design

The basis of the analysis of TIS dynamics in this study is the event history analysis (Poole et al., 2000). The details of this approach have been thoroughly described in Chapters 2 and 3. In this case study we deviate, however, from our earlier approach on a number of points.

This study, just as the previous case studies, is based on the construction and analysis of a database of events. This database consists of articles from national and regional newspapers, professional journals and information from websites. However, an important difference in our approach here is that we rely less on a systematic longitudinal survey of data sources than we did for the gasification and biofuels cases. The systematic tracking of data sources for the whole period 1980-2007 was considered too time consuming, especially since a lot of data sources were not available in digitalised format, and especially not for the period before 1990. As a result of this, we decided to depart from the quantitative mapping approach developed in our previous case studies, and focus more on the qualitative analysis, thereby combining as much as possible the partially available data sources for the different periods in time.

An important implication of this choice was that more time was needed to be spent on investigating other sources of data than the media mentioned above. Most importantly, we made use of historical accounts. Especially, for our study of the earlier period (1980-1995) we made use of Schaeffer (1998) and Van der Hoeven (2001). These excellent studies of the Dutch HyF history provided us with detailed information on the history of the Dutch HyFIS (although without actually applying the concept). An important contribution of this study is therefore a (re) interpretation of these histories, by using the TIS framework. This is possible because both studies contain, besides analytical sections, more or less chronological thick descriptions of events.

Another data source which was used more intensively than in our other case studies was interviews. Initially, twelve interviews were conducted with various experts of the Dutch HyF field, including policy makers and entrepreneurs. After the analysis was done, a smaller number of additional interviews was conducted, during which the first analytical results were checked for errors, and 'loose interpretations'.

So the empirical work for this case study relies on the construction of a narrative, based on the inquiry and interpretation of a variety of data sources, including an event data base, containing data from digitalised media (covering especially the most recent time period 1995-2007), a number of historical accounts (covering the period 1980-1995) and expert interviews (which were especially useful as a validity check).

7.3 Setting the stage

The period in which the development of the HyFIS is studied starts in the early 1980s and ends by 2007. To prevent the reader from losing track of the big picture, this section provides a bird's-eye view of the development of the HyFIS. This is done by giving a description of HyF technology and its value-chain, by providing a rough overview of key structures within the HyFIS and by picturing a historical timeline of its development. This sketch serves as a background for the event history analysis in Section 7.4. See Box 7.1 for an overview of abbreviations used throughout this chapter.

7.3.1 HyF technology

A fuel cell is a device that produces power from an electrochemical reaction. It is a battery albeit one that works with a continuous supply of fuel. In most designs hydrogen is used as a fuel but it is also possible to use methanol or natural gas. A fuel cell consists of two electrodes (an anode and

Box 7.1 List of common abbreviations

CHP system	Combined Heat and Power system
ECN	Energy Research Centre of the Netherlands.
FC	Fuel Cell
FCV	Fuel Cell Vehicle
HyF	Hydrogen and Fuel Cells
HyF IS	Dutch Hydrogen and Fuel Cell technologies Innovation System
MinEZ	Ministry of Economic Affairs
MinVROM	Ministry of Spatial Planning and the Environment.
MinVW	Ministry of Traffic, Public Works and Water Management.
Novem/SenterNovem	The national government's executive agency for energy and innovation.
TUd	Technical University Delft
TUt	Technical University Twente

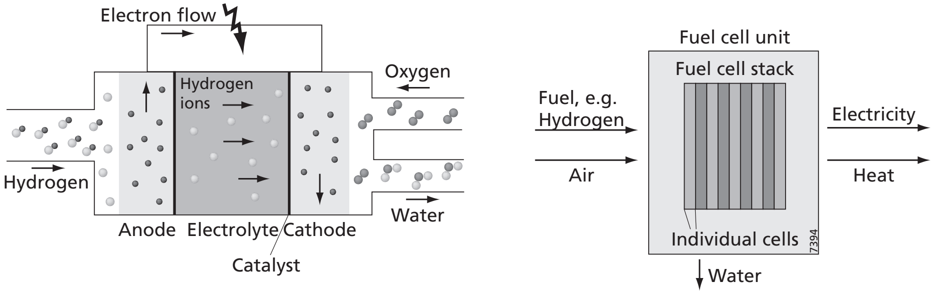

Figure 7.1 A fuel cell (left) and a fuel cell unit (right).

a cathode) separated by an electrolyte. The electrolyte is a carrier of charged particles; it serves as a medium for the products of the electro-chemical reaction. The electrodes carry the electric current released by the reaction. The reaction itself is made possible by a catalyst material which adheres to the electrodes.

Figure 7.1 provides a sketch of the design of a hydrogen fuel cell. The figure demonstrates how hydrogen gas flows into the fuel cell at the anode side and is split into protons (positively charged hydrogen ions) and electrons. On the side of the cathode, oxygen (from the air) flows into the fuel cell. The hydrogen ions are pushed into the electrolyte whereas the electrons (being unable to pass the material) are led through an electric circuit. The electrons and hydrogen ions meet at the cathode where they are recombined with oxygen (which is split into negatively charged ions) to form water molecules. During the reaction energy is released, partly in the form of electricity (the electron flow) and partly in the form of heat. In terms of materials, the fuel cell reaction consumes hydrogen and oxygen and releases water. Some fuel cells are designed to convert fossil fuels such as methanol or natural gas; these work similar but they produce CO_2 as well.

A single fuel cell provides a small amount of power. To meet a realistic demand multiple fuel cells need to be combined in a stack, a connected series of fuel cells. Such a fuel cell stack needs to be integrated into a so-called fuel cell unit, consisting of multiple stacks, circuitry, compressors, sensors, etc. (Van der Hoeven, 2001).

There are five types of fuel cells, named after the electrolyte used; AFC, PAFC, PEMFC, MCFC and SOFC. The characteristics of these designs differ with respect to the materials used for

Table 7.1 Five fuel cell types.

Fuel cell type	Temperature (°C)	Application domain	Technology generation
AFC Alkaline Fuel Cell	25-250	FCVs	1G
PAFC Phosphoric Acid Fuel Cell	150-200	CHP	2G
MCFC Molten Carbonate Fuel Cell	600-1000	CHP	2G
SOFC Solid Oxide Fuel Cell	600-1000	CHP	3G
PEMFC Proton Exchange Membrane Fuel Cell	60-100	FCVs	3G

Source: FCW (2007).

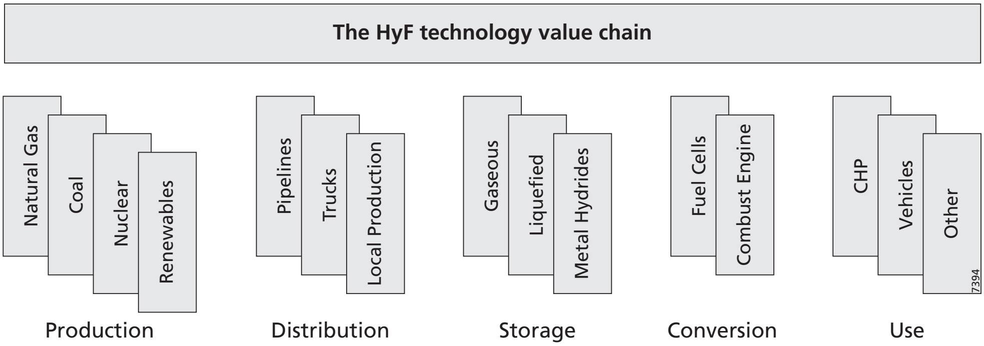

Figure 7.2 The HyF value chain; source: Bakker and Van Lente (2008).

the various components. Different fuel cell types are based on different knowledge bases and connected to different applications; see Table 7.1. A key variable related to both factors is the operating temperature. High-temperature fuel cells are mostly used in CHP applications whereas low-temperature fuel cells are mostly used in FCVs.

During the history of fuel cell development, a typology has been used that characterises the different fuel cell types, according to a development perspective, in terms of technology generations.[116] Initially, first-generation (1G) fuel cells, the AFC and the PAFC, were distinguished from a second-generation (2G) fuel cell, the MCFC (Schaeffer, 1998). The first-generation fuel cells were considered near-commercial but less promising than the MCFC. When the SOFC and PEMFC were developed, later in time, they were labelled third-generation (3G) technologies. The influence of these technological features will be discussed as part of the analysis in Section 7.4.

On a system level the fuel cell technology makes out a small part – the conversion part – of a HyF value chain; see Figure 7.2. Other parts are production, distribution, storage and use.

Production

First of all, it should be stressed that pure hydrogen cannot be found in nature. It needs to be produced. The often propagated ideal is to produce hydrogen, through the electrolysis of water, from green electricity, but currently it is more economical to produce hydrogen from natural gas.[117] In any case, the production of hydrogen will cost energy and this is therefore an important part of the HyF value chain to assess, especially when considering its (potential) contribution to a sustainable energy system.

Distribution and storage

After production, the hydrogen needs to be distributed to the location of use. The technology required to do this is partly available, as hydrogen gas streams are handled on a daily basis in the

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[116] Schaeffer (1998) reflects in detail on the establishment and consequences of this division, pointing out how a prevailing logic of technology generations promotes promising but less mature technologies at the cost of holding back those closest to the market.

[117] See Hekkert et al. (2005) for an overview of various natural-gas based automotive fuel chains.

petrochemical industry. The downside is that this distribution system is fit for a local demand and does not stretch beyond industrial areas. Its expansion would mean massive investments. A fundamental problem related to the expansion of the infrastructure is the storage of hydrogen. The compact storage of hydrogen is only possible by either compressing or liquefying it; both techniques use a large amount of energy.

One way to avoid storage of hydrogen is to prevent handling of hydrogen, by producing hydrogen at the location of use. This requires a small-scale fuel reformer that efficiently converts natural gas or another hydrocarbon into hydrogen. Reformer technology has been useful for stationary applications but it has so far not proven itself on board vehicles.

Application

The final part of the HyF value chain is the application. Two main areas may be distinguished: stationary and mobile applications. The stationary applications involve the use of fuel cells in CHP systems. Fuel cell CHP systems are considered an efficient and clean way to produce heat and power. Mobile applications involve FCVs: electric cars that are powered by fuel cells. The relative importance of both application domains has changed over time.

7.3.2 Outline of the HyFIS

This section provides an outline of the HyFIS, mainly in terms of the actors involved in HyFIS development. The outline is organised according to the five system components presented in Chapter 2; supply-side, demand-side, government structure, knowledge structure and intermediary structure.

On the *supply-side* of the HyFIS, fuel cells and fuel cell applications are developed by a small number of engineering companies, such as Stork and De Schelde and later Nedstack. FCVs are barely developed at all, as car manufacturers are absent in the HyFIS. FCVs therefore need to be imported. The production and distribution of hydrogen is in the hands of traditional gas/fuel industries like Gasunie, Shell, Air Products and Air Liquide. This is also the case for storage technologies, although here strong connections exist with technology institutes, universities and car manufacturers.

On the *demand-side* the most important actors are energy utilities, public transport companies and (foreign) car manufacturers. Energy utilities utilise hydrogen and fuel cells in CHP systems and car manufacturers utilise fuel cells as a power source in FCVs. Practically all demand is stimulated through government subsidies. Only very recently do we find the first (near)-market applications in forklifts and back-up systems.

With respect to the *government structure*, various ministries, most importantly MinEZ and MinVROM, have supported HyF Technology for most of the period studied. The most salient is the Fuel Cells Development Programme (NOB), a large demonstration programme running from 1980 to 1998. Regional governments have been important as well. Since 2000, municipalities have embraced HyF technologies as a solution to the problem of local air pollution. On the international level, the European Commission plays an important role by supporting public-private partnerships on large technology demonstrations. Dutch actors play an influential role on this level too.

For the *knowledge structure*, a key role is played by the technology institutes TNO[118] and ECN. It is especially ECN, supported by the national government, that pushes the HyFIS forward by developing fuel cell technologies. Indeed, Dutch fuel cell research is internationally recognised for its quality. The downside is that most of ECN's efforts are put into MCFC and PAFC fuel cells, technologies that have recently been surpassed by the PEMFC and SOFC. In recent years, research in the HyFIS has concentrated more on production, storage and distribution, mainly through companies like Shell, Air Products and Gasunie in co-operation with universities.

The *intermediary structure* constitutes the necessary linkages between system components. In the early stage these linkages are established by organisations like Novem, the government's executive energy agency. The role of Novem is to bring policy makers and entrepreneurs into contact with each other. In many cases Novem also acts as an HyF advocate. In recent years networks such as the Dutch hydrogen association have complemented Novem's role, thereby making the intermediary structure less dependent on government support.

7.3.3 Timeline

The HyFIS emerges in the 1950s and 1960s when Dutch researchers contribute to the development of the AFC and the MCFC. The work consists of research and development that fits within NASA's space programme in the USA. With their R&D activities, the Dutch make an important contribution to international *Knowledge Development*. Due to the relatively poor availability of data for this period, these developments will not be part of our detailed analysis. Starting in the 1980s, four periods have been distinguished; see Table 7.2.

In 1980, the oil crises of the 1970s are fresh in mind. This makes the issue of energy supply a key driver for HyF development all over the world. The most important development in the Netherlands is the setting up of the NOB. This dedicated fuel cell development programme, directed by MinEZ and ECN, boosts *Knowledge Development*. It focuses especially on MCFC and PAFC technology. A drawback is that the ambitions behind the NOB – to induce the building of a new industry – are not matched by *Entrepreneurial Activities* among industries, with the consequence that a lot of time passes before demonstration projects are actually started. The main reason is the poor economic feasibility that the MCFC turns out to have.

In the 1990s, security of supply becomes less of an issue and the environmental movement loses some of its steam. Around this time ECN manages to establish a partnership with two large assembly/engineering companies, Stork and De Schelde. Under the name BCN,[119] the parties manage to successfully construct a working MCFC system. But a devastating conclusion by the end of the 1990s is that the MCFC, as well as the PAFC, is not commercially feasible (Schaeffer, 1998; SenterNovem, 2007). Fortunately, ECN anticipates the decline of the PAFC and MCFC technologies by shifting resources to a third generation of fuel cells, the SOFC and the PEMFC. Both research trajectories become increasingly important towards the end of this period.

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[118] TNO: Dutch Institute for Applied Science.

[119] Dutch Fuel Cell Corporation. In Dutch: *BrandstofCel Nederland* (BCN).

Table 7.2 Five episodes of HyFIS development.

Episode	Developments	Dominant Tech.	External factors
1980-1991	Setting up of Fuel Cell Programme (NOB)	MCFC, PAFC	Security of supply, Environmental issues
1992-1998	Fuel cell demonstrations (MCFC, SOFC)	MCFC, SOFC	Liberalisation, Low oil price
1999-2003	Shifting technology, shifting policy	PEMFC, SOFC	Car industry picks up PEMFC
2004-2007	Increasing visibility/user involvement	PEMFC	Climate change, EU policy

The end of the NOB in 1998 comes at the same time as the international field of HyF technology undergoes a boost as PEMFC technology is embraced by car manufacturers abroad.[120,121] The result is a reorientation of the HyFIS towards the PEMFC. A key development is the policy paradigm changing to a market-oriented approach in which firms themselves are to take the initiative, not governments and technology institutes (IEA, 2000). Another development is a broadening of the HyFIS to include not just fuel cells but increasingly the whole fuel cell value chain (ECN, 2007; SenterNovem, 2007).

In the new millennium, environmental issues, most notably climate change, become more important again. The hydrogen economy concept, propagated by the USA and the EU, is turned into a propelling vision of a sustainable future. The majority of activities become centred around mobility applications for the PEMFC. As a result, many firms enter the HyFIS and the first commercial applications of fuel cells are developed. A key development is the emergence of a large variety of PEMFC demonstrations.

7.4 The event history of the HyFIS

In this section, the HyFIS is subjected to a dynamic analysis, thereby providing a detailed account of the development of system functions and the motors that occurred. Furthermore, the mutual interaction between motors of innovation and the structural configuration of the TIS will be discussed. The section is structured as a chronological narrative consisting of the four episodes presented above. For each episode, the shifts in the external environment of the HyFIS are sketched in the first section. Then a narrative is presented in terms of events of which the contributions to system functions will be denoted by [F1, F2, … F7]. At the end of the episode, a reflection is given on the narrative, focusing on the motors that occurred, the structural drivers and barriers that enabled it and the impact it had on the HyFIS structure.

7.4.1 Rebirth (1980-1991)

The 1970s were characterised by a global decline of fuel cell activities due to generally disappointing research outcomes. The exception was the USA, where developments were

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[120] The PEMFC was developed as part of NASA's Gemini programme. Around 1990 the PEMFC becomes a serious candidate for civilian applications as well. An international milestone is the successful demonstration, in 1993, of a fuel cell bus by Ballard (SenterNovem, 2007).

[121] After having experimented with battery-electric drive trains for years without commercial success, the German car manufacturer Daimler decides to shift its course of action entirely in the direction of the fuel cell-electric drive train (AD, 1996b; FZ, 2007; MinVROM, 2007; Technical University Delft, 2007).

sustained through NASA's Space Shuttle programme and through government support for fuel cell CHP systems (Schaeffer, 1998; Van der Hoeven, 2001; ECN, 1998). In the 1980s three external factors lead to a rebirth of fuel cell developments in Europe. First of all, with the second oil crisis fresh in mind, alternative energy sources receive political priority. Secondly, the environmental movement manages to put air pollution and climate change firmly on the political agenda. The third factor consists of a positive series of developments in the USA where energy companies announce the demonstration of CHP applications (Schaeffer, 1998).[122]

The political pressure for clean energy technologies leads to a renewed interest in fuel cells in the Netherlands as well [F4] (Schaeffer, 1998; Van der Hoeven, 2001; ECN, 2007). Fuel cells are characterised as efficient and clean. Moreover, they fit in well with the Dutch gas-centred energy supply system (Schaeffer, 1998).[123] Articles begin to appear in professional journals [F2, F3] boasting about the foreign successes in the field of fuel cell research [F4]. The general impression among researchers and policy makers is that the Netherlands, and Europe in general, lag behind (Schaeffer, 1998; Van der Hoeven, 2001; ECN, 1998). Urged by scientists, research institutes and technology developers, MinEZ makes plans to support fuel cell research [F4, F7] (Schaeffer, 1998; Van der Hoeven, 2001). The fuel cell is at this time mainly considered as a means to make the conversion of natural gas into electricity as clean and efficient as possible. The use of hydrogen as an energy carrier is of marginal interest at this time (ECN, 2007; SenterNovem, 2007). The idea is to use natural gas as an energy carrier and to apply reformer technology for the production of hydrogen 'on-site'.

To determine the economic feasibility of the fuel cell, MinEZ issues feasibility studies [F2]. The results are generally not too positive, especially where economic feasibility is concerned [-F4]. But scientists, inspired by developments in the USA, manage to keep drawing positive attention to fuel cells [F4]. By the end of 1983, MinEZ consults representatives from industry and academia, with delegates from DSM (chemical engineering), Gasunie (chemical engineering), Stork (assembly), the Technical University Delft (TUd), PEO[124] and NEOM[125] [F3]. The outcome is the proposal for a government support programme, the NOB,[126] large enough to induce industry building [F4, F6] (Schaeffer, 1998; Van der Hoeven, 2001). It is decided that the MCFC, a 2G fuel cell technology, is the best candidate for support [F4].

The specific focus on a single technology may be considered narrow given the uncertainties associated with emerging technologies. On the other hand, the NOB dedicates a small share of the programme to the support of PAFC field-tests as well [F4]. The AFC, the only other option currently in sight, is already being developed by Elenco, a joint venture of DSM and the Belgian

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[122] It is especially the announcement of a 4.8 MW PAFC power plant to be installed in New York that attracts attention (Schaeffer, 1998).

[123] The use of natural gas for production of heat and power has rapidly expanded ever since a gas field in Groningen was discovered in 1959.

[124] PEO is the office for Energy Research Projects (Dutch: *Projectbureau Energieonderzoeksprojecten*), later PEO is merged with NEOM to form Novem/SenterNovem.

[125] Dutch Energy Research Company (Dutch: *Nederlandse Energieontwikkelingsmaatschappij*), later NEOM is merged with PEO to form Novem/SenterNovem.

[126] Dutch: *Nationaal Onderzoeksprogramma Brandstofcellen*.

Study Centre for Nuclear Energy and Bekaert [F1, F2, F3] (Schaeffer, 1998). Elenco is supported by Novem through the EUREKA programme [F6] in a project which aims to construct an AFC fuel cell bus (Kordesch and Cifrain, 2003; Van der Hoeven, 2001; Air Products, 2007; GVB, 2007). The project is executed by Air Products, Ansaldo, Elenco, Saft, De Lijn and GVB [F1, F2, F3] (Air Products, 2007; GVB, 2007).

The NOB will be directed by ECN (Schaeffer, 1998; Van der Hoeven, 2001). Before the programme starts, another round of workshops and feasibility studies is issued, focusing on operational factors such as system design and market exploration [F2, F3] (Schaeffer, 1998; Van der Hoeven, 2001). A disappointing outcome is that fuel cells seem to offer limited economic opportunities [-F4] (Schaeffer, 1998; Van der Hoeven, 2001). Natural gas prices are low and an important alternative technology, the gas turbine, is rapidly gaining ground in terms of costs and environmental performance (SenterNovem, 2007). As a result the programme is redefined from an industry building programme into an R&D programme [F4]. The idea is to develop fuel cell prototypes with the main objective being to develop a knowledge base that Dutch industry may draw on (Van der Hoeven, 2001). Proposed budgets are downsized, but the NOB nevertheless commences (Schaeffer, 1998; Van der Hoeven, 2001) [-F6].[127]

For the MCFC trajectory, the first step is to bring in foreign knowledge. An agreement is arranged with IGT, an American engineering company [F3] (Van der Hoeven, 2001).[128] The second step is to find project partners. On the supply-side there are actors from academia (TUd) and from the assembly industry (Stork, De Schelde) [F1, F3]. The commitment of demand-side actors, however, turns out to be limited. By 1987 things look promising when Hoogovens, a steal manufacturer, shows interest in connecting a CHP system to its rest stream, which is rich in hydrogen, as a way to win back energy [F1, F4]. After feasibility studies and negotiations [F2, F3] that last for more than a year, Hoogovens, however, declines because the expected payback time is considered too long [-F1, -F4] (Van der Hoeven, 2001).

The promise of large firms participating in the MCFC has meanwhile led to high expectations among MinEZ and ECN [F4]. The optimism is again supported by positive developments in the USA, where IGT has announced commercialisation plans for the MCFC [F4] (Van der Hoeven, 2001). As a result the original industry building ambitions are regained and budgets are upgraded [F4, F6] (Schaeffer, 1998; Van der Hoeven, 2001).[129] The NOB is now a spearhead of Dutch energy policy.

The critical issue, however, remains to find demand-side actors willing to adopt the MCFC. From 1988 to 1992 various energy companies are approached to consider participation but without success [-F1, -F4]. It is through the dedicated support by ECN, backed up by Novem and MinEZ, that the NOB is continued anyway [F4, F6]. Eventually they manage to draw in two energy distribution companies interested in acquiring knowledge on clean energy technologies [F1,

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[127] They are downsized to Fl 10 mln for three years. Including contributions from ECN and the EU's Joule programme, the total budget now amounts to Fl 20 million (Van der Hoeven, 2001).

[128] IGT has been developing the same technology that TNO abandoned in 1969.

[129] Budgets (for five years) are increased to Fl 60 million (Fl 45 million of which is government money) of which 40 million is allocated to the MCFC project [F6] (Schaeffer, 1998).

F4].[130] In 1992 the MCFC demonstration project commences. By this time ECN has established a joint venture with Stork and De Schelde, known as the Dutch Fuel Cell Corporation (BCN).[131]

The developments around BCN and its projects will be further analysed in the next section. This section will be concluded with a short account of the other technological option developed within the NOB: the PAFC [F4, F6]. The idea behind the PAFC project is to adopt a fuel cell stack for application into a CHP system. The preparations for this field test start in 1987 in the period when the NOB is expanded. The project is executed by KTI Zoetermeer, a Dutch subsidiary of the US-based KTI [F1] (Van der Hoeven, 2001).[132] The original plan was to install a 25 kW PAFC system at Hoogovens' site to stimulate knowledge exchange between the PAFC and the MCFC projects. When Hoogovens withdraws from participation an alternative site is found at TUd (Schaeffer, 1998; Van der Hoeven, 2001; SenterNovem, 2007; Technical University Delft, 2007). The stacks and other components are imported and assembled into a CHP system with success [F2, F3].[133] The system is the first of its kind in Europe [F4] (Schaeffer, 1998; Van der Hoeven, 2001; SenterNovem, 2007; Technical University Delft, 2007). Despite the success, support for the project from the NOB is stopped in 1990 [-F1, -F4, -F6]. This is because KTI has been taken over by Mannesmann, a German steel company, and MinEZ is not willing to finance a foreign party with Dutch tax money (Van der Hoeven, 2001). Nevertheless the positive results of the field trial encourage MinEZ and Novem to continue supporting PAFC development. Plans are made to install a larger unit of about 200-300 kW [F4] (Van der Hoeven, 2001).

Motors

The most developed system functions in this period are *Knowledge Diffusion*, *Knowledge Development*, *Guidance of the Search*, *Resource Mobilisation* and occasionally *Entrepreneurial Activities*. In terms of interactions, the period starts with scientists and policy makers contributing to *Knowledge Diffusion* and *Guidance of the Search*. Based on developments in the USA, they manage to influence policy makers through *Support from Advocacy Coalitions*, leading to a strong contribution to *Guidance of the Search* and *Resource Mobilisation* embodied in an industry development programme: the NOB. Within the framework of the NOB, technology developers and policy makers embark on a joint effort to commercialise MCFC technology, as reflected in contributions to *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search* and to a lesser extent *Entrepreneurial Activities*. Depending on the outcome of *Knowledge Development*, this affects (sometimes positively but often negatively) *Entrepreneurial Activities* and *Guidance of the Search*, thereby leading to shifts in *Resource Mobilisation*, in the form of adjustments in the budgets, and *Guidance of the Search*, in the form of adjustments to the goals of the NOB programme. Note that most instances of positive *Guidance of the Search* did not result from *Knowledge Development* within the HyFIS but from ongoing *Knowledge Diffusion*, by scientists, based on developments in the USA.

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[130] PNEM and PEN; their intentions are mainly related to public-private cooperation agreements within the framework of the Environmental Action Plan (MAP), aimed towards realising CO_2-emission reductions (Van der Hoeven, 2001).

[131] Dutch: *Brandstofcel Nederland* (BCN).

[132] The engineering company has gained experience with the construction of fuel cell systems in the USA (Van der Hoeven, 2001).

[133] The PAFC field trial has a budget of about Fl 5 million (Schaeffer, 1998).

Given the central position of *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search* and *Resource Mobilisation*, it seems fit to label this dynamic a *Science and Technology Push (STP) Motor*. Note that once developments are set in motion, they unfold from a single government programme which is continuously supported by a small group of researchers and technology developers.

For the AFC trajectory, dynamics look different, as here a demonstration project was supported by a variety of actors, including firms. However, since the activities around the AFC are rather marginal they are not considered part of any motor, nor do they have a significant impact on the *STP Motor*.

Structural drivers and barriers

The main driver of the *STP Motor* is a group of enactors: the scientists and technology developers that initiate the setting up of the NOB. Even when the *STP Motor* was running at full steam, this group continued to fuel its dynamics with positive expectations, often neglecting the negative results of feasibility studies and market explorations. The enactors managed to persuade policy makers on the national level (the most important selectors during this period) to support the HyFIS by aligning the idea of the fuel cell as an energy saving technology with the government's ambition of industry building. They managed to offset negative research outcomes with future promises based on experiences in the USA and were successful to such an extent that the policy makers actually became more like enactors themselves. Next to the enactors, the NOB programme is an important driver of a more institutional type; it gives an impulse to *Guidance of the Search* and *Resource Mobilisation* and, with the exception of the AFC trajectory, all subsequent contributions to system functions occur within the framework of this institution.

Meanwhile, feasibility studies recurrently point out that the market perspective for the MCFC was poor, with the effect that potential selectors from industry, especially launching customers, are unwilling to participate in the NOB, resulting in a poor contribution to *Entrepreneurial Activities*. The situation arises where the government aspires to develop a fuel cell industry, yet no demand-side firms are interested in doing so. A related structural barrier is the sudden emergence of the gas turbine as a low-cost competitor in the market for clean and efficient CHP systems. This unexpected development now starts to undermine the whole purpose of the NOB programme. For the PAFC trajectory, this barrier is less of a problem, since here a more modest strategy is pursued, not industry building but learning-by-doing. Unfortunately, the PAFC runs into problems related to the government's rules for public financing.

Impact on TIS structures

The most important impact of the *STP Motor* is the establishment of a knowledge base in 2G fuel cell technology. This becomes clear from the results established on MCFC and PAFC prototypes by ECN, TUd and KTI and most notably from the construction of the first PAFC-based CHP system in Europe. Another key outcome is that HyF technology, and the related industry building ambitions, have become a spearhead of Dutch energy policy. This should be considered as an important contribution to the build-up of institutions in the sense of both formal rules and cognitive/normative rules.

An overview of the drivers, barriers and impacts is presented in Table 7.3.

Table 7.3 HyFIS drivers and barriers and impacts underlying an STP Motor in the period 1980-1991.

	Actors	Institutions	Technologies
Drivers	• Scientists and technology developers occupy the enactor role (knowledge structure/supply-side). • The national government is the main selector (government structure). • The enactor group manages to persuade the national government to support HyF technologies. The strategy of the enactors is to make powerful promises by referring to a combination of environmental issues, economic issues and technological breakthroughs abroad.	• Oil crisis (external). • Environmental pressure (external). • Government ambitions of industry building (external). • The perspective of lagging behind internationally. • The NOB programme.	• The fuel cell's possible role in clean efficient CHP systems (external). • Technological breakthroughs in the USA (external).
Barriers	• The group of enactors and selectors is very small. • Limited involvement of launching customers (demand-side).	• Government rules for public financing hamper international cooperation (external). • The positive expectations of the fuel cell are not widely shared among industries (external).	• Competition from the gas turbine (external). • The fuel cell is technologically immature and costly.
Impacts	• A small network is formed consisting mostly of scientists, technology developers (intermediary structure).	• The construction of a shared vision among a small group of enactors. • The setting up of government support programmes as the spearhead of Dutch energy policy.	• The establishment of a knowledge base on 2G fuel cells.

7.4.2 A technology push (1992-1998)

The 1990s are characterised by general government cutbacks which lead to the downsizing of funds available for energy research (NRC, 1994a; NRC, 1995a). Another external factor is that, at the same time, the energy directorate of MinEZ is rapidly carrying out liberalisation policies, with, as a result, increasing market uncertainty. A third external factor is an important international shift in the focus of fuel cell development. For 1G as well as 2G fuel cells (AFC, PAFC and MCFC) it turns out that despite occasional technological successes and despite long-term market support programmes (in Japan and the USA), production costs remain high compared with other technologies on the CHP market (Schaeffer, 1998). At the same time, 3G fuel cells (SOFC and PEMFC) are rapidly undergoing a series of technological improvements which make it possible to reduce their costs.

Given that ECN and TUd developed a knowledge base in MCFC technology and the project is firmly in place, BCN commences with the MCFC demonstration in 1992 [F1, F2]. The project – labelled BCN-1 – turns out to be technologically feasible and a prototype stack of 2 kW is constructed in the same year [F2] (Schaeffer, 1998; ECN, 1993; Technical University Delft, 2007). But scaling up to commercial size at reasonable costs turns out to be a problem [-F4] and, by the end of 1993, the partners conclude that demonstration is out of reach (ECN, 1995; Technical University Delft, 2007).[134] The consequence is that BCN-1 stops halfway [-F1, -F4].[135]

The project is reorganised to consolidate the acquired knowledge [F4]. ECN and TUd continue research on a basic level (Van der Hoeven, 2001). One of the goals is to finish the construction of a 10 kW stack [F2]. This is successfully realised in 1994 but the economic prospects are still bleak [-F4] (Schaeffer, 1998). The main conclusion is that the MCFC can only be economically feasible if a more advanced version is developed. A proposal for the development of this 'next generation' MCFC, however, does not survive an external evaluation by a consultancy [F2, F4] (Luiten and Blok, 1999; Van der Hoeven, 2001; ECN, 1995). The judgment is that the MCFC cannot compete in the market with gas engines and turbines [-F4] (Van der Hoeven, 2001).[136]

In the second half of the 1990s, financial cutbacks and liberalisation tendencies urge MinEZ and ECN to cut budgets [-F6] (Schaeffer, 1998). The idea of industry building is abandoned but the MCFC project is continued. The strategy is to increase international cooperation and to attract European funding (Schaeffer, 1998). To decrease risk, the focus will be on system integration rather than the construction of stacks (Van der Hoeven, 2001; Technical University Delft, 2007). In 1996 a project is started, retrospectively named BCN-2, with the aim to construct a 40 kW

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[134] In engineering terms the situation is understood as a result of the design strategy taken. The fuel cell stack needs to be integrated into a CHP system but because of a preoccupation with the stack, BCN has neglected to take into account the required dimensions of other system components and now these pose large costs (Van der Hoeven, 2001).

[135] The evaluation reveals a variety of perspectives. The SEP, Novem and ECN consider the outcome an unfortunate result of a well conducted feasibility study. The distribution companies, however, consider it a waste of their resources (Van der Hoeven, 2001).

[136] The key problem is that the application domain is too small. For applications greater than 20 MW, gas turbines are more cost effective, while for applications smaller than 0.5 MW, gas engines are more cost effective (Van der Hoeven, 2001).

CHP system to be applied in hospitals [F1, F2] (Van der Hoeven, 2001). A search for partners leads to the participation of British Gas, Gaz de France and Sydkraft [F3] (Van der Hoeven, 2001). Unfortunately, the feasibility studies [F2] show, again, that the system will be uncompetitive, even if mass produced (Van der Hoeven, 2001; Technical University Delft, 2007) [-F4]. In 1998, BCN stops the project [-F1] (Van der Hoeven, 2001; ECN, 1998).

The PAFC trajectory runs into the ground as well. Because of the initially high expectations, a plan is made, by Novem and MinEZ, to utilise PAFC technology in conjunction with a small gas turbine [F3, F4] (Van der Hoeven, 2001; ECN, 1997b; NRC, 1994b). A search for partners eventually leads to energy utility MEGA and DSM [F1, F3]. However, when it turns out that the few companies able to construct PAFCs cannot meet the specific technological requirements of DSM, the PAFC project is stopped in 1995 [-F1] (Van der Hoeven, 2001; IEA, 2000).

With respect to the AFC trajectory, the Elenco project establishes a milestone by producing an AFC fuel cell bus [F2, F4]. Unfortunately, Elenco goes bankrupt before the buses can be put into service [-F1, -F4] (Van der Hoeven, 2001; Air Products, 2007). In 1995, the AFC trajectory ends.[137]

The decline of these technologies is in line with international trends (Van der Hoeven, 2001).[138] Therefore, ECN has gradually been shifting research efforts within the NOB to a next generation of technologies; the SOFC and the PEMFC [F2, F4] (DV, 1995). The latter technology is the more exotic, therefore most attention goes to the SOFC.[139] The SOFC fits well with the knowledge base developed for the MCFC because both fuel cells are made of ceramic components (in contrast to the PEMFC) (ECN, 2007; Nedstack, 2007; Technical University Delft, 2007). The research is situated at ECN and is carried out in cooperation with TNO, TUd and Technical University Twente (TUt) [F2, F3] (Luiten and Blok, 1999; Schaeffer, 1998; Van der Hoeven, 2001; Technical University Delft, 2007). The activities are later expanded to involve projects with Siemens [F1, F3] (Schaeffer, 1998).[140] The projects are co-financed through the EU Joule programme [F6] (Luiten and Blok, 1999; Van der Hoeven, 2001). In 1994-1995, the projects yield important outcomes as two launching customers, Sulzer (Swiss) and Siemens (Germany), are found willing to commercialise SOFCs for their CHP systems [F1, F3, F4] (Schaeffer, 1998).

The attention on the SOFC does not just originate from ECN but also from energy firms not involved in the NOB. In 1993 the same energy companies that were involved in BCN-1 develop plans for a field test with a CHP system [F1, F3] (Van der Hoeven, 2001; DV, 1995). The technology is bought from Westinghouse (from Pittsburgh, USA) [F3] (Van der Hoeven, 2001).[141] The project

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[137] Nevertheless, Elenco's knowledge is still carried on today within ZEVCO, a British company that has successfully installed the AFC drive train into a number of London cabs (Van der Hoeven, 2001).

[138] Despite a last attempt by the USA government to push the PAFC down the 'learning curve', in 1996, by subsidising the installation of 200 units, no significant cost reductions have been established since (Van der Hoeven, 2001).

[139] The SOFC was actually already taken up in the NOB in 1990, as a backup for the MCFC.

[140] The co-operation allows for a synergy between ECN's ceramics knowledge and Siemens' stack knowledge.

[141] The company that has been pioneering SOFC technology in the USA since the 1970s.

is financed partly by Novem and partly by the firms themselves [F6].[142] The plan is to install a 100 kW fuel cell and connect it, as a test, to the district heating system of Westervoort near Arnhem [F4] (Schaeffer, 1998; ECN, 1993). Technical and institutional difficulties delay the construction until 1997 [-F4] (Van der Hoeven, 2001; SenterNovem, 2007). The main issue is the adaptation of American technology to European standards [F2] (Van der Hoeven, 2001). When the system is installed, in 1998, the first trial is a failure; after merely 4000 hours the materials show an extraordinarily amount of degradation [-F4]. The stack is sent back to the USA for revisions [F3]. A second trial, in the same year, yields positive results, both technologically and economically [F4] (ANP, 2001a; Technical University Delft, 2007).[143] The unit is kept in operation for three years, after which plans are made for commercialisation in 2004 (BD, 2001; IEA, 2004b).

By the end of 1998 the NOB is subjected to an evaluation. Despite the successes in the SOFC trajectory, most projects have encountered severe problems, especially in the light of industry building ambitions [-F4] (ECN, 1998). The accumulation of negative results urges the ministry to stop the programme [-F4,-F6] (Van der Hoeven, 2001; ECN, 1998). The NOB is considered a success with respect to *Knowledge Development* but a failure where industry building and emission reduction are concerned (Van der Hoeven, 2001; ECN, 1998).

Motors

The dominant system functions during this episode are still *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search*, *Resource Mobilisation* and, now becoming more important, *Entrepreneurial Activities*. In terms of interaction, the *STP Motor* identified in the previous period remains active. After all, it is still the *Guidance of the Search* and *Resource Mobilisation*, fulfilled through the NOB, that provides continuity to the developments within the HyFIS. A notable development, however, is the abandonment, also within the NOB, of all projects related to 1G and 2G fuel cells, after a series of negative outcomes urges technology developers to recognise the poor market perspective of these technologies. This is a change with respect to the previous period when scientists and technology developers managed to push further development anyway, by neglecting research outcomes and/or by referring to new international successes. The dynamic is nevertheless very similar to what was observed for the previous period, only here it is the SOFC and the PEMFC technologies that bring the promise of success.

Structural drivers and barriers

In terms of drivers, the HyFIS is still heavily affected by external developments in the international HyF field, mostly concerning the decline of the AFC, PAFC and MCFC trajectories and the rise of 3G fuel cells. Internal to the HyFIS, the key driver is the NOB, which – with ECN and technology developers as the dominant enactors – continues to feed the *STP Motor*. A positive development set in motion by the same enactors is to rapidly pick up on this technological shift. In fact, the PEMFC and SOFC options were already being developed in parallel with the PAFC and the MCFC, as part of a portfolio strategy. In terms of *Guidance of the Search*, this is a difference compared with the original approach pursued within the NOB, where the MCFC

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[142] The trial is excluded from European subsidies as the technology used is considered competitive with the ECN-Siemens system.

[143] During this time Siemens buys Westinghouse and adopts the Westinghouse SOFC (tube) design, thereby abandoning its own (plate) design.

was basically the only option that received serious support. The promise carried by the 3G fuel cell technologies triggers a renewed interest among various selectors to participate in the setting up of demonstration projects. These selectors are driven by a search for knowledge as market implementation is certainly not yet within reach. The demonstration projects nevertheless result in important contributions to *Guidance of the Search*.

Despite some launching customers playing a crucial role in this period as technology selectors, the demand-side of the HyFIS remains weak. This is due to the fact that research results consequently point out that fuel cells cannot be expected to compete with alternative technologies on the CHP market. Another barrier, external to the TIS, was the liberalisation trend in the energy sector.

Impact on TIS structures

The main outcome of the *STP Motor* in this period is the development of a knowledge base, not so much based on feasibility studies and market explorations but increasingly on pilots and practical demonstrations. Unfortunately, most of these demonstrations show that commercialisation attempts are bound to fail. This relates to another important outcome, the termination of the NOB, and with it the core of the *STP Motor* itself. Despite the termination of the programme, there remains a strong supply-side and a knowledge structure with powerful enactors at its basis. On top of this, a number of firms seem ready to enter the HyFIS, willing to support the promising 3G fuel cell technologies. As will become clear in the next period, these firms become important enactors that will take the lead in the development of projects.

An overview of structural drivers, barriers and impacts is presented in Table 7.4.

7.4.3 Reorganisation (1999-2003)

In the new millennium, environmental issues become more urgent in political arenas and the fuel cell is increasingly considered as the basis of a sustainable energy system, now especially including the mobility domain.[144] A key event is the Californian ZEV policy that started in the early 1990s and is now beginning to affect fuel cell developments.[145] As a result of this policy, Daimler buys the Canadian company Ballard Power Systems, the world's number one PEMFC producer, and starts developing fuel cell vehicles. Daimler's choice for this technology draws in other large car manufacturers as well. The money involved in fuel cell research increases internationally (Goverde, 2006; Schaeffer, 1998; AD, 1996b; ECN, 1998; NRC, 1998a; NRC, 1998b; NWV, 2007).

High expectations for the PEMFC and the SOFC have built up among Dutch scientists and policy makers as well [F4] (AD, 1996a; DV, 1996; FD, 1996b; IEA, 2004b; NRC, 1995b; NRC, 1996). The NOB has been terminated but based on the positive outlook for 3G fuel cell technologies, ECN manages to convince MinEZ and Novem to reallocate financial resources to various generic subsidy programmes, most notably the EOS energy subsidy programme [F4, F6, F7]. This way, ECN can continue to shift its research agenda from the MCFC to SOFC and PEMFC technologies [F2, F4] (Van der Hoeven, 2001; IEA, 2004b; ECN, 2007; SenterNovem, 2007).

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[144] Until 1995 fuel cell research was focused on power production but now mobility becomes the main driver.

[145] California's ZEV (Zero Emission Vehicles) policy was issued in 1990. It consists of a directive to make 10% of the Californian car market completely emission free by 2003.

Table 7.4 HyFIS drivers, barriers and impacts underlying an STP Motor in the period 1992-1998.

	Actors	Institutions	Technologies
Drivers	• Technical universities, ECN and other technology developers still occupy the enactor role. • The most important selectors are governments and (a small number of) launching customers. • Enactors and selectors are connected in a network (intermediary structures). • Selectors are increasingly from abroad, e.g., the EU government and foreign energy companies. (government structure/demand-side). • The strategy taken by enactors and supportive selectors is to persuade launching customers to participate in subsidised demonstration projects. The idea is that successful demonstrations will draw in more enactors and selectors. • Another strategy taken is to diversify support by allocating resources to a broad variety of technologies including 3G technologies.	• Persistent high expectations of HyF technologies among enactors. • The NOB programme is broadened to include a variety of technologies (2G and 3G). • The EU Joule programme (external). • The development of a broad R&D portfolio within the NOB.	• Rise of 3G fuel cell technologies (external).
Barriers	• Launching customers are still barely involved (demand-side).	• General government cutbacks in energy research (external) • Demonstrations recurrently point out that cost reductions are difficult to realise.	• Decline of 1G and 2G fuel cell technologies (external). • Competition from the gas turbine (external). • The fuel cell is still technologically immature and costly. • Progress is made in the development of 2G technologies but results are disappointing.
Impacts	• The knowledge structure and the supply-side of the HyFIS is strengthened.	• The NOB programme is terminated. • The belief in the promise of the fuel cell is compromised by a series of negative results.	• The knowledge base on 2G technologies is strengthened.

The shared knowledge base (ceramics) with the MCFC makes the SOFC the easier candidate, and indeed ECN manages to commercialise its past NOB activities by starting a successful spin-off company (InDEC) that specialises in the supply of ceramic fuel cells [F1] (Van der Hoeven, 2001; ECN, 2007).[146] For the PEMFC, the necessary adaptations are more fundamental as its knowledge base differs from the PAFC and MCFC fuel cells with respect to the materials used. Fortunately, ECN had already started a small basic research track on PEMFC, in co-operation with TNO in the 1990s by buying a Ballard stack and running tests on it [F2, F3] (Van der Hoeven, 2001; IEA, 2004b). The first applications have also been studied, in co-operation with Volvo, Volkswagen and Siemens [F1, F2, F3] (AD, 1995). These activities were co-financed by Novem and the EU [F6] (Schaeffer, 1998).

ECN's research tracks, including specific long-term development objectives, are largely included in the EOS programme. National HyF support continues along broadly similar lines as in the NOB. An important change to the national support scheme, though, is that the structure of these subsidy programmes becomes more open to proposals from other firms. Thereby a framework is created that facilitates firms to join HyF research projects on their own initiative. Such project proposals are mostly subjected to 'tender procedures', meaning that projects – including non-HyF related projects – have to compete with each other in terms of criteria of innovativeness and sustainability [F4, F6, F7]. The implication is that support is no longer exclusively directed by MinEZ, via ECN, towards particular technologies but that projects are proposed and legitimated by firms themselves (IEA, 2000; MinVROM, 2007; Nedstack, 2007; Technical University Delft, 2007). Another important change is that, since HyF technologies are increasingly considered a solution to climate and mobility issues, MinVROM and MinVW are becoming more involved in financing HyF projects [F4, F6] (SenterNovem, 2008b).

ECN has been the central actor in Dutch fuel cell development so far and this remains so. But the promising outlook of PEMFC technology results in an increased involvement of firms [F1, F4]. For instance, DSM introduces a foil to improve Ballard's stack design [F2] (Van der Hoeven, 2001). This foil, Solupor, is useful as a matrix to hold the electrolyte [F4]. In co-operation with ECN and Novem, DSM manages to set up a plant for the production of the Solupor which will eventually be adopted by Ballard [F1] (Van der Hoeven, 2001; ECN, 2004). A second example is AKZO Nobel, a chemical company which, beside other activities, is involved in the development of membrane separation techniques.[147] The company has, in co-operation with ECN, developed a polymer that turns out to be a good electrolyte for the PEMFC [F1, F2, F4] (ECN, 2007; Nedstack, 2007; SenterNovem, 2007). Plans for commercialisation are aborted when AKZO Nobel is involved in a merger (SenterNovem, 2007), eventually resulting in its abandonment of all fuel cell activities [-F4]. Nevertheless, the people responsible for the work continue the development within a spin-off company named Nedstack [F1, F4] (ECN, 2007; Nedstack, 2007; SenterNovem, 2007; Technical University Delft, 2007). Nedstack will become an important builder of PEMFC stacks in the years to come.

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146 The downside of this effort is that the original plan was to involve incumbent industries to move into the field. Unfortunately, the ceramics sector is not interested due to the limited size of the market (ECN, 2007).

147 The membranes are, for instance, also used for the production of salt.

The focus within the HyFIS has so far been on the fuel cell as a centralised energy conversion device for the natural-gas based energy supply system. Therefore the firms involved have mainly been fuel cell system developers, on the supply-side, and energy companies, on the demand-side of the HyFIS [F1, F2]. A reorientation is set in motion by the promise of PEMFC technology and its (decentralised) applications in the mobility domain [F4].[148] As a result, more attention is given, often by firms previously not part of the HyFIS, to other parts of the HyF value chain, including production, distribution and storage of hydrogen (RTD, 2004; MinVROM, 2007; SenterNovem, 2007).

One example is the project undertaken by the directors of the Kemira fertiliser plant in the Rotterdam harbour area [F1] (RD, 2001; RD, 2004a). The plant is closed and a plan is made to invest Fl. 100 million to rebuild it into a hydrogen production facility [F4, F6]. The plan is to produce hydrogen from natural gas, sequestrate the CO_2 released in the process, and to deliver this to Gasunie, the state gas company. By blending the hydrogen in the natural gas network a large reduction of CO_2 could be established without using fuel cells at all (MinVROM, 2007). The development of production and distribution technologies is also taken up by Shell Hydrogen, a business unit of Royal Dutch Shell. Shell Hydrogen specialises in the development of refuelling infrastructure and in reformer technology for mobility applications [F1, F2, F6] (Solomon and Banerjee, 2006; HP, 1999; NRC, 1998b).[149] Shell and Kemira are but two examples of a number of fuel processing industries that start developing technologies that fit into a PEMFC infrastructure [F1, F2, F6] (TG, 2000; Nedstack, 2007; Plug Power, 2007; SenterNovem, 2007).[150]

The increasing importance of HyF technology in the mobility domain is underlined by the CUTE project [F1]. CUTE is directed by DaimlerChrysler and Ballard and supported by the EU [F4, F6] (GVB, 2007). The project, which actually started in 1998, involves the demonstration of PEMFC buses in nine European cities with the purpose of developing and testing various well-to-wheel chains, including the production and distribution of hydrogen [F2]. The key actor in Amsterdam, one of the test sites, is GVB, Amsterdam's public transport company, which regards hydrogen as a welcome opportunity to develop a clean transport system [F1, F4] (GVB, 2007).[151] Other partners are Hoek Loos (pressured storage), Shell (infrastructure) and Nuon (supplier of green electricity) [F1, F2, F3]. As with the previously projects mentioned, CUTE focuses on infrastructure-related issues (GVB, 2007; Technical University Delft, 2007).

The initiative for these projects comes primarily from firms depending on subsidies. To acquire these, they rely on their lobbying power, which is directed to local and national governments but also the EU (which is becoming increasingly fond of HyF technology) [F7]. For example, GVB acquires 30% of the necessary finances from the EU and, with the aid of Novem, it manages to persuade MinVROM, the municipality of Amsterdam and various firms to provide funding

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[148] The connection to potential mobility applications raises the prospect of a market since the economic value of automotive power is much higher than that of stationary power.

[149] Reformer systems convert natural gas, or another hydro-carbon, depending on the design, into hydrogen.

[150] Other examples are Gastec, the Dutch division of Plug Power and Hexion (later Hygear).

[151] The GVB, the local transport service, has been involved in Elenco's AFC project in the early 1990s, and since then it has undertaken various environmental innovation attempts, especially with natural gas and LPG (GVB, 2007).

as well (ANP, 2000a; ANP, 2000b; DV, 2000; SenterNovem/IPE, 2007). Another example is the Kemira project, which depends on an eco-tax exemption (RD, 2001; RD, 2004a). The project partners lobby the national government [F7], although without success [-F4] and the project is eventually abandoned [-F1] (RD, 2004a). Novem often acts as a mediator to arrange funding [F3, F6].

Motors

On the outset of this episode the *STP Motor* is still present, as *Knowledge Development*, *Guidance of the Search* and *Resource Mobilisation* activities, formerly part of the NOB programme and now part of EOS, continue to shape the HyFIS. In fact, the *STP Motor* results in some successful *Entrepreneurial Activities*, thereby positively feeding back on *Guidance of the Search*. However, the pattern of events is gradually changing as firms start taking the initiative to develop *Entrepreneurial Activities*. Driven by a renewed *Guidance of the Search*, related to 3G technologies, these technology developers lobby the government for financial support, thereby targeting *Support from Advocacy Coalitions* and *Resource Mobilisation*. If successful in acquiring funding, the firms embark on *Knowledge Development* in the form of studies and prototype development and *Entrepreneurial Activities* in the form of demonstration projects. The outcomes affect *Guidance of the Search*, thereby feeding back on *Entrepreneurial Activities* again, in the form of new firms entering the TIS. The *Knowledge Diffusion* function becomes very important as it serves to facilitate the spread of expectations through the HyFIS; this is crucial as there is no longer a single group of enactors that may do this.

Note that the *Entrepreneurial Activities* have a pivotal position in this virtuous cycle. Therefore this motor will be called an *Entrepreneurial Motor*. It differs from the *STP Motor* where the *Entrepreneurial Activities* are an important outcome but not so much an essential driver of further developments. After all, *Guidance of the Search* and *Resource Mobilisation* in the *STP Motor* are determined by expectations of scientists, technology developers and policy makers, not by actual results of *Knowledge Development* and *Entrepreneurial Activities*.

Structural drivers and barriers

The main external driver of this period is the rise of the PEMFC as a promising new technology. The promise is especially powerful since it is backed up by car manufacturers (abroad) making large investments. The enactors within the HyFIS see commercial opportunities for developing PEMFC technology. They make use of this development by fuelling expectations, thereby contributing to *Guidance of the Search*, among potential selector groups external to the HyFIS, most importantly the national government. A driver of a more institutional nature is formed by government policies that support the shift from 2G technologies to 3G technologies. This involves sustaining ECN's activities as well as financing a variety of other projects, i.e. *Guidance of the Search* and especially *Resource Mobilisation*. As a result of the renewed institutional support, a variety of companies, many of which were previously outsiders to HyF technology, enter the HyFIS, thereby boosting *Entrepreneurial Activities* and strengthening the pivot of the *Entrepreneurial Motor* that emerges. The reorientation towards 3G technologies is also driven by the strategy of ECN itself, which manages to move its activities away from its core technologies to the SOFC and the PEMFC, thereby contributing to *Knowledge Development* and *Guidance of the Search*. In this sense ECN is operating increasingly as a selector.

Table 7.5 HyFIS drivers, barriers and impacts underlying an Entrepreneurial Motor in the period 1999-2003.

	Actors	Institutions	Technologies
Drivers	• The enactor group consists of a variety of actors, particularly research institutes, technology developers (DSM, AKZO Nobel, Nedstack, InDEC) (knowledge structure/supply-side). • Important selectors are governments (government structure) and an increasing number of companies, especially car manufacturers and fuel cell developers (demand-side). • The enactors support a variety of fuel cells and fuel-cell-related infrastructure technologies. The enactors make renewed promises, based on the 3G technologies and the massive investments made by car companies abroad.	• Sustainable mobility becomes an important policy issue (external) • The vision of a sustainable hydrogen energy system becomes dominant (external). • The broad research portfolio of ECN facilitates a quick reorientation towards 3G technologies. • Subsidy programmes like EOS provide generic funding for new HyF projects.	• The 3G technologies, especially the PEMFC, become the dominant technologies (external). • Mobility becomes the dominant application domain (external). • The 3G technologies happen to match with the knowledge base already built up around 2G technologies.
Barriers	• Launching customers are still lacking (demand-side). • Increasing dependence on foreign development (demand-side). • Lack of networks (intermediary structure)	• The TIS is becoming more complex due to the increasing number of actors, technologies and institutions involved. There is a lack of institutions that provide co-ordination.	• Further decline of 1G and 2G fuel cell technologies (external). • The fuel cell (also 3G) is still technologically immature and costly (external). • The focus on decentralised applications of fuel cells means that the limitations of infrastructure become more pressing.
Impacts	• A variety of firms enters the TIS (technology developers and launching customers) thereby strengthening the enactor and selector group (knowledge structure/supply-side/demand-side).	• Energy policy is becoming more generic and less focused on specific projects.	• The knowledge base is adapted to 3G technologies. • The first technological infrastructure is developed.

The *Entrepreneurial Motor* builds for a large part upon the technological and institutional progress established by the *STP Motor*. Without ECN's expertise and without its networks (involving policy makers and other important selectors), the *Entrepreneurial Motor* could not have been shaped as quickly as it was.

A severe barrier of the *Entrepreneurial Motor* is still the absence of a strong demand-side. Launching customers are still lacking. Another barrier is the increased complexity of the HyFIS as, from a technological, institutional and actor perspective, the HyFIS structure is rapidly broadening. With more firms involved across the value chain, promoting various technologies and tapping into support schemes directed by different government structures, co-ordination becomes difficult.

Impact on TIS structures

This period is characterised by a phase-out of the *STP Motor* and the (gradual) build-up of the *Entrepreneurial Motor*. Government policies are no longer based on support for specific technologies but on generic funding via tender procedures. Partly as a result of this, the HyFIS develops into a larger system, more varied in terms of firms (supply-side enactors) as well as government structures. Another outcome is the technological and industrial reorientation towards PEMFC technology and hydrogen infrastructure. Despite the original focus on the MCFC, the HyFIS has adapted well to the shifting international trend. This is especially reflected in the expansion of the knowledge base, which includes various 3G technologies, and from the increased focus on HyF infrastructure development.

An overview of structural drivers, barriers and impacts is presented in Table 7.5.

7.4.4 A proto-market (2004-2007)

The EU massively increases its support for HyF technology (Solomon and Banerjee, 2006; RTD, 2004). Climate change is the main driver, though security of supply is becoming important as well as oil prices are rapidly increasing. The EU's main strategy is to establish a public-private partnership network, leading to a joint undertaking (Joint Technology Initiative) to direct large demonstration projects (SenterNovem, 2007; SenterNovem, 2008b).[152] Another driver is the increasing regulatory pressure with respect to air quality. EU emission norms have been implemented in Dutch law in 2001 (DG, 2001; EU, 1999) and these are exceeded in many areas (MNP, 2005) thereby providing local governments with incentives to support alternative fuels.

Demonstrations are increasingly abundant in this period and lead to a greater visibility of HyF technology (IEA, 2000; SenterNovem, 2007). A key example is GVB's work as part of the CUTE project. By 2004, two PEMFC buses are in service in Amsterdam [F1, F2] (GVB, 2007) and the first Dutch hydrogen refuelling station is built. The experiment is successful in technological terms, but also in the sense that, for the first time, private users are involved [F4] (GVB, 2007; Nedstack, 2007; SenterNovem, 2007; SenterNovem, 2008b; Technical University Delft, 2007). Other examples are Formula Zero, a company designing a PEMFC race cart concept, and Air Products, a gas supplier planning to demonstrate a hydrogen infrastructure, including a 200 kW SOFC stack, in a residential area [F1, F2, F4] (RD, 2005; Air Products, 2007). Nedstack, the spin-off

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[152] The EU plans to contribute 500 Mmillion € over six years, to be matched by the industries involved (EU, 2007).

from AKZO Nobel, contributes to the demonstration trend by building the first PEMFC power plant at AKZO Nobel in Delfzijl [F1, F2, F4].[153] On the international level, Shell is involved in the construction of the world's first hydrogen refuelling stations in Reykjavik, Washington and Tokyo [F1, F2, F4, F6] (ANP, 2003a; FD, 2003). The projects are executed in cooperation with GM, which supplies a fleet of FCVs [F3] (ANP, 2003a; FD, 2003).

In general, these projects are partly funded by the companies themselves and partly by government subsidies connected to the generic programmes mentioned before [F6]. ECN and SenterNovem are involved as suppliers of knowledge and as mediators [F2, F3] (RD, 2005; Air Products, 2007; FZ, 2007). Local governments support this demonstration trend as well. This started already with the municipality of Amsterdam financing GVB's activities within CUTE (GVB, 2007), but now also Arnhem and Rotterdam make plans for supporting PEMFC applications [F4, F6] (ANP, 2005; DG, 2004a; SenterNovem/IPE, 2007). Local governments are particularly driven by the urgency of the air pollution problem [F4, F5]. Another important incentive is the opportunity of local economic development [F4]. In Arnhem as well as in Amsterdam, the initiators are local entrepreneurs pressing for government support [F1, F7] (GVB, 2007; Nedstack, 2007).[154]

The HyFIS is expanding as all kinds of actors and firms are entering that were previously uninvolved. This expansion is also visible in research communities, as underlined by the launch of the SH_2 programme.[155] The SH_2 is a research programme with funding of 18 million €, set up as a public-private partnership [F3, F4, F6]. The focus is on catalytic processes (MinVROM, 2007; SenterNovem, 2007) and especially on hydrogen production and storage [F2, F4] (NWO, 2007; MinVROM, 2007; Nedstack, 2007; SenterNovem, 2007). Notable partners are Shell, Nuon and Gasunie.

With the expansion of the HyFIS in terms of actors, institutions and activities, there is an increasing need for co-ordination. The mediating roles of SenterNovem and ECN are becoming more important. Also, formal networks are established through which knowledge is exchanged. A key event is the formation of the Dutch Hydrogen Association (NWV) by SenterNovem and a variety of firms (NWV, 2007; Technical University Delft, 2007). The NWV plays an important role in knowledge exchange [F3] (Air Products, 2007; NWV, 2007; Technical University Delft, 2007). The SH_2 mentioned above also contributes to the exchange of knowledge in the field, especially within the research community [F3] (SenterNovem, 2007; Technical University Delft, 2007). It is also worth mentioning the activities of the OECD's International Energy Agency (IEA), now becoming important as a network for the absorption of international knowledge [F3] (SenterNovem, 2007; SenterNovem, 2008b).

Larger fuel cell applications are manufactured by multinationals, especially car manufacturers. In the Netherlands such system integrators are lacking. This poses a problem as the choices that such companies make with regard to their applications are crucial in determining the value of other HyF products. For example, ECN experiences troubles with commercialising their PEMFC technology [-F1, -F4] (ECN, 2007). To solve this, ECN decides to develop a fuel cell application

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[153] The 50 kW PEMFC power plant is constructed by a consortium consisting of Nedstack and AKZO Nobel.

[154] For example: GVB, Nedstack, Hexion, Gastec, Nuon.

[155] ACTS Sustainable Hydrogen set up by the Dutch Research Council.

itself [F1]. The result, in 2007, is the HydroGEM, a PEMFC vehicle developed partly with technology from DaimlerChrysler [F2, F3] (GVB, 2007; Plug Power, 2007). The HydroGEM is the first Dutch-made hydrogen powered vehicle [F4].[156] Air Products has constructed the required refuelling station, the second one in the Netherlands, on ECN's site in Petten [F1, F2, F3, F4, F6] (Air Products, 2007).

The dependency on foreign system integrators is also illustrated by Shell's exploration of reformer technology. In 2001 the oil company established a joint venture with UTC Fuel Cells, named Hydrogensource [F1, F3]. When, a few years later, car manufacturers massively turned to on-board hydrogen storage options, the prospects for on-board reforming turned bleak [-F4] (HS, 2004; Technical University Delft, 2007) and Hydrogensource was dissolved [-F1] (HS, 2004). Shell has now stopped pursuing on-board reforming, and has turned to the development of an infrastructure, in co-operation with car manufacturers abroad [F1, F3, F4]. Its strategy is to strengthen its role as a lobbyist [F7] by taking a role in important platforms mostly on the EU level (FZ, 2007; Plug Power, 2007; SenterNovem, 2007; SenterNovem, 2008b).

The national government, meanwhile, has continued to support HyF development mostly by means of generic funding [F4, F6].[157] So far the generic support schemes provided by MinVROM, MinEZ and MinVW have been sufficient, even to expand the level of activities built up in the past (SN, 2003; SN, 2005b).[158] Nevertheless firms and policy makers increasingly call for technology-specific policies that could serve to co-ordinate and bundle the large variety of activities and eventually stimulate market development [F4, F7] (Van der Hoeven, 2005; SN, 2003; SenterNovem/IPE, 2007). This awareness is associated with the emergence of the so-called transition approach among policy makers [F4]. In a way, transition policies imply a return to the industry building strategy developed in the 1980s (MinEZ, 2007; MinVROM, 2007; NWV, 2007; SenterNovem/IPE, 2007). The idea is to equip public-private partnerships, so-called transition platforms, with the task to develop strategies for the support of specific technological trajectories. For HyF technology this is done by the Platform New Gas (PNG) (Van der Hoeven, 2005; PNG, 2006) which, in 2006, advises the national government to provide direction to the HyFIS by focusing support on three regional clusters: Rotterdam, Arnhem and the northern provinces [F4, F7] (PNG, 2006).[159]

The government follows the recommendations of the PNG and thereby makes a step in the direction of a technology-specific policy approach based on the (long-term) vision that HyF

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[156] It is used as a service vehicle on ECN's site.

[157] The exception being ECN's research tracks as part of the EOS programme.

[158] Indeed public funding is high compared with other European countries. The annual budget for hydrogen and fuel cell projects has exceeded 30 Mmillion €; about 10 Mmillion € is of public origin (IEA, 2004b; SN, 2003; SN, 2005b).

[159] The first cluster, the Rotterdam harbour area, is considered suitable for large demonstrations since in this area a hydrogen production infrastructure is already in place. The second cluster, the Arnhem region, is considered a promising site for an emerging assembly industry since this is the basis for companies like Nedstack, Hexion, Plug Power and a supportive municipality. The third cluster is to be established in the northern provinces around ECN and the Wadden islands, with, as a main idea, to cultivate a fertile environment for R&D and small demonstrations (PNG, 2006; Nedstack, 2007; SenterNovem/IPE, 2007).

technologies are to play a role in a future energy system. At the time of writing, by 2008, it is not clear to what extent this approach will be successful. In any case it seems reasonable that the HyFIS will continue to develop progressively since the rise in fuel cell activities is part of an international trend of growing positive expectations. This development is accompanied by large cost reductions of PEMFC fuel cells [F2] (Nedstack, 2007; Technical University Delft, 2007)[160] and the first commercial fuel cell applications [F5] (most notably back-up systems for ICT services and forklifts) (FZ, 2007; Nedstack, 2007; Plug Power, 2007). Obviously these emerging markets contribute little to the substitution of fossil fuels, as yet. But as production gradually increases, further cost reductions may be expected, bringing the PEMFC ever closer to the commercial energy market [F4].

Motors

The dominant system functions in this period are still *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search*, *Resource Mobilisation* and *Support from Advocacy Coalitions*, with the latter becoming more important. A system function, so far barely present, that starts to develop is *Market Formation*. In terms of interaction, the progression of events follows the logic of the *Entrepreneurial Motor*, but its dynamic has become stronger. This is true with respect to the number of events but also with respect to the nature of events. For example, the *Entrepreneurial Activities* are increasingly fulfilled by large firms formerly not involved in the HyFIS. Also, *Knowledge Diffusion* is strengthened by actors forming networks and the nature of *Resource Mobilisation* changes as support comes increasingly from large firms and EU programmes. Most importantly, the HyFIS changes with respect to *Guidance of the Search* as a number of demonstration projects results in real PEMFC applications which are visible to the public. In short, the system functions that make up the *Entrepreneurial Motor* are strengthened through improvements of various parts of the HyFIS.

Structural drivers and barriers

The main external drivers in this period are the HyF specific policies of the EU on one hand, and the air quality regulations as maintained by local governments on the other. On top of this, there is important progress in bringing down the costs of PEMFC technology. These external developments affect the dynamics of the *Entrepreneurial Motor* as they provide the incentives for local governments and firms, still mostly on the supply-side, to enter the HyFIS, thereby effectively becoming enactors of HyF technology. The air quality regulation induces *Market Formation*, as it sets conditions that strongly favour zero-emission vehicles. The enactors manage to strengthen the HyFIS in important ways, constituting two more drivers. Firstly, the enactors start to connect more to each other and also to selectors, the most important ones being the national government, the EU and foreign car manufacturers outside the HyFIS, thereby contributing strongly to *Knowledge Diffusion* and also to *Support from Advocacy Coalitions*. The second driver is the setting up and successful realisation, in a joint effort of enactors and selectors, of PEMFC demonstrations visible to the public. Obviously, these provide important contributions to *Entrepreneurial Activities*, *Knowledge Development* and *Knowledge Diffusion*. Through their visibility, they especially contribute to *Guidance of the Search*, thereby making the entry of new enactors and selectors more likely.

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[160] For a learning curve perspective, see also Tsuchiya and Kobayashi (2004).

The international dimension is a driver of the HyFIS but it is also a threat in the sense that the HyFIS becomes increasingly dependent on foreign industries. This is true for the demand-side, which increasingly depends on car manufacturers and other system integrators, but also for the government structure which becomes increasingly reliant on policies originally designed by the EU government. This relates to another weakness, the absence of co-ordination. The larger part of HyF activities in this episode is initiated by firms, enactors and selectors, each with its own vision and goal. This variety has so far stimulated HyF developments but enactors and selectors increasingly urge the national government to co-ordinate and bundle the great variety of activities. National policies provide *Guidance of the Search* in the form of support for research trajectories pursued by ECN. But with the increasing number and variety of enactors and selectors entering the HyFIS, the government should also provide *Guidance of the Search* for the more market-oriented projects.

Impact on TIS structures

The *Entrepreneurial Motor* has resulted in the entry of a variety of actors, mostly enactors supplying fuel cells, infrastructure and system components. In this respect the dynamic continues along similar lines as in the previous period. There are, however, two structural impacts that have not been observed before. The first is related to an external driver: the rise of successful realisation of PEMFC applications in the form of visible demonstration projects. This gives a renewed boost to a belief in HyF technology among potential technology selectors. Indeed, with ongoing cost reductions of PEMFC technologies, the promise of a market gains credibility. A second impact is that networks are established from which political activities are developed. These networks are, so far, rather weak in terms of influence, but they hold the promise of a new driver because their aim is to build a system-wide infrastructure and to set up technology-specific policies. Such a strategy may give a more co-ordinated direction to the HyFIS, thereby bringing it closer to a take-off.

An overview of drivers, barriers and impacts is presented in Table 7.6.

7.5 Conclusion

The aim of this chapter was to analyse the development of the Dutch HyFIS, with as a general goal, to provide insights into the dynamics of TISs in the formative stage. In order to fulfil this aim, we attempted (i) to identify motors of innovation, (ii) to point out their underlying structural drivers and barriers, and (iii) to assess their impact in turn on TIS structures. This section provides a summary of the results from this study.

7.5.1 The STP Motor

Two motors of innovation were identified. The first motor, the *Science and Technology Push (STP) Motor* was dominated by *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search* and *Resource Mobilisation*. Its dynamic involved expectations and research outcomes, communicated mostly by scientists and technology developers contributing to *Guidance of the Search*. Eventually this led to the setting up of a government-supported R&D programme, which reinforced *Guidance of the Search* and, directly linked to it, *Resource Mobilisation*, in the form of R&D subsidies. This resulted in *Knowledge Development*, in the form of basic research, feasibility studies and pilots with, depending on the outcomes, a reinforcement of *Guidance of the Search*. This led to the expansion of the R&D programme, thereby closing a virtuous cycle. Eventually, the

Table 7.6 HyFIS drivers, barriers and impacts underlying an Entrepreneurial Motor in the period 2004-2008.

	Actors	Institutions	Technologies
Drivers	• Research institutes and an increasing number of technology developers (DSM, AKZO Nobel, Nedstack, InDEC) are still the most important enactors (knowledge structure/supply-side). Local governments are also taking on the enactor role as the urgency of the air quality issue increases (demand-side/government structure). • The main selectors are a large number (local, national, EU) governments and some utilities. • The strategy taken by enactors and selectors is to form networks. These involve knowledge networks (e.g. IEA, SH_2, NWV) but also more policy-industry related networks (e.g. the public-private partnerships). • The international network relations also grow stronger (intermediary structure). • A second strategy is to develop visible demonstrations and involve the public.	• EU-level policies and public-private partnerships (external). • Local air quality regulations (external). • Local economic development issues (external). • Generic subsidy programmes like EOS provide generic funding for HyF projects. • Public-private partnerships. • The level of co-ordination in the HyFIS increases.	• The 3G technologies, especially the PEMFC, become the dominant technologies (external). • Mobility becomes the dominant application domain (external). • The costs of 3G technologies are going down rapidly (mostly external). • The technologies become visible to the public due to abundant technology demonstrations in the public sphere.
Barriers	• Launching customer and system integrators are lacking (demand-side). • Increasing dependence on selectors abroad (demand-side). • Lack of networks (intermediary structure).	• There is still a lack of institutions that provide co-ordination. • There is a lack of systemic policies.	• The fuel cell (also 3G) is still technologically immature and costly (external). • The focus on decentralised applications of fuel cells means that the limitations of infrastructure become more pressing.
Impacts	• Numerous networks are established. Especially the more politically oriented organisations aim for the development of a system wide infrastructure and technology specific policies.	• There is a promise of a market for 3G technologies.	• The costs of 3G technologies are rapidly decreasing. A multitude of applications show that the technology is reliable.

positively developing *Guidance of the Search* function also led to a number of firms participating in government initiated *Entrepreneurial Activities*.

The following structural drivers, barriers and impacts were identified:

- The *STP Motor* was largely driven by a small group of enactors, including mostly scientists and technology developers. Their key strategy was to link up to policy makers (the selectors) and set up a government-supported R&D programme which focused on a single technology. The enactors managed to do this by continuously raising positive expectations of the future of HyF technology. They did this by referring to vision of a long-term future but also by referring to external developments, e.g. so-called technological breakthroughs in the USA.

- A structural weakness related to this motor was the lack of demand-side actors willing to support the TIS. This hampered *Entrepreneurial Activities* and *Market Formation* and caused the *STP Motor* to falter. As a result of this, the development of commercial applications did not succeed. There have been a few (technologically) successful demonstrations that supported the demand-side but these emerged only after a long period of pre-development and were often economically disappointing. This weakness was heavily reinforced by external developments, for example, the development of the gas turbine as an alternative for efficient CHP applications.

- The strategies underlying the *STP Motor* were based on the idea that a large concentrated infusion of resources into R&D would eventually result in the cost reductions necessary for commercialisation of the technology. Not surprisingly, a main impact of this motor was the build-up of a strong knowledge base. Another impact of the *STP Motor* was the development of institutions, both formal and informal, in support of HyF technologies.

7.5.2 The Entrepreneurial Motor

The second motor observed was the *Entrepreneurial Motor*. At the core of this motor's dynamics were *Entrepreneurial Activities*. Driven by *Guidance of the Search*, technology developers and demand-side firms lobbied the government for financial support, thereby contributing to *Support from Advocacy Coalitions* and *Resource Mobilisation*. If successful in acquiring funding, the firms embarked on *Knowledge Development*, in the form of studies and prototype development, and *Entrepreneurial Activities* in the form of technology demonstrations. The outcomes affected *Guidance of the Search*, and thereby fed back into *Entrepreneurial Activities,* in the form of new businesses entering the TIS.

- Characteristic of this *Entrepreneurial Motor* was that developments were not supported by top-down government policies. Instead, projects were initiated by a variety of firms, involving the supply-side as well as the demand-side of the TIS. Support schemes from the government were still present but in the form of *generic* subsidy programmes and not as targeted R&D schemes. As a result, firms operated as enactors; they promoted their own projects and requested resources from the government (the main selector) instead of the other way around. Firms with successful projects returned with new proposals to obtain additional support. This led to a surge in the variety and intensity of a range of system functions. External influences, in the form of technological and institutional developments abroad, played an important role as well, for example, the setting up of EU policies and the technological breakthrough of PEMFC technologies provided an important window of opportunity for actors within the TIS to exploit.

- A weakness of the *Entrepreneurial Motor* was the lack of coordinated action on behalf of enactors. As a result of this, the enactors were unable to draw in support from important selectors external to the TIS. This especially hampered the *Guidance of the Search* function.

- A main impact of the *Entrepreneurial Motor*, was an increasing variety of enactors and selectors. This corresponded with a steady development of the demand-side and intermediary structures of the TIS. The technological variety of the system also increased. Various HyF technologies were developed in parallel and were increasingly integrated into practical applications.

Despite the fact that motors primarily involve internal TIS dynamics, it should be stressed that dynamics were strongly coupled to external influences. For example, the *STP Motor* was driven by scientists and technology developers 'importing' technological knowledge from abroad or collaborating with foreign companies. Also, when the *Entrepreneurial Motor* emerged, national policy and firms were increasingly preoccupied with car industries and EU level policies.

7.5.3 Concluding remarks

At the outset of this chapter it was mentioned that the HyFIS has remained in the formative stage for a long period of time without having been subject to a breakdown. The analysis has pointed out that this development could be ascribed to the continuous development of two motors of innovation, an *STP Motor* and an *Entrepreneurial Motor*.

Both motors were driven by enactors which continued to feed positive expectations to a group of selectors, in spite of evidence suggesting that commercialisation was still far away. These enactors managed to frame the disappointing outcomes of R&D as positively as possible, either by referring to (new) future visions or by opportunistically referring to shifting external developments.

Another strategy of the enactors was to follow a portfolio strategy by backing up multiple fuel cell technologies in parallel. Even when one fuel cell technology was turned down by selectors, the enactors shifted their focus to developing another technology, a 'next generation' of fuel cells, and thereby managed to persuade selectors to continue supporting their activities.

All the time, enactors managed to expand their networks gradually, building up more developed institutions and more reliable technologies. Through building up structures, the *STP Motor* was followed up by a more powerful *Entrepreneurial Motor*. This way the Dutch HyFIS gradually developed into a more complete TIS over time. It started out with a rather one-sided structural configuration, able to contribute to no more than a narrow sub-set of system functions. Eventually, the enactors (and supportive selectors) managed to realise a TIS, consisting of a variety of structures, which was contributing to a broad range of system functions.

The next step of research will be to find out more precisely what structural combinations lead to what motor of innovation, and to find out whether motors of innovation tend to follow one another in general. If this proves to be true, then this implies a form of cumulative causation which relates not so much to the progressive development of system functions within a TIS, but to the progressive development of a TIS from one stage to another.

8 The automotive natural gas TIS (NL)

8.1 Introduction

The focus of this chapter is on the application of natural gas as an automotive fuel through the development and utilisation of Automotive Natural Gas (ANG) technology. So far, a range of technologies have been considered which required not just the development of markets and infrastructure but also the development of the technology itself. This case is an exception in the sense that ANG technology is relatively mature (Verbeek, 2002; NGV, 2008). Moreover, as far as the production and distribution of the fuel is concerned, ANG technology involves merely incremental changes to the incumbent energy system. This is because natural gas has been used for heat and power production in the Netherlands ever since the 1960s (Verbong and Geels, 2007). This contrasts with biofuels or hydrogen technologies for which radically new production facilities and/or distribution infrastructures have to be developed.

As an alternative to petrol and diesel, the combustion of natural gas results in a lower vehicle emission of nitrogen oxides (NO_x), particulate matter (PM) and CO_2 (TNO, 2003). Furthermore, the use of natural gas could improve security of supply by alleviating the dependency on oil (SenterNovem, 2008b). Another reason for considering natural gas as an alternative automotive fuel is that currently few other alternatives to oil-based fuels are available.

Despite the availability of a strong knowledge structure, a strong supply-side and even an attractive price setting of natural gas compared with petrol or diesel, the history of ANG technology has been hampered for more than 30 years. As one expert stated it only a few years ago: ‘You can say the product is right, the price is right, the advantages for health and environment are very obvious and still there is no success’ (Verbeek, 2002). Recently, however, the developments around ANG technology seem to be taking off as a modest market for Natural Gas Vehicles (NGVs) is emerging. It will be interesting to find out how the ANG Technology Innovation System (ANGTIS) has managed to develop and overcome its barriers to realise a take-off.

The following research questions are central to this study:

RQ 1: What were the motors of innovation that (positively and negatively) constituted the development of the ANGTIS in the Netherlands between 1970 and 2007?

RQ 2: What were the underlying structural drivers and barriers that explained the emergence of the various motors of innovation in the ANGTIS?

RQ 3: How did the various motors of innovation in turn influence ANGTIS structures?

The outline of the chapter is as follows: Section 8.2 gives the research design of this case study, pointing out differences from the approach taken in previous case studies. Section 8.3 provides the reader with an empirical background on the ANG technology and its history in the Netherlands, thereby setting the stage for an in-depth analysis in Section 8.4. Conclusions are given in Section 8.5.

8.2 Research design

As in the previous case studies, the empirical work for this case study relied on the construction of a narrative, based on the interpretation of a variety of data sources, including an event database containing data from digitalised media (covering especially the most recent time period 1995-2007), historical reports written by stakeholders (covering the period 1970-2000) and expert interviews which covered the whole history but especially the more recent developments. For this study, ten interviews were conducted with various experts in the field. The interviews were also used to check the validity of the narrative. The approach taken is comparable to our study of the Hydrogen and Fuel Cell Technologies Innovation System in the previous chapter.

8.3 Setting the stage

The period in which the development of the ANGTIS is studied starts in the 1970s and ends in 2007. To prevent the reader from losing track of the big picture, this section provides a bird's-eye view of the development of the ANGTIS. This is done by giving a description of ANG technology and its value chain, by providing a rough overview of key structures within the ANGTIS and by presenting a historical timeline of its development. This sketch serves as a background for the event history analysis in Section 8.4.

8.3.1 Technology overview[161]

Natural Gas (NG) as used for automotive purposes is identical to the natural gas (also methane or CH_4) used for the production of heat and power. As an automotive fuel, NG offers some advantages to petrol and diesel. It is known to outperform petrol and diesel in terms of emissions, especially with respect to NO_x and PM (Verbeek, 2002; TNO, 2003). NG is also considered to be a welcome alternative to oil in the face of energy supply issues (Verbeek, 2002). But what is most unique, compared to other alternative automotive fuels, is that ANG technology is readily available and the cost structure of ANG technology is rather attractive, it is even competitive with petrol and diesel (GT, 2006). Figure 8.1 gives an overview of price development over the years (EnergieNed, 2006).[162] Since the 1970s, the price of NG has been coupled to the oil price (ECN, 1997b; GT, 2006). Prices rose in the 1970s and in the early 1980s as a consequence of the oil crises (ECN, 1997b). From the late 1980s to the late 1990s prices remained stable, only to increase again when oil became scarcer again from 2000 on (primarily due to a rapidly increasing demand). As with petrol and diesel, the price of NG is largely made up of taxes, consisting of VAT and eco-tax.[163,164] The price and tax rates of NG decrease with the amount purchased.[165] The tax-burden has gradually increased during the years from around 15%, in the 1980s and the early 1990s, to 30% of the market price since the late 1990s (EnergieNed, 2006; GT, 2006). For petrol and diesel,

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[161] This section is based on information available on websites and on interviews with experts from SenterNovem (AM, 2008; NGV, 2008; SenterNovem, 2008b).

[162] See also ECN (1997a).

[163] Eco-tax or *Regulerende EnergieBelasting* (REB).

[164] The tax-burden has gradually increased over the years from around 15%, in the 1980s and the early 1990s, to 30% of the market price since the late 1990s (EnergieNed, 2006; GT, 2006).

[165] For example, in 2005 the Dutch NG price range was 13-52 million € cents/m^3 depending on the scale of use (EnergieNed, 2006). The energy content of 1 m^3 of NG is comparable to that of 1 litre of petrol.

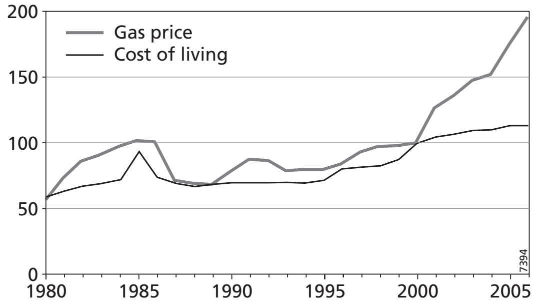

Figure 8.1 NG price development, indexed at 2000, estimated for small users, including taxes. Source: EnergieNed (2006).

already more costly to produce, the relative tax burden has been higher, making up as much as 40-60% in 1980 and 60-70% in 2000 for diesel and petrol respectively (ECN, 2000).

The main drawback of ANG technology lies in the investment costs. There are a number of technological innovations necessary to make ANG technology a success (Verbeek, 2002). The production and distribution infrastructure of NG is well developed, since NG has long been used in the Netherlands for providing heat and power. To be used in vehicles, however, NG needs to be highly compressed.[166] Technically this amounts to the installation of a system of compressors, storage buffers and the adjustment of pump systems at (existing) refuelling stations.[167] For vehicles the required adjustments are small. All that is needed is a new (high-pressure) storage tank and the tuning of a regular petrol motor to the characteristics of the new fuel. The first NGVs used were retrofitted petrol vehicles.

It was already mentioned that ANG technology may build upon a readily available distribution infrastructure. From a technical perspective this is an important asset. However, there are also frictions in the form of locked-in technologies. The most important competitors in this sense are petrol and diesel, which make up 97% of the mobility domain. In fact, the production of NG is for a large part in the hands of the same oil industries that produce petrol and diesel. Since the growth of NG may eat into this incumbent market, the incentives to develop this option on the part of incumbent fuel producers are weak. Another competing technology is Liquefied Petrol Gas (LPG), which is produced by the oil industry as a by-product of the oil refining process. Emissions, energy characteristics and cost structure are in many ways similar to NG, except that, for LPG, the refuelling infrastructure has existed since the 1960s, and a small percentage of Dutch

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[166] Typically from 0.2-8 bar to 200 bar. Another possibility is to produce Liquefied Natural Gas (LNG). This can be produced by cooling and/or pressurising NG. It has a higher energy density than compressed NG and is therefore economically attractive when the fuel has to be distributed over large distances.

[167] An alternative to the construction of public refuelling stations is the construction of private ones. The idea is that private drivers connect their car to the mains gas supply at home, which is widely used in the Netherlands for heating and cooking. The drawback of these slow-fill systems is that it takes a long time to fill the tank, meaning that refuelling has to take place overnight.

vehicles already use LPG.[168] Again, the incumbent fuel producers do not have a strong incentive to challenge the use of LPG by promoting a substitute.

Since ANG technology is itself not climate neutral, nor renewable, advocates of ANG technology tend to point out possible linkages to other emerging TISs, most notably around biogas and hydrogen. The idea is that NG could eventually be replaced by biogas, a biomass-based renewable, and this could be done without the necessity of additional infrastructure investments. A similar reasoning holds for (bio)hydrogen which could be blended with NG in increasing amounts. This way the deployment of ANG infrastructure may provide a stepping-stone for a hydrogen economy to come. Alternative emerging TISs may also be a disruptive factor in the development of NG. For example, if liquid biofuels should provide a successful alternative to petrol and diesel, the need for NG could rapidly vanish.

8.3.2 Key structures

This outline serves to introduce those actors, institutions and technological features that proved especially relevant in understanding the development of the ANGTIS. The outline is organised according to the five system components as presented in Chapter 2.

On the *supply-side*, the ANGTIS consists of suppliers of NG, refuelling infrastructure and NGVs. The NGVs, in the early days, are mostly provided by dedicated companies that provide retrofit services. Later on, when NGVs are produced by (foreign) car manufacturers, their role is overtaken by car importers. The supply of NG and refuelling infrastructure is arranged by gas companies. Later on, when the ANGTIS expands, the supply of infrastructure is increasingly taken up by engineering companies. In fact, as the ANGTIS develops, the supply of ANG technologies is taken up more by vertically-integrated companies (i.e., companies controlling a large part of the value chain).

The *demand-side* of the ANGTIS consists primarily of fleet managers, particularly municipalities, provinces, gas companies and public transport companies. It is these utilities and municipalities that provide the primary stimulus to the ANGTIS. The key incentives for these actors, throughout the period studied, are environmental issues (see below). Both supply-side and demand-side companies increasingly operate within platform organisations such as NGV-Holland and Aardgas Mobiel, consisting of fuel suppliers, infrastructure suppliers, contractors, energy companies and car companies. From these platforms emerge marketing strategies and political lobbies that strongly influence the course of the ANGTIS.

The *government structure* of the ANGTIS is strongly intertwined with the demand-side of the ANGTIS. Throughout the period studied, ANG technology is supported and pushed forward by procurement programmes of local governments and utilities. The role of the national government, in contrast, is ambiguous. In the early days, the national government provides support for demonstration projects but this is later stopped when conflicting viewpoints arise from different ministries. The key issue is the excise duty on NG. The excise rate is low but the question arises whether or not to keep it that way. Moreover the excise rate is not fixed but determined on a yearly basis. This makes it a source of uncertainty.

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[168] See Centraal Bureau voor Statistiek (2004).

With respect to the *knowledge structure* two sub-systems can be distinguished. On one hand, there are organisations working directly on applications of ANG technology. These are the engineering companies involved in the adoption of NGVs; their goal is basically to improve the performance and reliability of NGVs and NG refuelling infrastructure. On the other hand, there are the technology institutes and consultancies which undertake explorative research, involving feasibility studies, emission tests and engine development.

The *intermediary structures* constitute the links between the other system components. This role is performed by organisations such as SenterNovem (the government's innovation and energy agency) and, towards the end of the period studied, also by public-private partnerships such as the transition platforms PNG and PDM.[169] These transition platforms are part of the Dutch transition policy; they aim to facilitate innovation by strengthening the interaction between policy makers and firms. All these organisations are closely connected to the government structure of the ANGTIS. On the private side the ANGTIS consists of networks that connect supply-side and demand-side activities. In later stages incumbent firms and branch organisations are included in the ANGTIS as well.

8.3.3 Five episodes[170]

This section pictures five episodes in the history of the ANGTIS. Each episode points out the key events – and the involved actors, institutions and technological features – within the ANGTIS but also the major shifts in the external environment. The later episodes involve shorter periods of time; this is because less is happening in the early years. The five episodes and the key developments are summarised in Table 8.1.

The first episode runs from 1970 to 1989. Developments around ANG technology start when the oil crisis posits a necessity to develop alternative fuels. The first activities are undertaken by municipalities and utilities in the form of adoption projects. Programmatic policy support is provided through government subsidies. The adoption of ANG technology seems to take off at first but it is plagued by many start-up problems (Cogas, 2007). On top of technical difficulties, the ANGTIS also becomes subject to a liberalisation trend. As a result utilities increasingly turn to risk-aversive business models. By the end of the 1980s developments begin to decline.

Table 8.1 Five episodes of ANGTIS development.

Episode	NGTIS developments	Tech. maturity	External pressures
1970-1989	Emergence	Immature	Liberalisation, Oil crisis
1990-1999	Decline	Immature	Liberalisation, Lowering oil prices
2000-2003	Re-emergence	Mature	Air pollution
2004-2005	Up-scaling	Mature	Air pollution
2006-2007	Take-off/Market expansion	Mature	Air pollution, Climate change, High oil price

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[169] Platform New Gas (Dutch: *Platform Nieuw Gas*), Platform Sustainable Mobility (Dutch: *Platform Duurzame Mobiliteit*).

[170] The empirical basis for this crude timeline is derived from the detailed analysis in the next section. References to the literature can be found there.

In the second period, the 1990s, most projects come to a halt. One driver is the ongoing liberalisation trend that causes utilities to focus entirely on their core business, which is to produce heat and power. Another is the decreasing oil price, which reduces the incentive to develop alternative fuels. The period is further characterised by a number of activities developed by two organisations; the municipality of Haarlem (in the western province of North Holland) and the gas company Cogas (in the eastern province of Overijssel/Twente). These organisations continue their projects, and even expand to other places. Basically it is through these activities that the ANGTIS is kept 'alive' throughout the 1990s. The developments are supported by the EU's Thermie programme and by a small number of regional actors.

In the third period, running from 2000 to 2003, the ANGTIS expands again. The key event is an increasing pressure from European air quality regulations. In the Netherlands the local governments carry responsibility for implementing these regulations and therefore it is these actors that become active proponents of ANG technology. What is also important is that ANG technology is undergoing swift developments abroad, especially in Germany. Partly as a result of this, NGVs and NG refuelling stations become more reliable.

The fourth episode runs from 2004 to 2005. At this time the air quality regulation becomes an even more powerful incentive. Wherever norms are exceeded, governments are forced by law to call construction plans to a halt. Now ANG development is taken up by municipalities across the country. The prime movers mentioned above provide the required knowledge to support this development. Moreover the advocates of ANG technology become politically active as knowledge networks and branch organisations are formed which especially influence the position of the national government.

The fifth and final episode runs from 2006 to 2007. On top of issues of air quality come climate change and rising oil prices, thereby strengthening the idea that alternative fuels are necessary. The key outcome of the political actions, fed by the growing sense of urgency, is national government support for ANG technology. A set of policy measures is issued among which, most crucially, is a fiscal package beneficial to ANG technology. The result is a further expansion of the ANGTIS. An important indication is the fact that incumbent firms such as car importers, energy companies and infrastructure contractors become involved in backing ANG technology. The capital they provide is crucial for the development of a nationwide refuelling infrastructure.

8.4 The event history of the ANGTIS

In this section, the ANGTIS is subjected to a dynamic analysis, thereby providing a detailed account of the development of system functions and the motors that occurred. The section is structured as a chronological narrative consisting of the five episodes distinguished in Section 8.3. For each episode, the shifts in the external environment of the ANGTIS are sketched in the first section. Then a narrative is presented in terms of events; the contribution of events to the system functions is denoted by [F1, F2, … F7]. At the end of the episode, a reflection is given on the narrative, focusing on the motors that occurred in that episode, the structural drivers and barriers that enabled it and the impact it had on the ANGTIS.

8.4.1 Emergence (1970-1989)

The first use of NG in cars dates back to the 1970s when the oil crisis posits a necessity to develop alternative fuels. Natural gas is abundantly available in the Netherlands at this time, at low cost. During the 1980s oil prices drop again but at the same time environmental issues become more pressing.

The first experiments are initiated by enthusiastic managers of utility companies, particularly gas companies, following examples in the USA [F3, F4]. Gas companies in Utrecht en Groningen start with the adoption of retrofitted NGVs [F1, F2] (Verbeek, 2002). Driven by the promise of cheap, clean and abundantly available NG, the gas companies build up a fleet of about 80 vehicles [F4]. They also construct their own refuelling stations [F6]. A number of other gas companies follow this example [F1, F2, F3]. In the late 1980s bus companies start adopting NGVs as well [F1, F2, F3].[171] The companies are encouraged by actors involved in earlier experiments [F4] (Verbeek, 2002) and supported by the ABC programme, a subsidy programme launched by the national government [F4, F6]. Factory-made NG buses are at this time not available, so part of the programme consists of a retrofit plan for the adaptation of old diesel buses (Verbeek, 2002). This is done by TNO, a technology institute, and Den Oudsten, a manufacturer of buses [F1, F2, F3, F4].

Despite the enthusiasm of the utilities, the outcome of the experiments is generally not positive [-F4]. The problems are the reliability of the refuelling infrastructure and the NGVs and the limited range of the NGVs. Also the costs of investment and maintenance are higher than expected (NGV, 2007).

Motors

The succession of events can be characterised as pivoting around *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion* and *Guidance of the Search*. The dynamics emerge when *Guidance of the Search* arising from the enthusiasm of a handful of utilities leads to *Entrepreneurial Activities*, in the form of adoption experiments, and *Knowledge Development* and *Knowledge Diffusion*, in the form of feasibility studies and the exchange of learning experiences. The sequence turns into a virtuous cycle as the experiments are copied by other utilities, thereby feeding back on *Entrepreneurial Activities*, *Knowledge Development* and *Knowledge Diffusion*. In so far as the results are positive, they boost *Guidance of the Search* as well. (Unfortunately this is often not the case.) Due to the central role of the *Entrepreneurial Activities* in this motor it seems appropriate to denote this virtuous cycle as an *Entrepreneurial Motor*.

Structural drivers and barriers

The *Entrepreneurial Motor* characterises the development of the ANGTIS for almost twenty years, in spite of the techno-economic drawbacks that ANG technology turns out to have. This motor is constituted by government actors and utilities operating on the supply-side of the ANGTIS. Key structural drivers are (i) the external pressure of the oil crisis combined with (ii) the enthusiasm of a group of enactors in the form of dedicated companies aiming for an alternative to oil-based fuels. These enactors are dedicated to NG since it is their core business to supply it. Moreover, they are for a large part their own launching customers, thereby constituting the demand-side of the

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[171] GVB Groningen, RET Rotterdam, HTM The Hague and (later) GVB Amsterdam.

Table 8.2 ANGTIS drivers, barriers and impacts underlying an Entrepreneurial Motor in 1970-1989.

	Actors	Institutions	Technologies
Drivers	• The main enactors are gas companies attempting to draw in ANG technology selectors (supply-side and demand-side). • Important selectors backing up ANG technology are governments (government structure) and bus companies (demand-side). • The enactors manage to draw in selectors by giving practical demonstrations of the possibility of ANG technology and promising a solution to pressing policy issues.	• High oil prices (external). • Environmental issues (external). • Promise of cheap and clean technology, partly based on US experience (external). • Specific subsidy programmes.	• Low variable costs of NG. • Availability of NG and ANG technology. • Low emission characteristics.
Barriers	• The group of enactors and selectors supporting ANG technology is small and closely linked to public services, i.e., utilities.		• Reliability problems. • High investment and maintenance costs. • Limited range of NGVs.
Impacts	• A network is established consisting of a small number of enactors and selectors (intermediary structure).	• The setting up of governmental support programmes.	• The first applications of ANG technology provide insights in (unexpected) technological bottlenecks.

ANGTIS as well. By contributing primarily to *Entrepreneurial Activities* and, indirectly, to a range of other system functions these enactors constitute the main driver behind the *Entrepreneurial Motor*. Eventually these enactors manage to draw in some selectors, in the form of government authorities and, on the demand-side, public transport companies. The enactors are able to do so because external conditions – high oil prices and readily available NG – put the selectors' interests in line with their own.

The downside of the story is that the basis of this motor is limited to a small group of actors closely tied to the government. A key barrier that obstructs a broader development is the poor techno-economic performance of ANG technology so far. Both weaknesses have a negative effect on *Guidance of the Search* and *Market Formation*.

Impact on TIS structures

A main impact is the formation by enactors and selectors of a network in which knowledge on ANG technology is exchanged. Another important outcome is the installation of government support schemes that establishes a basis for future developments, especially in supporting technology demonstrations. A third impact is the gradual diffusion of ANG applications among various energy utilities. A fourth impact is that experiments point out that ANG technology suffers from numerous technological and economic bottlenecks.

An overview of drivers, barriers and impacts is presented in Table 8.2.

8.4.2 Decline (1990-1999)

In the 1990s the oil price is at a historical low but environmental issues remain pressing in national politics. The prime focus of energy policy, though, becomes the liberalisation of the energy sector. Only in the late 1990s do environmental issues, fuelled by the debate on climate change, gain a central position again.

The general tendency in this period is projects being abandoned and enthusiasm for ANG technology declining [-F1, -F4] (SN, 2008). The number of NGVs in service reached in the 1990s is 500-600 (Verbeek, 2002). This number now starts to decline as gas companies tend to shift focus to their core business. They embrace regular fossil fuels or, when it comes to innovation, LPG or a combination of diesel and particulate filters. Also, they abandon the exploitation of refuelling infrastructure [-F6].[172] The termination of projects leads to a negative image of ANG technology among potential adopters [-F1, -F4] (Verbeek, 2002).

The actors that committed themselves earlier to ANG technology nevertheless continue to contribute to the build-up of the ANGTIS. For example, Gas Company Noord-Holland and Energy Company Amsterdam adopt NGV vehicles to become part of their fleets [F1, F2]. Both companies construct refuelling stations as well [F6] (Verbeek, 2002). Another example is Cogas planning the first public NG refuelling station at a Shell outlet in Almelo, to be finished in 2001 [F1, F2, F6] (Cogas, 2007). Many other projects are started in the second half of the 1990s. An

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[172] Take, for instance, ENW, an energy company which, as a result of mergers, possesses a large part of the existing NG refuelling infrastructure. When ENW merges into energy company Nuon, it abandons the project and tries to sell the refuelling stations in Velsen, Haarlem, Alkmaar and Amsterdam (Verbeek, 2002).

important development is the participation of municipalities aiming for clean road transport in the inner cities (Verbeek, 2002; LK, 2001). The projects are supported by a national subsidy programme and also by the European Thermie programme [F6].

The techno-economic results of these projects are still not positive [-F4]. The investments remain high and technical issues keep posing problems (FEM, 2004). Nevertheless, two developments can be singled out as important precursors to a more fruitful development of the ANGTIS in the future. The first is that various projects involve political lobbying. This is reflected in the establishment of NGV-Holland, a platform which serves to promote ANG technology [F4, F7] (Verbeek, 2002). By means of promotion and lobbying, ANG advocates manage to persuade governments and intermediaries to establish licensing procedures and safety standards, for instance, for NG refuelling stations and indoor parking of NGVs [F4] (Verbeek, 2002).[173]

The second development is the emergence of small niche markets. This starts as early as 1990 when Canal Bus, a company operating boats on the Amsterdam canals, adopts NG for its boats [F1, F2]. Due to the absence of noise and smell, NG boats are allowed in waters where diesel boats are forbidden [F5] (Verbeek, 2002). Similar benefits result in the formation of niche applications for (indoor) ice-swabbing vehicles, for forklifts and shovels that operate in glass factories [F1, F2] (Verbeek, 2002; TO, 2002). The developments are stimulated by gas companies around Amsterdam and Rotterdam [F4] which provide the NG refuelling stations [F6]. As in the abovementioned projects these firms run into difficulties when gas companies become subject to reorganisations, but most niches are eventually retained (Verbeek, 2002).

Motors

Three forms of cumulative causation can be identified for this period. First, there is the dominant dynamic in the 1990s of a declining ANGTIS: a motor of decline. Many utilities that propagated ANG technology in the 1980s stop developing new projects or abandon the use of ANG technology altogether. This abandonment of *Entrepreneurial Activities* results in negative *Guidance of the Search*, and since this affects potential ANG adopters it becomes increasingly difficult to gather support necessary for new *Entrepreneurial Activities*. The decline of *Entrepreneurial Activities* subsequently leads to a decline in *Knowledge Development* and *Knowledge Diffusion*. Note that this vicious cycle is made up of a very short loop, primarily involving *Entrepreneurial Activities* and *Guidance of the Search*. Whereas, for the build-up, *Knowledge Development*, *Knowledge Diffusion*, *Support from Advocacy Coalitions* and *Resource Mobilisation* are important as well.

It can, however, be argued that the *Entrepreneurial Motor* is still active, although it has been stripped to its core in terms of structures. A handful of enactors manages to keep up a basic level of *Entrepreneurial Activities*, *Guidance of the Search*, *Knowledge Development* and *Knowledge Diffusion* basically according to the same interaction pattern as in the previous period, although there is an important augmentation. This is the stronger contribution to *Support from Advocacy* and *Guidance of the Search* as enactors become more active in promoting ANG technology among businesses and in lobbying governments for *Resource Mobilisation* and, again, *Guidance*

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[173] Cogas' NG pump, for example, becomes a reference installation to the field, but only after Cogas convinces the relevant normalisation institute that it is safe (Cogas, 2007).

Table 8.3 ANGTIS drivers, barriers and impacts underlying an Entrepreneurial Motor in 1990-1999.

	Actors	Institutions	Technologies
Drivers	• Only a few dedicated enactors remain active, mostly gas companies and municipalities (supply-side/demand-side). • The selectors are governments, especially municipalities (government structure/demand-side). • The enactors manage to join forces with the selectors by promising a solution to pressing policy issues. Their strategy is to develop a policy environment, e.g., licensing procedures, safety standards. • Selectors remain active in niche markets (demand-side).	• Environmental issues (external). • EU Thermie programme (external). • Market niches provide stability.	• Low variable costs of NG. • Availability of NG and ANG technology. • Low emission characteristics.
Barriers	• Many of the enactors (gas companies) turn into selectors after a series of mergers. • Massive exit of enactors and selectors.	• Lowering oil prices (external). • Liberalisation in the energy sector (external). • Risk-averse attitude of selectors. • The belief in the feasibility of ANG technology has diminished and even turns negative.	• Reliability problems. • High investment and maintenance costs. • Limited range of NGVs.
Impacts	• Most enactors and selectors have abandoned the ANGTIS. • Networks are established by a handful of remaining actors, including municipalities and gas companies (intermediary structure).	• A policy environment is established (licences, standards).	• ANG technology diffusion is reversed.

of the Search. The dynamic is strengthened by a number of demand-side companies that regard ANG technology as a business opportunity. The *Entrepreneurial Activities* developed by these companies are primarily the result of *Market Formation* in the form of emerging niche markets for applications where low emissions come with a high advantage. Note that these ANG applications are less dependent on external resources.

Structural drivers and barriers

The dominant development in this episode is characterised by a motor of decline. Its dynamic is (externally) driven by the liberalisation trend. It could be argued that when gas companies are merged into larger energy utilities, these enactors are effectively turned into selectors. These newborn energy companies typically apply an evaluative logic that puts innovation second to reorganisation. Even when innovation is considered, the meagre outcomes of the projects undertaken so far do not encourage a choice for ANG technology at all. This negatively affects *Guidance of the Search* and *Entrepreneurial Activities*. The few market niches are not prone to boost further developments either, but they do provide some stability in the turbulent liberalisation context as most niche-based projects are retained throughout the 1990s.

The *Entrepreneurial Motor* observed in the previous period remains active due to the commitment of a small enactor group consisting mainly of gas companies. The enactors' main strategy is to continue their projects and to join forces with municipalities, thereby targeting *Guidance of the Search* and *Support from Advocacy Coalitions*. They also draw in selectors in the form of national and European governments; this is basically what keeps the ANGTIS alive during this episode. The selectors are mainly driven by environmental issues.

Impact on TIS structures

In terms of impact it should be stressed that the ANGTIS declines. Only a small number of enactors remains active during this period. Nevertheless, they contribute to the build-up of the ANGTIS, particularly by setting up a platform that strengthens the intermediary structure of the ANGTIS. Moreover, the enactors manage to establish licensing and safety standards for NGVs and refuelling infrastructure.

An overview of drivers, barriers and impacts is presented in Table 8.3.

8.4.3 Re-emergence (2000-2003)

The EU sharpens air quality norms, which are implemented in Dutch law by 2001 (DG, 2001; EU, 1999). This provides governments, especially on the local level, with strong incentives to support alternative fuels (SenterNovem, 2008b). ANG technology is internationally taking off and, as a result, by the end of this period, the supply of ANG technology is becoming an international matter, as car manufacturers start supplying factory-made NGVs (NGV, 2008).

Municipalities are specifically interested in NG, since using it not only reduces PM but also NO_x emissions, a problem not addressed by diesel-particle filters (SenterNovem, 2008b). Unfortunately, there is as yet barely a refuelling infrastructure and most ANG projects have come to a halt. The poor condition of the ANGTIS becomes clear when compared with developments in other European countries where ANG technology is emerging. In Germany, for instance, top-down policy directives have been imposed to develop a refuelling infrastructure (Verbeek, 2002; WNGB, 2007) and a low excise rate has been fixed to last until 2020.

The developments that do go ahead are still driven by NGV-Holland [F4]. Within this network, ANG technology is supported by basically two groups of actors: a coalition around the municipality of Haarlem (and Gas Company Haarlemmermeer (RWE)) and around Gas Company Cogas (DT, 2003). These groups build upon experience gained earlier. Their activities revolve around a series of demonstration projects [F1], the goal of which is to demonstrate the merits of ANG technology in practice (Verbeek, 2002).

The first demonstration project, called GAIA[174] is initiated by the municipalities of Haarlem, Amstelveen and the Province of North Holland [F1, F2, F3]. The project aims to get 200 NGV trucks on the road [F4] (Verbeek, 2002; DT, 2003). The parties involved are refuse-collection companies, recycling businesses and the operator of Schiphol airport; the latter provides a site for a second refuelling station to be constructed by RWE [F6] (Verbeek, 2002; DT, 2003). A second Haarlem project, called PRO-Aardgas, is specifically aimed towards private drivers [F1, F2, F4]. To accomplish this, the municipality establishes a network with car dealers in the area [F1, F3].[175] A scheme is installed in which a 25% discount is offered on the extra costs (1500-4000 million €) of purchasing a new NGV [F4, F6]. Up to 350 consumers may benefit from the subsidy scheme. Support is also provided for the installation of refuelling stations at public sites [F4, F6] (SN, 2008).

The Cogas project is situated in the rural region of Twente (province of Overijssel). Cogas has converted its own car fleet and installed a public refuelling station in Almelo [F1, F2, F6] (DTC, 2004a). The gas company releases a plan to diffuse NGVs and NG refuelling stations throughout Twente [F4, F6].[176],[177] It provides users with a 50% discount on NG [F4, F6].[178] The project is backed by car dealers and by the Almelo municipality [F1, F3, F4] (SN, 2008).

The gas companies and municipalities, organised within NGV-Holland, lobby for support from the national government [F7], with the result that most projects are financed through the national government's DEMO programme, a subsidy scheme executed by SenterNovem [F6] (NGV, 2008; SN, 2008).[179] The projects are a success in terms of ANGTIS build-up as they lead a variety of actors to re-enter the ANGTIS [F1] (2003; Van der Hoeven, 2005; Verbeek, 2002; MoH, 2008). This is also the result of gas companies and municipalities consciously informing, promoting and lobbying for ANG technology [F3, F4, F7]. A case in point is NGV-Holland coming up with a strategy of lobbying the government and breeding commitment with new parties (Verbeek, 2002; NGV, 2008). A key event that supports this build-up is the formation of DutCH4, a developer of

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174 *Gas Als Ideale Aandrijving* (GAIA) (SN, 2008).

175 Fiat, Opel, Volvo.

176 The aim of '*Mobiliteitsplan Twente Schoon*' is the conversion of 100 vans and 210 personal cars within two years (SN, 2008).

177 To support this, Cogas plans the set up of a second NG refuelling station. This refuelling station will be installed in Hengelo by the end of 2004 with the support from DutCH4 (2004b).

178 Car dealers (Fiat, Ford, Mercedes-Benz, Opel, Peugeot and Volvo) supply bi-fuel cars (NGV, 2008).

179 The project budgets are in the order of 4 Mmillion € (NGV, 2008; SN, 2008).

turnkey ANG systems [F1].[180] DutCH4 provides knowledge to realise ANG projects successfully [F1, F2, F3]. On top of this, DutCH4 invests in infrastructure and actively mobilises municipalities to adopt ANG technology [F6, F7] (DT, 2003).[181]

The wide use of ANG technology results in important improvements to the techno-economic feasibility of ANG applications [F2, F4]. This learning process is for a large part the result of international developments as well.[182] The near-commercial status of ANG technology provides a boost to the willingness of actors to enter the ANGTIS (Verbeek, 2002; FEM, 2004). The national government, however, remains inert to the upsurge. Indeed support from the government's DEMO programme, the dominant source of subsidies, is stopped because ANG technology has developed beyond the stage of demonstration [-F4, -F6] (Verbeek, 2002; SN, 2008; SenterNovem, 2008b). This occurs at the very time when, according to firms, support in the form of demonstrations should be replaced by market stimulation measures. More specifically, the firms demand a fiscal policy that fixes (low) excise-rates for at least a decade, thereby constituting a competitive market for ANG technology [F7](Verbeek, 2002; Westdijk, 2003; TO, 2002).[183]

Despite the absence of supportive national policies, some direction is provided to the field when the results of a vehicle emission test, issued by MinVROM,[184] show that NG is, on all dimensions, favourable to diesel, petrol and LPG [F2, F4] (TNO, 2003; Dutch4, 2007). The decision to take NGVs into the test at all is taken after a lobby by NGV-Holland [F7] (NGV, 2007).

Motors

It is still the gas companies and local governments which provide momentum to the ANGTIS by contributing to *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion* and *Guidance of the Search*. A key difference however, compared with the previous period, is that *Support from Advocacy Coalitions* and *Resource Mobilisation* are becoming very strong. At first this is mainly reflected in lobby activities aimed at generating subsidies for single projects. But later on, these activities are increasingly directed at *Market Formation* and *Guidance of the Search*, in the sense that they embody a plea for top-down government policies. When successful, these efforts result in a boost to *Guidance of the Search*, leading to new *Entrepreneurial Activities*.

The conscious orientation of the enactors on the ANGTIS as a whole is a reason to denote this dynamic as a *System Building Motor*. A key feature of this new motor is that entrepreneurs are organising themselves, forming networks, and drawing new enactors and selectors into the TIS, especially local governments, intermediaries and interest groups. With this strong *Support from Advocacy Coalitions* they attempt to enforce the creation of a mass market for the emerging

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[180] The founders of DutCH4 are individuals who have gained experience with some of the projects previously mentioned (DutCH4, 2002). They cover a wide range of competences including supply, infrastructure, vehicles and markets (FEM, 2004).

[181] It does this by buying up existing refuelling stations and by constructing new ones in the Haarlem-Schiphol area and in Twente (FEM, 2004).

[182] This means that retrofitters become obsolete (FEM, 2004).

[183] Once such market stimulation policies are in place, industries may consider developing a nationwide refuelling infrastructure (Westdijk, 2003).

[184] Ministry of Spatial Planning and the Environment (*Volkshuisvesting, Ruimtelijke Ordening en Milieu*: VROM).

technology. Note that the rise of this motor is largely the result of the *Entrepreneurial Motor* which has paved the way in terms of actors (more selectors), institutions (more aligned), technologies (more mature) and networks (more integrated).

Structural drivers and barriers

As environmental issues become more urgent, a number of selectors – in this instance, numerous municipalities – become more receptive to positive results as communicated by the enactors. This strengthens especially *Guidance of the Search*. A related driver is the technological progress established. Encouraged by this, enactors provide a boost to the ANGTIS by organising themselves into networks that actively pursue marketing, promotion and lobbying strategies, thereby targeting a whole range of system functions, most notably *Support from Advocacy Coalitions*.

Note that the marketing activities are as yet stimulated with a rather limited budget (i.e., not by fiscal regulations) insufficient for a large scale infrastructure deployment. This is an important drawback as compared with Germany. A related barrier is the poorly developed demand-side of the ANGTIS. Commercial organisations and private drivers are as yet not interested in adopting ANG technology. This is due to the absence of a clear fiscal policy framework. As long as NG pricing remains uncertain, commercial parties will remain hesitant to invest in infrastructure required for large- scale NG diffusion, and hence *Market Formation* will remain weak.

Impact on TIS structures

The most important impact of the *System Building Motor* is its tendency to draw selectors – governments and firms – into the ANGTIS, in this case these involve (formerly uninvolved) municipalities, car dealers and, most recently MinVROM. The involvement of these actors results in a bandwagon effect. A good example is how TNO, ordered by MinVROM, brings ANG technology to the fore in a vehicle emissions test. With the positive results of this test, the ANGTIS is likely to draw in even more selectors in the future. A related structural change established during this period is that ANG technology has become more mature, meaning that it is ready for widespread application. It should be noted that this effect is largely the outcome of international learning activities, although with a strong contribution from Dutch companies, and therefore not entirely the result of the ANGTIS. The inclusion of selectors and the diffusion of ANG technology relates to a third impact; a renewed belief in the techno-economic feasibility of ANG technology among enactors and selectors not yet part of the ANGTIS.

An overview of drivers, barriers and impacts is presented in Table 8.4.

8.4.4 Up-scaling (2004-2005)

The new air quality regulation starts to have a large impact since norms are being exceeded in many areas and this leads, via court decisions, to a full stop on construction plans in these areas (BD, 2005; MNP, 2005; NRC, 2005; SNM, 2006). As a result NG becomes increasingly attractive as a short-term alternative automotive fuel. On top of this, the climate issue and high oil prices become increasingly pressing policy issues. This is underlined by the EU through its announcement of a goal of 20% utilisation of alternative automotive fuels, including NG, by 2020 (Westdijk, 2003; FEM, 2004; SenterNovem, 2008b).

Table 8.4 ANGTIS drivers, barriers and impacts underlying a System Building Motor in 2000-2003.

	Actors	Institutions	Technologies
Drivers	• The enactor group has grown and consists of gas companies and a number of municipalities looking for a solution for local environmental issues (supply-side/demand-side/government structure). • A number of municipalities have turned from selectors into enactors. • The enactors form a network and develop strategies to draw in enactors and selectors from outside the TIS (intermediary structure). • The strategy of the network is to connect with municipalities, car dealers, governments and other selectors. They persuade these selectors on the basis of successful demonstrations of ANG technology in practice. They also promise a technological solution to important policy issues. Moreover they make attempts to create markets for NGVs.	• Air quality regulation (external). • Adapted policy environment (licences, standards). • Support for demonstration programmes (EU, national).	• Low variable costs of NG. • Availability of NG and ANG technology. • Low emission characteristics. • The ANG technology has matured, meaning that reliability is no longer a problem.
Barriers	• Lack of launching customers (demand-side).	• Limited budgets for infrastructure development. • Lack of long-term (fiscal) policy support.	• High investment costs. • Lack of refuelling infrastructure.
Impacts	• Selectors are increasingly drawn in, governments (local and national) as well as firms (supply-side/demand-side/government structure).	• A strong belief in ANG technology among enactors and selectors.	• Adoption of NGVs and NG refuelling infrastructure increases. • The ANG technology is ready for widespread application.

Table 8.5 NG refuelling sites available in the Netherlands by 2004.

Location	Owner	Users
Haarlem	Nuon	Nuon, Municipality of Haarlem
Velsen	Nuon	Local refuse collection services
Schiphol	Schiphol Airport	Schiphol Airport/public
Amstelveen	Eneco Energy Amstelland	Eneco Energy Amstelland, Municipality of Amstelveen
Almelo	Gas Company Cogas	Gas Company Cogas/public
Amsterdam	Canal Bus	Canal boat operators

Source: NGV (2008; 2007), SenterNovem (2008).

By 2004, the ANGTIS accounts for about 120 NGVs – approximately 40 in the Haarlem-Schiphol region and 80 in the Twente region – which are supported by six refuelling stations (SN, 2008); see Table 8.5. These figures pale compared to the 70,000 NGVs utilised in Germany at the same time (DTC, 2004a) but due to the building prohibition, high oil prices and the lobbying of the ANG community, interest now grows across the nation [F4, F5, F7] and an increasing number of municipalities adopt NGVs for their fleets and stimulate businesses and utility companies to do so as well [F1, F2, F3, F4, F7].[185] These developments are supported by DutCH4 as it is taking over the business of Cogas [F1].[186] The gas company's original plan to provide NG infrastructure coverage in the Twente region is now turned into a plan to set up nationwide coverage (DTC, 2004a; DTC, 2005a) [F1, F4, F6]. Funding for these projects is provided through generic programmes [F6] (NGV, 2007; SenterNovem, 2008b).[187]

As part of these projects, feasibility studies are conducted with the purpose of revealing the economic advantages of ANG technology to potential adopters across the country [F2, F3] (DG, 2004b; DG, 2004c; FD, 2005b; LC, 2005a).[188] The results are generally positive [F4] (SN, 2008; MoH, 2008). The diffusion of knowledge across regions is additionally promoted by DutCH4 and SenterNovem [F3, F4] (NEN, 2004).

More generally, it can be stated that the ANGTIS is expanding to transcend the regions in which it emerged. The ANGTIS heads towards a national take-off as multiple provincial governments and especially incumbent industries are becoming involved. The provinces typically set up conditions for concessions, compelling public transport companies to use NGVs [F4, F5] (AC, 2006; Connexxion, 2007; MoH, 2008).[189] The Haarlem region is the first to utilise NG buses (since

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[185] For instance, projects are started in Nijmegen, Tilburg and Breda (in the province of North Brabant) (DG, 2004b; DG, 2004c; FD, 2005b) and in Groningen, Leeuwarden and Drenthe (the northern provinces) a number of municipalities organise themselves into a public-private partnership called Energy Valley (DG, 2004c; DTC, 2004b; DvhN, 2005c; LC, 2005a).

[186] Cogas remains active as a lobby organisation but decreasingly so (DutCH4, 2005a; DutCH4, 2005b; Cogas, 2007).

[187] Such as the UKR, EOS and the Transition programme. For instance, DutCH4 manages to gain financial support through the UKR scheme for the construction of the first ten pumps in the northern provinces.

[188] Some even study the possibility of utilising biogas, a climate-neutral renewable (TW, 2005b).

[189] Examples of provinces getting involved are Gelderland, Utrecht, Friesland and North-Holland (LC, 2005a; TW, 2005a; NGV, 2007).

the 1990s) [F1, F2]. Instances of large incumbents getting involved are three major Dutch energy companies (Gasunie, Eneco, Essent) [F1]. These incumbents have so far been sceptical about ANG technology but now they prepare a manifesto envisioning the dawn of ANG technology in the Netherlands [F4, F7] (FEM, 2004; MoH, 2008; WNGB, 2007). Based on positive research outcomes [F4] a growing ANG community lobbies national policy makers for supportive tax policies [F7] (DTC, 2005b; MoH, 2008).

The covenant raises resistance among incumbents as well [-F4, -F7], primarily the oil companies, some of which are shareholders of Gasunie (MoH, 2008; WNGB, 2007). The oil companies consider NG a competitor to existing technological options such as diesel. They attempt to obstruct the covenant but in the end they effectively fail to do so. Resistance also grows among municipalities and public transport companies, mostly where they are obliged to adopt ANG technology because of concession policies [-F4, -F7] (Dutch4, 2007; NGV, 2007; WNGB, 2007).

The resistance to change is underlined by MinVROM's unwillingness to support ANG technology with fiscal measures [-F4] (Van der Knoop, 2005; MinVROM, 2004).[190] Its viewpoint is that ANG technology is not a long-term solution, either for reducing NO_x or PM, or for reducing CO_2.[191] The ministry's vision receives much criticism [F7] especially from a working group within the Transition Platform on Sustainable Mobility (PSM), a public-private partnership connected to a variety of ministries, including MinVROM.[192] The PSM working group, backed by 40 companies (including the four major energy companies (FEM, 2004; MoH, 2008)), municipalities and NGOs, succeeds in convincing MinVROM to provide specific policy support for ANG technology after all [F4, F7] (Van der Knoop, 2005; AC, 2005; SN/E, 2005; SNM, 2005; SenterNovem, 2008b; WNGB, 2007).[193] By the end of 2005, MinVROM announces a policy package [F4] (DT, 2005; GC, 2005).[194] For the next year 12 million € is to be provided for the greening of buses and service vehicles of local governments [F6]. Also, MinVROM promises to approach the Ministry of Finance to design a fiscal framework supportive of ANG [F4] (DutCH4, 2005c).[195]

Motors

The developments in this episode can be considered as the progressive unfolding of the *System Building Motor* already present in the previous episode. *Entrepreneurial Activities*, *Guidance of the Search*, *Support from Advocacy Coalitions*, *Resource Mobilisation* and *Market Formation* remain the most crucial activities, along with *Knowledge Development* and *Knowledge Diffusion*. Comparing

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[190] As articulated in its White Paper on traffic emissions.

[191] The White Paper states that NG may be an interesting alternative car fuel for the short term, but that, as petrol and particularly diesel combustion techniques are continuously improved, the environmental performance of NG will be offset within years.

[192] Within the so-called energy transition programme, such platforms were installed as a means to circumvent the rather inert organisational structures of the ministries.

[193] Note that Gasunie plays a leading role within PNG.

[194] A majority of political parties is supportive of specific policy measures as well (DTC, 2005c; HP, 2005; NGV, 2005).

[195] The 12 Mmillion € subsidy is considered meagre by the NG community (DT, 2005; ED, 2005b; RV, 2005; NGV, 2007). In comparison, MinVROM is allocating 400 Mmillion € to a stimulation package for particle filters (Dutch4, 2007; MoH, 2008), which is regarded as an unsustainable end-of-pipe solution.

Table 8.6 ANGTIS drivers, barriers and impacts underlying a System Building Motor in 2004-2005.

	Actors	Institutions	Technologies
Drivers	• Enactors and selectors form powerful networks increasingly directed at establishing institutional change by political means (intermediary structure). • Among the selectors are incumbents, governments as well as firms. • The strategy of enactors and selectors is to persuade selectors to support market creation. They promise that ANG technology holds a solution to a range of very urgent policy issues.	• Air quality regulation (external). • Building prohibition (external). • High oil prices issue (external). • Climate change issue (external). • NG technology is regarded as a relatively easy solution to a number of problems.	• Low variable costs of NG. • Availability of NG and ANG technology. • Low emission characteristics. • The ANG technology has matured, meaning that reliability is no longer a problem.
Barriers	• Selectors, especially incumbent firms, resist entry (supply-side/demand-side). • Selectors, especially the national government, resist the support of market creation policies (government structure). • Private users are absent (demand-side).	• Limited budgets for infrastructure development. • Lack of long-term (fiscal) policy support.	• High investment costs. • Lack of refuelling infrastructure.
Impacts	• Resistance is broken, resulting in a massive entry of selectors including various government ministries, provinces (government structure) and energy companies (supply-side/demand-side).	• The release of a policy package dedicated to the support of ANG technology. • NG technology is becoming a political issue of national scope.	• Diffusion of ANG technology increases. Applications include buses and other highly visible environments.

these dynamics with earlier developments, it can be argued that the motor is expanding. An important result is that it involves an integrated nationwide development rather than a regional and dispersed development. Also, the number of events contributing to each system function is rapidly increasing. The most important progression can be observed in the *Support from Advocacy Coalitions* and *Guidance of the Search* as these system functions are now associated with national politics and the entry of a number of incumbent energy companies.

Structural drivers and barriers

External drivers are important during this episode, especially the air quality regulation in conjunction with the issue of climate change. The increased regulative pressure urges municipalities to find quick solutions to reduce traffic emissions. Based on this development, the enactors manage to persuade the national government, which is at the same time confronted with an increasing urgency to find alternatives to fossil fuels as a means to reduce carbon emissions. In the eyes of the government, ANG technology is revealed as a cost-effective technological solution to multiple problems. The role of supply-side selectors and intermediaries – SenterNovem, large gas companies and especially PNG – has catalysed this alignment of interests. This combination of structural drivers mainly affects *Guidance of the Search* and *Support from Advocacy Coalitions*.

A main barrier remains the absence of a refuelling infrastructure and the lack of a strong demand-side of the ANGTIS; note that it is still entirely made up of fleet owners, not private users. Long-term fiscal policies may tackle this chicken-and-egg problem but so far these remain absent. This explains the weak *Market Formation* function.

Impact on TIS structures

As in the previous period, a key outcome of the *System Building Motor* is the entry of a group of selectors formerly absent. These include large supply-side industries, with the means to develop a nationwide refuelling infrastructure, and the national government. The *System Building Motor* is now breaking the resistance among incumbents and especially among policy makers and politicians on the national level. The main outcome so far, is a policy package dedicated to support ANG technology. As a result of this political breakthrough, more selectors are preparing for ANGTIS entry.

An overview of drivers, barriers and impacts is presented in Table 8.6.

8.4.5 Take-off? (2006-2007)

Local air quality standards continue to be the main driver for ANG development. In conjunction with this, the political priority of climate change reaches an all-time high. The climate issue becomes especially important by the end of 2007 when biofuels, which have so far been embraced internationally as the most attractive short-term alternative car fuel, are increasingly contested. As a result ANG becomes the last refuge of the green (SenterNovem, 2008b). Another external factor is that the security of gas supply becomes a political issue, the most significant event being that Gazprom briefly cuts off gas supply to Ukraine, and thereby to the rest of Europe. However, the ANGTIS actually does not seem to be affected by this threat; instead it seems that so-called clean fossil energy sources gain ground.

By the end of 2006 the government announces two fiscal measures.[196] Firstly, it sets a low excise rate specifically for ANG [F4, F5].[197] It does not announce, however, for how long this rate will hold [-F4, -F5] (NRC, 2006; SenterNovem, 2008b). Secondly, the government sets a purchase tax-rate (BPM) that benefits energy efficient cars [F4, F5] (DutCH4, 2006b; NRC, 2006; WNGB, 2007).[198]

The government support results in the adoption of more NGVs among municipalities. In Leeuwarden, Groningen, The Hague, Nijmegen, Hengelo and Tilburg, NGVs are adopted as fleet vehicles and refuelling stations are installed or planned [F1, F2, F4, F6]. What is more interesting is that many of these municipalities prepare regulations to provide cheap parking permits and (in some cases) financial incentives for purchases of NGVs [F4, F5] (BD, 2006; DT, 2006b; DT, 2006c; DutCH4, 2006a; DutCH4, 2006b; DutCH4, 2006c; DV, 2006; LC, 2006). The involvement of provincial governments grows stronger as well, supporting the deployment of NG infrastructure [F6] (DG, 2006a; DutCH4, 2006d; PZC, 2006; SN/E, 2006).[199] They also design concessions that favour NG in public transport [F5] (DG, 2006a; DvhN, 2006; PZC, 2006).[200]

The demand-side of the ANGTIS is still largely made up of public actors and utilities. Private drivers are still absent since an NG refuelling infrastructure is still absent in most places, even though this is something that is now worked on [-F6].[201] A related problem is the uncertainty on the trade-in value of second-hand NGVs [-F4, -F5] (SenterNovem, 2008b). This is especially relevant for fleet owners that may be obliged, in the near future, to renew all their vehicles if even stricter conditions are to be met (PZC, 2006). Due to this uncertainty a number of public transport companies protest against the concession policies set up by provincial governments [-F7] (AC, 2006; DG, 2006a; FD, 2005a; Connexxion, 2007).[202] An impulse to the solution of this problem is given by the EU with the Procura project, which aims for the introduction of lease contracts and the formation of a 'second-hand' market for NGVs [F4, F5] (AD, 2006a).[203]

Despite the weak demand-side, the ANGTIS becomes stronger on the supply-side where DutCH4, Gasunie and partnerships like Energy Valley, support ANG technology mostly by financially and politically stimulating infrastructure development [F6, F7], but also by issuing discounts on fuel and NGVs [F6] (ED, 2005a; LC, 2005b; SN, 2006). A key event contributing to this development

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[196] The national government provides other stimuli as well: licensing procedures for the construction of NG refuelling stations are simplified (DutCH4, 2006a) and MinVROM purchases eight NGVs for its own fleet (ED, 2006a).

[197] The excise level is set at 3 million €cents/m^3.

[198] The scheme does not immediately work out well for NGVs, but after lobbying by car suppliers and the transition platforms, the scheme provides incentives favourable to NGVs.

[199] The provincial governments of Gelderland, Zeeland and Utrecht decide to stimulate NG.

[200] This is the case in North Holland (Haarlem/IJmond), Groningen and Gelderland (DG, 2006a; DvhN, 2006; PZC, 2006).

[201] This is in contrast to the German situation where by now hundreds of refuelling stations have been installed to serve private motor vehicles.

[202] In general, public transport companies plea for a more generic approach: setting emission norms, not fuel restrictions.

[203] The programme is executed by Ecofys, an energy consultancy.

is the start-up of Aardgas Mobiel, a platform that promotes ANG technology on behalf of car manufacturers [F4, F7] (AD, 2006b; Dutch4, 2007).

A salient shift among supply-side organisations is the large capital infusion into the system. The incumbents of the mobility sector, including branch organisation BOVAG, car dealers and manufacturers, now expect ANG demand to rise explosively [F4] (AD, 2006b; DT, 2006a; Bovag, 2007). The result is the entry into the system of so-called system integrators, mostly incumbent companies that arrange import and assembly of NGVs and NG refuelling stations [F1, F6] (SenterNovem, 2008b).[204] A related development is the formation of CNG-net, a joint venture of DutCH4 and Ballast-Nedam, a large (infrastructure) construction company [F1, F3].[205] CNG-net plans to realise 50 refuelling stations by the end of 2008, and 200 more in the years to come [F4, F6] (Dutch4, 2007).[206] DutCH4 provides the knowledge and Ballast-Nedam the money [F3, F6] (Dutch4, 2007). Formerly, such activities were undertaken by DutCH4 but, due to limitations of capital, only on a limited scale.

Note that ANG technology (NGVs and refuelling stations) is mostly manufactured abroad.[207] As a result the nature of technology development in the ANGTIS has shifted towards short-term practical issues, mostly related to market explorations and feasibility studies [F2] (SN/E, 2006). The more innovative research (new products, long-term developments) has been abandoned since ANG technology has matured (SenterNovem, 2008b). But now the research agenda broadens as an increasing number of parties addresses a new generation of ANG technology, for example in the field of liquid ANG technology and in the field of high-performance NG engines. Also biogas is increasingly regarded as an important topic of research, especially since liquid biofuels are increasingly contested (SenterNovem, 2008b). The urgency of the climate problem debate is also addressed through increasing attention to possible linkages between ANG technology and hydrogen fuel cell technology. In short, the ANGTIS orients itself towards innovative and future-oriented research topics.

Motors

Looking at the events in this period it becomes clear that *Guidance of the Search* and *Market Formation* – both in the form of national government policies – have a strong effect on *Entrepreneurial Activities* and, resulting from these, on *Resource Mobilisation* in the form of large investments, particularly in NG infrastructure. The latter two system functions are now stronger than ever before. The promise of a mass market for NG applications means that *Entrepreneurial Activities* now typically arise due to the anticipation of actors – enactors and selectors alike. In some cases these even result in new contributions to *Market Formation* in the form of (lower-level) policies such as concession policies, lease plans or green parking zones. With the promise of a market, the importance of *Support from Advocacy Coalitions* lessens as firms are willing to make investments, even without (additional) government support. This means that a new form of

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[204] Examples are PON (importer of NGVs) and Teesing (infrastructure development).

[205] DutCH4 has the knowledge and Balast-Nedam the money (Dutch4, 2007).

[206] The project amounts to an investment of about 10 Mmillion € in the next year and up to four times as much thereafter.

[207] An exception is the construction of a plant for the production of NG engines by Nonox (ED, 2006b; FEM, 2004; TW, 2006).

cumulative causation has emerged. Given the primacy of the promise of a market, it seems fit to label it a *Market Motor*.

It should be stressed that the emergence of the *Market Motor* is made possible by the technological and institutional structures, by the enactors and selectors and the networks established earlier by the *System Building Motor*.

Structural drivers and barriers

The ANGTIS developments are still driven by air quality norms and increasingly also by the climate issue. The most important internal driver of this motor is a shared belief, among enactors and selectors, translating into a joint *Guidance of the Search*, in the future of ANG technology as a means to contribute to mitigate both problems. This belief is underpinned by the national government putting up a regulatory framework that reduces uncertainty, thereby contributing to *Guidance of the Search* and *Market Formation*. The supply-side and the government structure of the ANGTIS have by now become very well developed. Also the intermediaries perform well in linking up these components. The key to the dynamic that arises is that enactors and selectors do not need to put as much energy into lobbying efforts anymore. Instead they contribute directly to *Entrepreneurial Activities* and *Resource Mobilisation*. Selectors – most notably provinces and municipalities formerly not involved – are increasingly active to improve the policy environment as well, thereby contributing to *Guidance of the Search* and *Market Formation*. Among these selectors are incumbent firms and system integrators willing to invest in the ANGTIS. An important barrier is (still) the lack of a long-term policy perspective as the duration of the excise-rate remains uncertain. Also the demand-side of the ANGTIS remains weak as it depends heavily on local government authorities as fleet owners; private users are barely present. Another barrier is that some of the support policies – especially the concession policies – cause resistance among selectors, thereby contributing negatively to *Guidance of the Search* and *Support from Advocacy Coalitions*.

Impact on TIS structures

A take-off has occurred. A key impact is the entrance of selectors on the demand-side of the ANGTIS. With the presence of infrastructure contractors and numerous fleet owners, a modest market diffusion process started. This is underlined by the figures in Table 8.7 which show that numerous refuelling stations are being built. Unfortunately, these developments lag far behind when compared with Germany, for instance.

An overview of drivers, barriers and impacts is presented in Table 8.8.

Table 8.7 Number of NGVs in the Netherlands and Germany measured in March 2007 and May 2007 respectively.

	Total NGVs	NGVs/ 1000 inhabitants	NGV share of total vehicles	Number of refuelling stations	
				Constructed	Under construction
Netherlands	603	0.04	0.01%	8 (1:75 cars)	22
Germany	60,000	0.73	0.12%	720 (1:83 cars)	13

Source: GVR (2007).

Table 8.8 ANGTIS drivers, barriers and impacts underlying an emerging Market Motor in 2006-2007.

	Actors	Institutions	Technologies
Drivers	• Enactors and selectors have established strong networks covering and connecting the supply-side and demand-side, the government structure and the intermediary structure of the ANGTIS. • A variety of new selectors is drawn into the ANGTIS, including provinces, municipalities and system integrators. • The strategy of enactors and selectors is to exploit the benefits offered by the promise of a mass market (demand-side) and develop plans to construct a nationwide refuelling infrastructure.	• Air quality regulation (external). • Building prohibition (external). • High oil prices issue (external). • Climate change issue (external). • Fiscal regulations benefit ANG use. • Local market creation policies benefit ANG use.	• Profits from bad reputation biofuels (external). • Low variable costs of NG. • Availability of NG and ANG technology. • Low emission characteristics. • The ANG technology has matured, meaning that reliability is no longer a problem.
Barriers	• Private users are barely involved as selectors (demand-side). • Resistance rises among selectors and enactors not willing to support ANG technology but 'forced' to do so (demand-side/government structure).	• Lack of long-term (fiscal) policy support. • Concession policies cause resistance.	• High investment costs. • Lack of refuelling infrastructure.
Impacts	• Selectors have strengthened the demand-side of the ANGTIS. These include infrastructure contractors and numerous fleet owners.	• The promise of a mass market for NGVs and ANG technology.	• Diffusion of ANG technology increases. • Applications include buses and other highly visible environments. • Refuelling infrastructure is being deployed.

8.5 Conclusion

The aim of this chapter was to analyse the development of the Dutch ANGTIS, with the general goal to provide insights into the dynamics of TISs in the formative stage. In order to fulfil this aim, we have attempted (i) to identify motors of innovation, (ii) to point out the underlying structural drivers and barriers, and (iii) to assess their impact in turn on TIS structures. This section provides a summary of the results from this study.

8.5.1 The Entrepreneurial Motor

Three motors of innovation were identified. The *Entrepreneurial Motor*, the first one observed, emerged in the 1970s and was active until well into the 1990s. It was characterised by interactions between *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion* and *Guidance of the Search*. In a more advanced form it was strongly connected to *Support from Advocacy Coalitions* and *Resource Mobilisation* as well.

The event sequence was characterised by utility companies and firms entering the TIS and venturing into *Entrepreneurial Activities*. This especially led to *Knowledge Development* and *Guidance of the Search*, which in turn reinforced *Entrepreneurial Activities*. On most occasions *Resource Mobilisation* was the result of firms lobbying for government subsidies. This contributed strongly to the *Support from Advocacy Coalitions* function. A main feature of the *Entrepreneurial Motor* was that the initiative for *Entrepreneurial Activities* did not come from one small group of government-backed enactors. Instead, these activities were the outcome of a multitude of enactors and a (smaller) number of selectors.

The following structural drivers, barriers and impacts were identified:

- In terms of structural drivers the basis of this motor was formed by a group of enactors, involving utilities and municipalities, that managed to persuade an increasing number of selectors (bus companies, boating companies, governments) into supporting demonstrations of ANG technology. In doing so they developed networks that connected the supply-side, demand-side and government structures of the ANGTIS.

- A structural barrier of the *Entrepreneurial Motor* was its narrow actor basis, especially the lack of firms on the demand-side of the ANGTIS. Another barrier was formed by the persistent (unexpected) techno-economical problems of ANG technology.

- Important impacts of this motor were the formation of networks that strengthened the intermediary structure of the TIS, the application of safety standards, licensing procedures and the allocation of subsidies, thus supporting the government structure. Another impact was the (gradual) development of the emerging ANG technology into reliable applications, reinforcing the knowledge structure of the TIS.

8.5.2 The System Building Motor

The system functions that formed the *System Building Motor* are *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search*, *Resource Mobilisation*, *Support from Advocacy Coalitions* and *Market Formation*. All seven system functions were involved. Note that the *Market Formation* function was barely present in the *Entrepreneurial*

Motor. Another difference lies in the connection between *Support from Advocacy Coalitions* on the one hand, and *Market Formation* and *Guidance of the Search* on the other. These connections were established through entrepreneurs that organised themselves in networks and managed to draw new enactors and selectors into the TIS, especially local governments, intermediaries and interest groups. They did this by lobbying the government, not for project-specific support measures, but for systemic policies aimed at *Resource Mobilisation* or *Guidance of the Search* beneficial to the emerging technological field as a whole. With this strong *Support from Advocacy Coalitions*, they attempted to enforce the creation of a mass market for the emerging technology. The outcome of these system-building attempts affected *Guidance of the Search* and *Resource Mobilisation*, with as a subsequent effect that even more *Entrepreneurial Projects* were developed by an increasing number of firms.

- This motor was driven by enactors and supportive selectors forming platforms and other networks. By strengthening the intermediary structure of the ANGTIS they managed to incorporate a multitude of selectors, for example, national government ministries and incumbent firms. Another driver was the increased reliability of ANG technology and its fit with the policy environment (standards, licences).

- A main structural barrier of the *System Building Motor* was the absence of a refuelling infrastructure and the lack of long-term (fiscal) policies to support its development. Another barrier was the rise of resistance among incumbent firms and governments. Since the growth of ANG technology would eat into the incumbent markets, incentives to support this technology on the part of incumbent fuel producers were weak or even negative.

- In terms of impact, this motor drove the ANGTIS from a local fragmented ANGTIS into a national integrated ANGTIS. A multitude of enactors and selectors were drawn in and networks were established across various components of the TIS. The most important outcome was the political breakthrough that resulted in the issuance of top-down market creation policies.

8.5.3 The Market Motor

The third motor of innovation observed was the *Market Motor*. Its dynamics, which emerged only recently, from 2007 on, were characterised by a strong contribution to *Entrepreneurial Activities*, *Knowledge Development*, *Knowledge Diffusion*, *Guidance of the Search*, *Resource Mobilisation* and *Market Formation*. All system functions were fulfilled, except for the *Support from Advocacy Coalitions*. The main reason was that *Market Formation* was no longer an issue of politics; a market environment had been created as the result of formal regulations. Instead, *Market Formation* was taken up as part of regular business activities, i.e., marketing and promotion strategies that are directly linked to *Entrepreneurial Activities*.

- The most important structural driver of this motor was that an institutional basis was formed that induced market creation for ANG technology. This means that firms did not need to lobby for (additional) resources anymore. Instead they could take the opportunity to start investing in a refuelling infrastructure and to develop marketing strategies of their own.

- The *Market Motor* was not entirely developed yet, as both the government structure and the demand-side structure were underdeveloped. This manifested itself in the limited role of private end-users and in the absence of refuelling infrastructure and long-term fiscal policies. Another barrier was (still) the resistance among a number of selectors.

- The most important impact of this motor was the increasing diffusion of ANG technology and the powerful promise of a mass market for NGVs and ANG technology.

8.5.4 Breakdown

Besides motors of innovation, vicious dynamics were also observed. This happened in the 1990s when a combination of internal and external conditions (a low priority of environmental issues, liberalisation policies in the energy sector, a disappointing techno-economical outcomes and a narrow actor base), led to a rapid breakdown of the ANGTIS. During this episode, developments were nevertheless supported by a small number of dedicated enactors which found refuge in niche markets. When external conditions shifted, the enactors managed to start a build-up again. Even when selector support was discontinued, enactors continued pro-actively to develop a TIS by consolidating the build-up already established, and waiting for better conditions to arise.

8.5.5 Concluding remarks

At the beginning of this chapter it was suggested that the analysis of the ANGTIS could provide important insights regarding the take-off of a formative TIS. The analysis has pointed out that the take-off of the ANGTIS occurred only after a long period of developments characterised by different motors of innovation, and even a period of severe decline. It was shown that each motor was driven (or hampered) by a particular configuration of structures. In turn, each motor contributed to the build-up and adjustment of these structures.

All the motors were coupled to developments external to the ANGTIS as well. These involved policies (environmental regulations, liberalisation policies, EU subsidies), economic trends (oil prices) and technological developments (the biofuels debate). However, it was primarily the TIS structures, including dominant strategies taken by enactors and selectors, that determined the specific effect of these external factors on the dynamics within the ANGTIS.

An important observation, in the light of a take-off, was that the more advanced motors arose from more developed TIS structures, for example, the *Market Motor* developed on the basis of a relatively mature technology which was embedded in supportive regulations and supported by a strong network of enactors and selectors. However, these advanced TIS structures were established by less advanced motors. The *Market Motor* could arise on the basis of the build-up established by the *System Building Motor* – i.e., market creation policies and government structures – and likewise, the *System Building Motor* could arise due to the build-up established by the *Entrepreneurial Motor* – i.e. the formation of strong networks, intermediary structures and demand-side structures.

With respect to the take-off, the *System Building Motor* was especially important. The driving force of this motor has been an inner core of dedicated enactors that were able and willing to organise themselves in networks, and to address not single projects but the TIS as a systemic whole, for instance, by lobbying for top-down market creation policies. The enactors managed to reach their goal by luring in selectors. The more support from selectors, and the larger their variety, the better. However, selectors could only be reached if internal and external conditions were sufficiently attractive compared with other options available to them. In this case, the *Entrepreneurial Motor* had largely provided such conditions. After all, enactors could rely on mature ANG technologies and institutions and actor networks that were established as part of the *Entrepreneurial Motor*.

A key barrier of the *System Building Motor* was the resistance from selectors residing in the incumbent energy system, including important national government structures. When this resistance was overcome, the ANGTIS developed further towards a take-off. Still, even after the rise of a *Market Motor*, the dynamics of the ANGTIS were hampered, most importantly by the absence of long-term government policies and, related to this, the absence of private end-users. Despite all the advantages that a mature technology offers, a complete ANGTIS has not yet been created. The *Market Motor* is powerful and effective as a promise for the (near) future, but it remains to be seen whether the high expectations that it raises will actually be fulfilled.

The next step of research will be to find out more precisely what structural combinations lead to what motor of innovation and to find out whether motors of innovation tend to follow on each other, in general.

Part III
Synthesis

9 Motors of sustainable innovation

9.1 Introduction

In this chapter an attempt is made to combine the insights from the five individual case studies in order to establish an integrated perspective on motors of sustainable innovation. In doing this the three main research questions will be answered:

RQ1: Which motors of sustainable innovation can be identified within the domain of emerging sustainable energy technologies?

RQ2: Can the rise, retention (and decline) of motors of sustainable innovation be explained in terms of TIS structures (actors, institutions, technologies, networks) and external influences and to what extent do these motors, in their turn, impact on TIS structures?

RQ3: Based on the motors of sustainable innovation, as identified, how can TISs in the formative stage be evaluated?

The chapter is structured as follows. Section 9.2 provides a brief overview of the case studies that form the empirical basis of this chapter. Section 9.3 presents a synthesis of the case study results by proposing a typology of four motors of sustainable innovation (RQ1). For each motor it is indicated what were typical structural drivers and barriers and what were typical structural impacts as observed across various cases (RQ2). This synthesis also provides evaluative insights by pointing out the relative strengths and weaknesses of each motor, in terms of structural drivers and barriers (RQ3). In Section 9.4, the synthesis is taken further by the development of what will be called the Succession Model of Innovation. This model is an attempt to relate the various motors of innovation to each other and to consider them as (sub)stages within the formative stage of a TIS. It will be argued that each motor of innovation, by its impact on TIS structures, may cause a TIS to develop into a more complete (and more complex) structural configuration which, in turn, is prone to bring about a more advanced motor of innovation (RQ1, RQ2). In Section 9.5, a series of evaluative insights is provided on the basis of the Succession Model of Innovation. The section also translates these insights into strategic lessons for practitioners (RQ3).

9.2 Overview of case studies

This section provides a short summary of the dynamics that characterised each of the case studies. The overviews should primarily be considered as a guide to the reader. They provide an insight into the most salient internal dynamics at play in various TISs. Moreover, they serve to create an overview of important external factors that shaped these dynamics in the various TISs.

9.2.1 Internal dynamics

Biomass gasification in the Netherlands

The dynamics of the Biomass Gasification TIS (BGTIS) were characterised by a slow and troublesome build-up followed by a rapid decline. The build-up started out slowly in the 1980s within a community of scientists and engineers that had so far been developing coal gasifiers. Switching to biomass seemed feasible as the first small-scale BG applications had already been developed by that time. In the 1990s, Biomass Gasification (BG) technology came to be regarded as an enabling technology for the creation of a sustainable energy production system. This technological promise was largely fed by scientists, technology developers and policy makers. What is interesting in this case is that the dynamics were widely supported by local governments and energy companies and resulted in the start-up of numerous demonstration projects across the country. The effect was that numerous small firms entered the TIS to develop their own projects. An important lesson learned in the 1990s was that BG technology posed far more technical problems than was originally expected. By 1998, the 'hype' came to an end, the main reason being the trend of liberalisation within the energy system. Energy companies cut spending on technological innovation. This, combined with the disappointing technological outcomes of BG demonstrations, led to a sudden decline of the BG trajectory.

Biofuels in the Netherlands

The dynamics of the Biofuels TIS (BFTIS) are characterised by a conflict between advocates of a first generation (1G) and a second generation (2G) of biofuel technologies. The first developments date from the 1990s. In these years, farmers, small firms and local governments led production and adoption experiments. The experiments were supported through EU policies but the national government was hesitant to provide support as it doubted the sustainability of 1G biofuels. In the late 1990s, this changed as policy makers began to realise that, to establish CO_2 reductions in the mobility domain, few technological options other than biofuels were available. At the same time, scientists and environmental organisations began advocating against these 1G biofuels. The argument was that they were costly, inefficient and downright unsustainable. Instead, they argued, support should be given to 2G biofuels. By 1998, a government R&D programme, GAVE[208], was set up that did just this. The result was that 1G biofuels gained support from the EU and local governments, whereas the national government turned its back on these options and focused exclusively on 2G biofuels. From the late 1990s the BFTIS was for a few years dominated by activities around 2G biofuels, involving government R&D projects directed at market demonstrations. However, the companies involved in 2G biofuels regarded the market perspectives unfavourably. Despite some successful outcomes, developments did not go as fast as expected due to a bleak market prospect. In the next period, 2004 and 2005, this changed. Despite the ongoing controversy around 1G biofuels, the EU decided to set a target for a minimum of 10% biofuels implementation by 2010. No distinction was made between 1G or 2G technologies. What followed was a surge in 1G biofuels activities. Hopes were that 2G technologies would soon be available as a substitute. The 1G biofuels were expected to pave the way for 2G biofuels. However,

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[208] GAVE stands for Climate Neutral Gaseous and Liquid Energy Carriers, in Dutch. This is a Dutch government programme that is implemented by SenterNovem on behalf of three Ministries (Spatial Planning, Housing and the Environment; Economic Affairs; and Transport, Public Works and Water Management).

recently, scientists and environmentalists have increased their opposition to biofuels in general, 1G and 2G alike.

Biofuels in Sweden

The development of the Swedish BFTIS was characterised by a gradual build-up without steep turns. The developments started already in the 1980s when farmers (organised in the LRF farmers organisation) lobbied for national support and were successful in setting up a pilot plant for the production of 1G bioethanol. Numerous projects, including adoption experiments with buses, were initiated by the SSEU, a public-private partnership. This organisation managed to draw in national government support for a variety of projects. In the 1990s the dynamics expanded under the influence of top-down government policies which led to the setting up of two support programmes, one aiming for the development of 2G biofuels and one for the broad demonstration of 1G biofuels. The SSEU and the LRF networks played a crucial role in legitimating support for these projects. Developments were legitimated on the basis of environmental issues on a local level, especially the air quality. By the end of the 1990s, advocates even managed to shape niche markets that supported the use of 'flexi fuel cars', thereby inducing the adoption of biofuels among end-users. Despite the presence of 2G advocates criticising the diffusion of 1G biofuels, the overall strategy of actors was to join forces and plead for the general support of the BFTIS. The result was that, from 2000 on, a broad policy package of market creation measures was introduced by the government. These measures involved not only financial instruments, like tax incentives, but also instruments that stimulated the adoption of biofuels technology in certain contexts, for example, 'green' parking zones.

Hydrogen and fuel cell technologies in the Netherlands

For the Hydrogen and Fuel Cells TIS (HyFIS), the dynamics involved multiple waves of activities. The first wave emerged by the end of the 1970s, against the background of the oil crisis, when the Molten Carbonate Fuel Cell (MCFC) was advocated as a viable option to reduce energy consumption. This idea was advocated by scientists and engineers and rapidly picked up by the national government. The result was, in the early 1980s, the setting up of a fuel cell development programme, the NOB[209], aimed towards the commercial demonstration of MCFC and PAFC power plants. From the 1980s to the early 1990s the TIS was dominated by activities unfolding from this programme. The programme did not succeed in realising demonstration plants as was the objective. The organisations involved – mainly R&D institutes and technology developers – encountered difficulties in finding launching customers. In fact, studies pointed out that fuel cell power plants did not stand a chance in a market environment, since by that time oil prices were low and there was a well performing alternative CHP technology, the gas turbine. By 1998 the NOB programme came to a halt, taking away the catalyst of all developments so far. At the same time, a second wave of activities emerged. This second wave was triggered by improvements in the performance of the Solid Oxide Fuel Cell (SOFC) and especially the Proton Exchange Membrane Fuel Cell (PEMFC). The PEMFC connected to a completely different application domain, (electric) vehicles. After a reorientation to the PEMFC, rising oil prices, climate change issues and local air quality issues provided a sense of urgency, which caused the HyFIS to receive support from governments, utilities and firms. From 2005 on, a variety of demonstrations was realised, with ever more visible results. An interesting feature of the HyFIS trajectory is that external

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[209] *Nationaal onderzoeksprogramma brandstofcellen*: National Research Programme [on] Fuel Cells.

developments like EU policies, technological breakthroughs, and influences from foreign car industries, strongly affected its dynamics, and yet it managed to develop and continue a powerful internal dynamic as well.

Automotive natural gas in the Netherlands

The dynamics related to the Automotive Natural Gas TIS (ANGTIS) were characterised by an early build-up in the 1970s, followed by a breakdown in the 1980s and then a new build-up from 2000 to 2007. The early build-up was induced by the oil crisis, which led gas companies and other utilities to experiment with alternative fuels for their fleets. This involved a growing number of adoption experiments supported by the national government and by the EU. The breakdown of the ANGTIS began in the 1980s when the oil price went down and the urgent need for alternative fuels disappeared. Also, the adoption experiments were unsuccessful in terms of costs and reliability. This, combined with the liberalisation trend in the 1990s, led most utilities to abandon innovative experiments. The result was a collapse of the ANGTIS. A handful of dedicated actors, mostly municipalities and gas companies, nevertheless continued supporting the ANGTIS. From 2000 on, developments started accelerating again as the result of tightened EU air quality regulations. This urged local governments to adopt alternative automotive fuels and Automotive Natural Gas (ANG) was one of the few available options. In 2004, these developments expanded as ANG advocates organised themselves in platforms and began lobbying the national government for support. The ambition was to broaden out the so far regional NG infrastructure to cover the whole nation. The TIS could expand even more as the technology and the institutions around it had developed further by that time. These activities provoked resistance, especially within the national government but also among incumbent industries. The result was a political battle which resulted by 2006-2007 in a positive outcome for the ANG advocates – a national policy package that aimed towards infrastructure building and the widespread diffusion of ANG vehicles.

9.2.1 External factors

The foregoing sections summarise the internal dynamics of each case study by briefly characterising periods of build-up and breakdown. From this it becomes clear that external factors play an important role in shaping these dynamics. The following external factors have been identified in most of the cases:

- One factor that affected TIS dynamics in general was the oil crisis of the 1970s, which turned out to be an important driver for the expansion of the BGTIS, ANGTIS and the HyFIS, particularly in the early 1980s. The BFTISs were not studied for that period.

- A second factor was the environmental movement that arose in the 1980s. Environmental advocacy groups took up problems with air pollution, water pollution and global warming. For the first time, environmental policies were designed to address these problems. As a result, industries started to develop cleaner technologies. This was observed in the BGTIS, ANGTIS and the HyFIS cases. The BFTISs were not studied for that period.

- The third factor is the liberalisation of the energy system, a policy trend that emerged in the late 1980s and became highly influential in the 1990s. The liberalisation policies were an important barrier, effectively blocking developments in the BGTIS and the ANGTISs in the 1990s. It is more difficult to claim this for the BFTIS and HyFIS, as other, more technological, factors were dominant in that period.

- The fourth factor is a bundle of issues related to sustainability that became pressing in the 2000s, namely local air quality, climate change and security of energy supply. Their great impact was not only the result of the individual importance of the issues, but was especially due to the fact that, combined, these problems addressed a broad spectrum of interests, from local to global and from the economic to the social. The result was an unprecedented surge in activities in most of the TISs studied.

- The fifth factor is that TIS developments were strongly dependent on support (or resistance) from abroad regarding technologies, markets, EU policies or promises resulting from international technological breakthroughs. The developments in other nations are crucial to understand how motors of innovation emerged within the Dutch or Swedish TISs.

- A sixth factor is the effect of other TISs (within a nation). There were many examples where TIS developments were either driven or blocked because of the influence from other TISs. Often it was the incumbent energy system that affected the TIS but quite often this involved other emerging TISs that competed with or complemented the TIS studied. For example, in the HyFIS, the development of the gas turbine severely hampered the development of fuel cells for CHP applications.

In Table 9.1 a historical overview is provided of the historical developments described in all the case studies, including the (general) external factors that affected the build-up and breakdown. The external factors should be regarded as the historical context within which TISs develop;

Table 9.1 Periods of build-up (+), breakdown (-) and stability (0) for different TISs.

Period	BG	BF-1G NL	BF-2G NL	BF-1G SW	BF-1G SW	ANG	HyF	External factors
1970-1974						+	-	Oil crisis
1975-1979						+	+	Oil crisis
1980-1984	+			+	0	+	+	Oil crisis, Environment
1985-1989	+			+	0	-	+	Liberalisation, Environment
1990-1994	+	+	0	+	+	-	+	Liberalisation
1995-1999	-	0	0	+	+	+	+	Liberalisation, Climate change
2000-2004	-	0	+	+	+	+	+	Local Air quality, Climate change, Security of supply
2005-2008		+	+	+	+	+	+	Local Air quality, Climate change, Security of supply

The TISs referred to are; BG (Biomass Gasification), BF (Biofuels), ANG (Automotive Natural Gas) and HyF (Hydrogen and Fuel Cells). The countries referred to are NL (the Netherlands), SW (Sweden).

they influence the internal dynamics, the motors of sustainable innovation. In some instances, motors are blocked and in other instances they are induced. Whether they are blocked or induced depends partly on the structural configuration of the TIS. For example, the setting up of EU-wide market creation policies may induce motors of innovation in countries which have not yet developed such policies themselves but it may block TIS developments in countries which have. This was observed in Chapter 6.

Note that external factors only provide a partial explanation of TIS development. After all, if a TIS is driven by external influences, there is still a variety of ways in which it can develop. For example, knowing about the oil crisis does not explain how the TISs affected by it started to substitute important parts of the incumbent energy system with alternative technologies, nor does it explain why these TISs failed to expand before the oil price decreased again. A detailed analysis of TIS internal dynamics would show that the TISs started out with a very small basis of actors, unreliable technologies and weak institutions. Moreover, a comparison of TISs would show that the internal dynamics differed significantly between TISs that were subject to the similar external conditions.

The external factors largely determine the general direction of TIS development (build-up or breakdown) but underlying these processes there are more detailed dynamics at play that should be uncovered. After all, it is on the level of the internal dynamics of a TIS that important strategic lessons are to be learned.[210] The next section will attempt to do this by identifying the motors of sustainable innovation that characterised periods of build-up and breakdown. The motors will be related to structural factors internal to the TIS and it will be pointed out how these structural factors were influenced by developments external to the TIS.

9.3 A typology of motors

This section presents a typology of motors of sustainable innovation based on the case studies presented in this book. Each of the motors is characterised in terms of dominant system functions and interactions between these system functions. Insights from the case studies are then provided, focusing on similarities but also on differences between cases. The motor is then discussed in terms of structural drivers and barriers that explain its emergence, retention (possibly) and decline. Finally, structural impact(s) are discussed. Throughout these sections, the important role of external influences will also be mentioned and discussed.

9.3.1 The Science and Technology Push Motor

The *Science and Technology Push* (*STP*) motor is dominated by *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4] and *Resource Mobilisation* [F6]. The role of *Entrepreneurial Activities* [F1] is important but it is typically weak or even absent. The *Support from Advocacy Coalitions* [F7] also played a role in some the cases.

The dynamic of the *STP Motor* involves a sequence consisting of positive expectations and/or research outcomes [F4] leading to the setting up of government- supported R&D programmes [F4] and, directly linked to it, the allocation of financial resources to an emerging technology

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[210] These may include how to handle external factors.

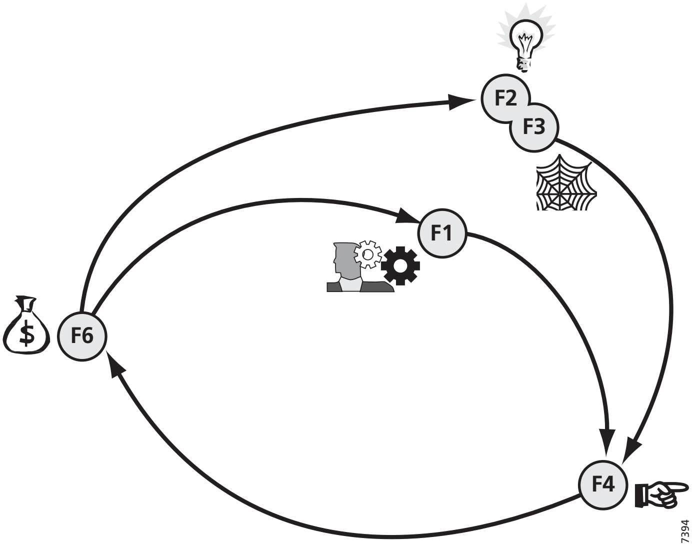

Figure 9.1 The Science and Technology Push Motor.

[F6]. This, then, results in a boost to 'scientific' activities in the form of research, typically, feasibility studies [F2], and also to conferences, workshops and other meetings [F3]. In the next step, or in parallel, government actors approach firms and research institutes to participate, as technology developers and launching customers, in projects aimed towards the realisation of pilots and demonstrations [F1]. The willingness of these firms to participate in such risky projects depends on the outcomes of the first feasibility studies [F4]. If these studies result in positive outcomes, firms may invest in the projects, thereby contributing to the expansion of the R&D programme [F4, F6]. With negative outcomes, the opposite may happen [-F4, -F6], although, with the programme and the resources in place, chances are high that dynamics will continue, even without industry support.

Figure 9.1 shows a schematic of the *STP Motor*. The virtuous cycle typically starts at *Guidance of the Search* [F4] and runs, via *Resource Mobilisation* [F6], to *Knowledge Development* and *Diffusion* [F2, F3], which lead to *Guidance of the Search* [F4] where the cycle started in the first place. A second cycle runs from [F4] to [F6] to [F1] to [F4], but this feedback loop is typically weak. Note also that *Market Formation* [F5] is typically absent,[211] in spite of the fact that the commercialisation of an emerging technology is typically a key objective of the scientists and policy makers that drive this motor.

Examples

The *STP Motor* was identified in the BG, the BF and the HyF cases. The clearest example was observed in the HyF case, where positive expectations and promises among scientists, technology developers and policy makers [F4] led to the setting up, in the early 1980s, of the NOB programme [F4, F6]. The NOB induced research activities, meetings and collaborations among technology

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[211] The exception being the quasi-market of patent licences, prototypes and R&D equipment.

developers [F2, F3]. The most important aim of the programme was to support the realisation of a Dutch hydrogen fuel cells industry, by setting up demonstration projects at a commercial scale. The programme was directed towards the MCFC and PAFC technologies. The demonstration projects never fully got off the ground, as during the search for partners it turned out that it was hard to find launching customers [-F1]. The lack of interest among firms was the result of the absence of a market perspective, as pointed out by numerous negative outcomes from feasibility studies [-F4]. The government actors, backed by the technology developers, remained positive anyway [F4]. The promise held by the fuel cell technology was kept alive by technology developers, partly on the basis of new research outcomes, but especially on the basis of external factors; international technological developments and the growing urgency of environmental issues [F4]. As a result, actors within the NOB continued pushing HyF technology [F2, F3, F4, F6]. The programme ran for 18 years before it was eventually terminated [-F4, -F6].

In the BF case the promise of biofuels, set off by scientists and technology developers, led to the setting up, in 1998, of the GAVE programme [F4, F6]. The programme was specifically aimed to support 2G biofuel technologies [F4]. It was designed to start out with the construction of partnerships and the conduct of feasibility studies [F2, F3] and to subsequently develop a commercial scale production system, i.e., a fuel production facility with a biomass supply chain attached. The projects developed within GAVE, resulted in promising research outcomes [F4]. Based on these outcomes, various firms attempted to set up demonstration projects [F1]. However, these activities never took off [-F1]. The budgets allocated were considered too low, especially since, without the promise of a market, the risks associated with the investments were perceived as too high [-F4].

In the Swedish BF case, a similar dynamic was observed. However in this case the Swedish Energy Agency was willing to finance the setting up of a 2G biofuels demonstration plant in 2003 [F1, F4, F6]. Moreover, parallel to these developments, the Swedish government was creating a market for 1G biofuels via tax incentives and other policies [F5]. These developments were considered as a stepping stone for a future 2G biofuels market, and thereby they stimulated entry of firms that could support the *STP Motor* [F4].

For the BG case, the *STP Motor* was initiated by promises of scientists and technology developers as well. This started in the 1980s and culminated, in 1993, in the NOB,[212] a government programme focusing on BG technology [F4, F6]. Like in the previous cases, the programme resulted in research activities, meetings and collaborations [F2, F3], but there are important differences. Firstly, the programme did not aim directly for the set-up of demonstration plants. Instead, it aimed for the construction of small trial plants, most notably at the ECN research institute. These were meant to provide industrial parties, especially launching customers, with useful knowledge on the influence of biomass characteristics on the technology's performance. Another difference is that firms were present that were willing to commit themselves to the emerging technology. Indeed, even incumbent energy companies were willing to invest [F1, F6]. The main reason was that, initially, these companies did not regard BG technology as a risky technology at all [F4]. The

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[212] National Biomass Research Programme (Dutch: *Nationaal Onderzoeksprogramma Biomassa*). Note that the NOB within the BG case is a different and completely unrelated programme (except of course that it was also a top-down R&D support scheme).

result was that a variety of demonstration projects was set up, the most important ones being the North Holland project and the Amer-plant project [F1]. A downside is that these projects never got off the ground due to unexpected technological difficulties [-F4].

Structural drivers and barriers

Based on the insight from the case studies it can be stated that the *STP Motor* emerges if the following structural conditions are present:

- There is an emerging technology 'fresh out of the laboratory'.
- There is a promise of the emerging technology holding a solution to societal problem(s), as conceived and communicated by a small network of scientists and firms, usually from the supply-side of the TIS.
- There is a growing sense of urgency among a group of policy makers with regard to one or more societal problems; these involve environmental issues but often also economic ones.
- The science and industry actors take the position of enactors; they are committed to the further development of the emerging technology. The policy makers are intimately linked to this group of enactors. They occupy the role of supportive selectors. After a choice is made for the support of the emerging technology, they may come to occupy the enactor role.

Note that it is the combination of actors (enactors and selectors), institutions and technologies that determines the conditions of the TIS. The sense of urgency and the promise of technology are dominant institutional factors here. After all, these prospective structures are continuously strengthened by promises of technological breakthroughs arising that are external to the TIS. With a strong prospective structure in place, enactors and supportive selectors have a basis to contribute to the system functions associated with the *STP Motor*: *Knowledge Development* and *Knowledge Diffusion* [F2, F3], *Guidance of the Search* [F4] and *Resource Mobilisation* [F6]. Eventually R&D programmes may be launched that provide a more formal institutional basis for *Guidance of the Search* [F4]. The *STP Motor* may then be sustained by a continuous influx of promises by enactors. These promises may be based on research outcomes, arising from successful projects within the R&D programmes, but they can also be based on external developments. The latter option is especially important when domestic projects do not deliver.

The *STP Motor* is characterised by certain barriers as well:

- The enactor group is small and supported by only one or two selectors. The enactor network is usually related to the government and typically to the supply-side of the TIS. This is a narrow basis to support a TIS.
- There is a weak involvement – of enactors or selectors – on the demand-side of the TIS. In other words, there are no launching customers willing to invest in R&D projects.
- The feasibility of the emerging technology is uncertain. A routine typically followed in this situation, by enactors and selectors alike, is to issue feasibility studies and to relate technological potentials to current market circumstances. These evaluations typically show that the technology cannot compete in the market, thereby confirming its status quo and increasing the fundamental uncertainty which surrounds it.
- To overcome uncertainty, enactors (scientists, technology developers) in close co-operation with the selectors, typically set up technology-specific support programmes. These programmes

are often rigid technology-push schemes that support only one technological option and exclude others, thereby leaving little room for failure. This was especially observed in the HyF and BF cases.

Impacts on TIS structure

The following structural impacts are typical for the *STP Motor*:

- A first impact of the *STP Motor* is the rise of a shared vision, a powerful prospective structure, that provides direction to the field. In the BF case, for example, the idea of utilising biomass in automotive applications was established through the GAVE programme. Prior to that, biomass was considered best applicable in power production. The *STP Motor* turned an idea which was radical at first into one widely shared among policy makers and (some) entrepreneurs. In terms of institutions, this affected the cognitive rule set of actors. For the HyF case, the vision was to establish a Dutch fuel cell industry by targeting the MCFC technology.
- If the *STP Motor* is sustained, it has a lasting impact on the knowledge structure and the supply-side of the TIS. The number of scientists and firms increases, and their relations become stronger. This was observed in both the BF and the HyF case. In the HC case, for example, a highly specialised research institute was built up which acquired government resources for years to come.
- A third impact is the setting up of formal institutions in support of the emerging technology; in the cases studied this typically took the form of technology-specific development programmes aimed to set up large demonstration projects. Where successful, the programmes reduced uncertainty and increased knowledge, although, as argued above, technology-push programmes have been known to increase uncertainty because of their 'monolithic' design.

9.3.2 The Entrepreneurial Motor

The *Entrepreneurial Motor* is partly similar to the *STP Motor*. Its dynamics are also characterised by a strong fulfilment of *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4] and *Resource Mobilisation* [F6]. What sets the *Entrepreneurial Motor* apart from the *STP Motor* is the strong presence of *Support from Advocacy Coalitions* [F7] and especially *Entrepreneurial Activities* [F1].[213]

The event sequence that characterises this motor starts with firms, utilities and/or local governments entering the TIS and initiating innovative projects [F1], usually adoption experiments or demonstration projects, because they see opportunities for commercial or societal gain in the future [F4]. Given the pre-commercial status of the emerging technology, the actors then require resources to cover part of their costs and to compensate the financial risks they take. For this, they lobby the national government [F7]. If all goes well, the financial resources are granted in the form of project-specific subsidies [F6]. Depending on the funding, the projects are started [F1]. The outcome, positive or negative, feeds back into the dynamic as it provides the incentive for other actors to initiate projects, or refrain from doing so [F4].

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[213] In some of the observed *STP Motor*s the *Support from Advocacy Coalitions* function played a role as well, but not as part of a feedback loop.

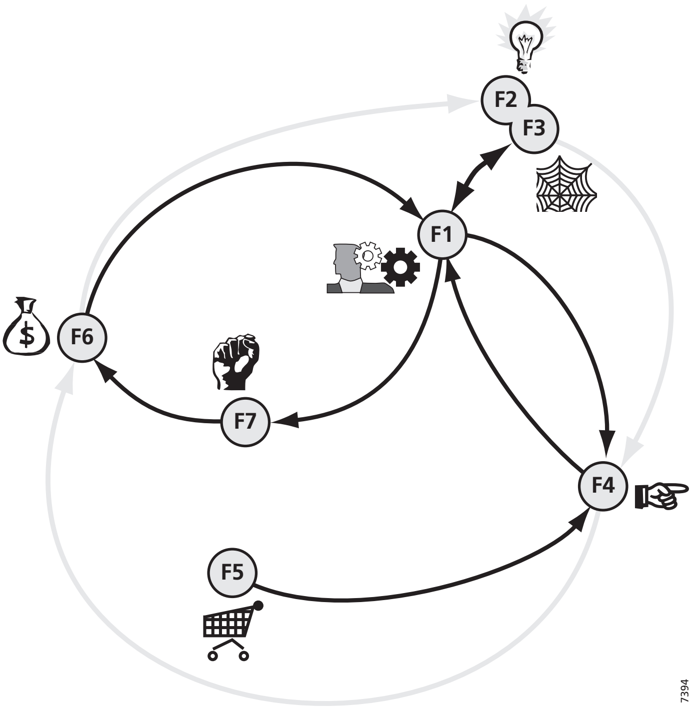

Figure 9.2 The Entrepreneurial Motor.

This sequence can be represented as a dual positive feedback loop. In Figure 9.2 these loops are indicated by bold arrows running; [F1] to [F7] to [F6] to [F1] and [F1] to [F4] to [F1]. The figure also makes clear that in some cases these dynamics are strengthened by the existence of niche market activities [F5]. These involve small markets, usually not developed within the TIS itself; instead they are more or less 'accidentally' present business opportunities, ready to be filled in by entrepreneurs. Since the size of these niches is not affected by the TIS, they are not considered part of a feedback loop, although they do contribute to the strength of *Guidance of the Search* [F4], and thereby, indirectly, to the *Entrepreneurial Motor*.

The periphery of the *Entrepreneurial Motor* is made up of connections that were already discussed as part of the *STP Motor*; hence these relations are represented in Figure 9.2 by non-bold arrows. However, an important difference is that in this motor *Entrepreneurial Activities* [F1] strongly interact with *Knowledge Development* [F2] and *Knowledge Diffusion* [F3]. This is because the feasibility studies and trials [F2] are now complemented by the learning-by-doing that takes place within the commercially oriented projects [F1]. This mutual relation constitutes a third feedback loop; [F1] to [F2, F3] to [F1]. Note that the *Entrepreneurial Motor* is related to the *STP Motor* in the sense that the interactions of the former remain largely intact and provide a basis for the latter to build upon.

Examples

The *Entrepreneurial Motor* was observed in the ANG and HyF cases and in both BF cases. In the biofuels case, it emerged in the 1990s when various small firms entered the field [F1] and started lobbying [F7] for subsidies [F6] to develop near-commercial 1G biofuels applications [F1], on the supply-side as well as on the demand-side. Examples are boating companies that were interested in the utilisation of clean technology, and an alcohol producer, Nedalco, that lobbied for a subsidy that would enable it to produce bioethanol for the automotive market. In some cases, lobbies were backed by local governments. Most projects were financially supported by the national government or by the EU, and some resulted in positive outcomes [F4], raising expectations among other firms that encouraged them to start similar projects [F1]. It should be noted, however, that in general, the outcomes were economically not feasible, largely as the result of a poor market environment [-F4]. Therefore, the motor did not really expand. The boating companies nevertheless have continued to use biofuels until today. Here the environmental regulations constituted a small niche market [F5] that made it attractive for entrepreneurs to continue, even when conditions worsened.[214] Important external factors were the EU and local environmental pressure.

In the Swedish BFTIS the *Entrepreneurial Motor* was also present but it grew much stronger because here the national government was willing to finance a variety of demonstration projects [F1, F6]. This development could be ascribed to the presence of organised networks, consisting of local governments and firms [F3] operating as advocacy coalitions [F7]. Where successful [F4], these demonstrations had a positive effect on the further development of the TIS, especially with respect to firms entering [F1].

In the HyF case, the *Entrepreneurial Motor* arose in the late 1990s when the NOB programme was drawn to an end. The promise of a freshly emerging PEMFC technology [F4] led many firms to take their chances and start up projects aimed towards commercialisation [F1]. At first these involved mainly spin-offs from the NOB era, but within a few years, a variety of new actors entered the TIS. These actors – consisting of technology developers (research institutes) as well as adopters (mainly energy utilities and local governments) – lobbied governments (usually the national government but also the EU) [F7] for financial support, often with success [F6]. If their projects had positive outcomes [F4], this fuelled enthusiasm within the TIS to develop even more projects [F1], and, more importantly, to convince new actors to jump on the bandwagon [F1]. The early adopters typically consisted of local governments and utility companies involved in public transport and energy production. These organisations were not subject to fierce market competition and operated, until recently, on a non-profit basis. They could therefore afford to invest part of their resources in experiments with high-risk technologies [F6]. Later, in the 1990s, when liberalisation policies took hold of the energy system, the dynamics were increasingly dominated by firms. As a result, the setting up of innovative projects [F1] became more dependent on lobbying activities [F7] and their outcomes in the form of government subsidies [F6]. At this time, developments also became dependent on the involvement of foreign car companies [F3]. Niche markets [F5] were also observed in the form of specific applications (forklifts, back-up

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[214] Niche dynamics were triggered by the introduction, in 1995, of stringent environmental standards designed to protect surface water quality. The biofuels came as a welcome alternative to diesel fuel since they were biodegradable.

systems and even space technology). These niches supported the promise of HyF technology [F4] but they have remained small and continued to depend on government financing [F7, F6]. Note that external factors – liberalisation, car industry linkages – have played an important role in shaping this motor.

The development of ANG technology started in the 1970s with the rise of a variety of procurement activities conducted by gas companies and public transport utilities [F1]. They set up adoption experiments because the utilities regarded ANG as a cheap alternative to conventional fuels [F4]. The utilities were supported with government resources [F6] and, as a result, throughout the 1980s, the number of ANG adopters increased [F1].[215] Their idea was that innovation would, in the end, prove worthwhile and result in an economically competitive and reliable alternative to conventional fuels [F4]. Despite negative techno-economic outcomes [-F4], the projects kept being financed. In the course of time, the energy sector became subject to liberalisation, turning the small gas companies, through mergers and take-overs, into larger, commercially oriented, energy production companies. Since firms became more risk-averse, the *Entrepreneurial Motor* weakened but it was kept alive through the nurturing effect of niche markets present [F5], especially for indoor vehicles.[216] Around 2005, the *Entrepreneurial Motor* accelerated again, first initiated by local governments under the pressure of air quality regulations [F5] and later backed up by commercial parties that lobbied for resources to develop extensive projects [F1, F7, F6].

Structural drivers and barriers

Based on these insights it can be stated that the *Entrepreneurial Motor* typically emerges where the following structural conditions are met:

- The presence of a relatively developed but still pre-commercial technology which is poorly aligned to present institutional structures.
- The promise of a commercial environment for this technology, as conceived by firms and/or utilities across the TIS, including a number of potential adopters, i.e. demand-side actors.
- (Local) governments and intermediaries willing to back the firms with project specific subsidies, typically because of pressing environmental issues and/or other external developments.
- Firms and utilities take the position of enactors, as this group takes the initiative of adopting and developing the technology further into practical applications.
- Governments and large firms act as selectors by building institutions and by serving as launching customers.

The political legitimacy means that firms and utilities are likely to get support from at least some selectors. The enactors may target *Guidance of the Search* [F4] and *Support from Advocacy Coalitions* [F7], thereby supporting the setting up of *Entrepreneurial Activities* [F1]. Selectors are then expected to contribute mostly to *Resource Mobilisation* [F6]. The role of local governments as selectors is especially important in situations where national government support is absent or weak, which was the case in all the examples. Often, local governments turned into enactors as

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[215] It is not clear if the utilities had to lobby for government support but it seems likely that there was some bargaining involved between the utilities and the government.

[216] Here the technology provided benefits in the form of relatively clean indoor applications, for instance, in glass manufacture. This provided a trigger for innovative adoption experiments.

their commitment to the emerging technology increased. In many cases, enactors were supported by selectors external to the TIS, for example by the EU and by car manufacturers.

The TISs in which an *Entrepreneurial Motor* emerges are characterised by the following structural weaknesses:

- Important selectors resist supporting the emerging technology. Often these include (parts of) the national government and especially incumbent firms. In the BF case, resistance also came from scientists and NGOs (environmental organisations).
- Selector support is often limited to temporary financing on a project-specific basis, while enactors typically require long-term support policies.
- The demand-side of the TIS is still weak. Despite the fact that demand-side enactors are becoming a main driver of the *Entrepreneurial Motor*, they lack support from crucial technology selectors that reside in the incumbent system.
- The lack of selector support, especially where governments are concerned, is for a large part caused by a weak organisation of the networks in which enactors operate. After all, in those cases where enactors managed to organise themselves in platforms and networks, they were more successful in drawing in national government and other selectors.

Impacts on TIS structure
The following structural impacts are typical for the *Entrepreneurial Motor*:

- The *Entrepreneurial Motor* starts out weak but as it is sustained, the motor expands, incorporating a growing number of enactors. This bandwagon effect generates the main structural impact of this motor: the build-up of a broad base of enactors, including local governments, supply-side and demand-side firms.
- Typically networks are formed, often by intermediary organisations. This is relevant as this supports the enactor group with a solid basis to drive further TIS dynamics. Still, coordination is often a problem; this was especially observed in the ANG case, where enactors deliberately developed a co-ordination strategy based on the strength of their network.
- A third impact of the *Entrepreneurial Motor* is that it reinforces the demand-side of the TIS, and especially its connection to the supply-side and the knowledge structure. Multiple cases show that as soon as demonstrations and adoption experiments prove that a technology works, more firms are willing to act as launching customers.
- A fourth impact is that strong improvements are made to the emerging technology due to learning-by-doing effects. This was observed in the ANG case and in the HyF case where technological progress – in terms of costs reductions and performance improvements – was an outcome of the experiments resulting from a strong *Entrepreneurial Motor*.
- A fifth impact is that the technology becomes more embedded in formal institutions, for example, licensing procedures, safety standards, quality standards.

9.3.3 The System Building Motor
The system functions that constitute the *System Building Motor* are *Entrepreneurial Activities* [F1], *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4], *Resource Mobilisation* [F6], *Support from Advocacy Coalitions* [F7] and *Market Formation* [F5]. This means

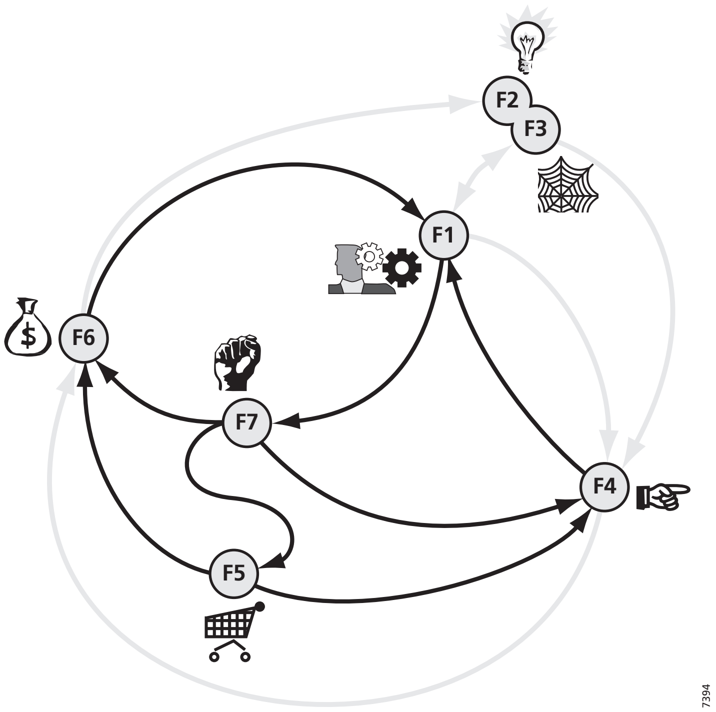

Figure 9.3 The System Building Motor.

that all seven system functions are involved in this motor. The important addition is *Market Formation* [F7], which was barely present in the *STP Motor*.

The event sequence associated with this motor starts with firms and other actors venturing into innovative projects, typically demonstrations, sometimes with successful outcomes [F1, F4]. As part of these ventures, they organise themselves in platforms with the aim of sharing knowledge but also to communicate and co-ordinate further technological development [F2, F3, F4]. Within the framework of these platforms, they also lobby for resources [F6, F7].

So far these relations are comparable to those of the *Entrepreneurial Motor*. The important difference lies in the connection between *Support from Advocacy Coalitions* [F7] on one hand, and *Market Formation* [F5] and *Guidance of the Search* [F4] on the other. These connections are established through entrepreneurs that increasingly organise themselves in networks. Through these structures they manage to draw in new enactors and selectors [F1, F3] – including local governments, intermediaries and interest groups – and to effectively lobby the government [F7], not for project-specific support, but for policies aimed to mobilise resources and to develop powerful institutions that support the TIS as a whole [F4, F6]. Most importantly, the aim of these networks is to enforce the creation of a mass market [F5] for the emerging technology. If the outcome of these system-building attempts, as they may be called, is successful, then this affects *Guidance of the Search* [F4] and *Resource Mobilisation* [F6], with as a subsequent effect that even more *Entrepreneurial Activities* [F1] will be developed by an increasing number of firms.

In Figure 9.3 the relations that are typical for this motor are represented by bold arrows running from [F1] to [F7] to [F4, F5, F6]. The feedback loop is closed by the connection from [F4, F6] back to [F1]. In addition, *Market Formation* [F5] reinforces [F4, F6] even more, thereby forming a second feedback loop that reinforces the first one. This second feedback loop is important as it underlines that markets are not already existing spaces to be filled in, but deliberately shaped environments that should be considered as the possible outcome of TIS dynamics.

The figure also shows that besides the core activities, the *System Building Motor* still involves a lot of the dynamics of the *Entrepreneurial Motor*. After all, *Entrepreneurial Activities* [F1] still connect to *Knowledge Development* [F2] and *Knowledge Diffusion* [F3], and if successful all these system functions will positively affect *Guidance of the Search* [F4], which will result in *Resource Mobilisation* [F6]. This is depicted in Figure 9.3 by the lighter arrows.

In terms of interactions, the *System Building Motor* overlaps with the *Entrepreneurial Motor*. In fact, the broad actor base that results from the *Entrepreneurial Motor* is probably a precondition for its emergence. The key difference with the *Entrepreneurial Motor* is that firms taking part in this motor are deliberately co-operating to strengthen *Guidance of the Search* [F4], *Support from Advocacy Coalitions* [F7], *Market Formation* [F5] and *Resource Mobilisation* [F6] in a co-ordinated way.[217] In the *Entrepreneurial Motor*, lobbies are usually aimed towards project-specific subsidies, whereas in the *System Building Motor* they are aimed to achieve policy measures that affect the expansion of the TIS as a whole.

Examples

The *System Building Motor* was observed in the ANG, HyF and BF cases. For the ANG case, the motor emerged, around 2002-2005, as a follow-up on the *Entrepreneurial Motor* that was already present. A key event was the setting up of NGV-Holland, a platform organisation promoting the diffusion of ANG technology. This platform was a network of technology developers and gas companies [F1, F3, F4]. Driven by a sense of business opportunity, related to a matured ANG technology, the platform developed a top-down approach to infrastructure building and *Market Formation* [F5, F6]. The strategy was to lobby the national government [F7] for generic policy support, and eventually *Market Formation*. This lobby was supported by regional governments as well. An important external influence was that air quality was becoming an urgent policy issue on this government level. As a result of these activities the TIS expanded, both geographically and in terms of actors and institutional structures. For the first time, private end-users became involved and the development of a refuelling infrastructure became a national issue, taken up by incumbent contractor firms [F1, F6]. Also, the issue of *Market Formation*, in the form of generic fuel tax exemptions, became part of a national political debate [F5, F7]. Where issued, these policies induced infrastructure investments [F6], and positive expectations [F4], thereby leading to a surge in new commercially oriented ANG businesses [F1] and a further strengthening of the platform organisation(s) and their lobbies.

In the HyF case the *System Building Motor* emerged around 2006-2007. Before 2006, the *Support from Advocacy Coalitions* [F7] was weak. But with the TIS becoming more dependent on EU

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[217] Van de Ven (1993) (p. 41) refers to this phenomenon when he states that: 'Entrepreneurial firms that run in packs will be more successful than those that go it alone to develop their innovations'.

policies and foreign car manufacturers, actors increasingly organised themselves in stakeholders platforms [F3, F4]. These platforms then started lobbying for technology-specific support policies [F7]. A key event was the transition platform, a public-private partnership, recommending the national government to develop a cluster approach to HyF development [F7]. This cluster approach involves support for infrastructure building and the setting up of large demonstration projects [F1, F6]. Another indication for a deliberate systemic strategy was the increasing involvement of incumbent actors, such as Shell, in public-private partnerships on the EU level [F1, F3], and contributing to *Support from Advocacy Coalitions* [F7]. Note that in this case, external factors have been especially important in shaping an emerging *System Building Motor*.

For the Dutch BF case, a somewhat similar dynamic unfolded in the same period, although in a weaker form. In fact, this example rather illustrates a failed attempt at system building. The external trigger was the upcoming EU directive, creating the promise of an emerging biofuels market [F4]. As a result, some firms, especially those involved in 1G biofuels [F1], started developing a regional production and refuelling infrastructure for biodiesel. A key example is the Solar Oil Systems (SOS) company, which developed projects aimed towards the production, distribution and utilisation of biodiesel [F1]. The SOS company managed to convince other firms [F4] to join projects in which, eventually, numerous small companies, financers, and governments were involved [F1, F6]. The result was the successful realisation of a production plant and other equipment [F2, F3]. To render these projects commercially feasible, the entrepreneurs, backed up by local government authorities, lobbied the national government for tax exemptions [F6, F7]. The integrated nature and the broad orientation of these activities fit the pattern described for the ANG case above but, still, in the biofuels case no real breakthrough was observed in the form of market creation policies until the EU government intervened. A main reason is that the strategy taken by the SOS company was not shared by other firms in the TIS [-F4]. Indeed many firms were not involved or, if they were, were merely interested in their own projects, and were even critical of other biofuel technologies. As a result the national government and incumbent companies did not put faith in the projects and refused to offer support.

A better example of a *System Building Motor* was observed in the Swedish BF case. Here, entrepreneurs organised themselves in public-private partnerships and farmers organisations [F1]. Their lobbying activities [F7] resulted as early as the 1990s in the setting up of a long-term policy support from the national government [F4]. This support included funding structures [F6], a variety of market creation schemes [F5]. In this case, even private end-users were involved. The policies also targeted the development and demonstration of 2G biofuels [F1, F2, F3]. The result was a rapid acceleration of biofuels activities across the nation, supporting the development of 1G and 2G biofuels projects [F1]. Local air quality issues have been the most important external factor for the legitimation of this development.

Structural drivers and barriers

The *System Building Motor* may arise as a follow-up to the *Entrepreneurial Motor*, when the structural conditions of the TIS are opening up, providing opportunities for actors within the TIS, and especially (also) for actors outside the TIS. These conditions include:

- The presence of a near-mature technology, typically beyond the stage of demonstration.
- The promise of a commercial environment for this technology, as conceived and communicated by enactors across the TIS, including supply-side and demand-side firms and usually (lower-level) governments.
- The enactors have by now organised themselves into strong networks with enough political momentum to take on firms and government structures (e.g., ministries not supportive of the emerging technology) that are entangled in the incumbent energy system.
- A variety of selectors is ready to invest in marketing and infrastructure.
- In some cases, end-users are becoming important, usually in a selector role.

The combination of these structural factors provides for a dynamic in which enactors manage to persuade selectors, mainly the national government and incumbent firms, to enter the TIS. In terms of dynamics, they provide a boost to *Entrepreneurial Activities* [F1], *Guidance of the Search* [F4], *Resource Mobilisation* [F6] and eventually *Market Formation* [F5]. In order to succeed, enactors need to group together in setting up coalitions, networks and political platforms. The critical success factor in realising, and sustaining, the *System Building Motor* is to develop a vision and a univocal 'political voice', thereby contributing to *Guidance of the Search* [F4] and especially to *Support from Advocacy Coalitions* [F7]. In the cases where the *System Building Motor* emerged, it was through political momentum that enactors managed to influence governments and (other) incumbent organisations, which then, through *Market Formation* [F5], created opportunities for enactors and selectors to become even more active. External factors have impacted the dynamics as well, especially by increasing the pressure on incumbent selectors to enter the TIS. For example, the EU government has played an important role in inducing the national government to support market creation for biofuels.

The TISs where the *System Building Motor* occurred were on the brink of developing substantial markets. Nevertheless, there remain weaknesses inherent to the structures involved:

- The mass application of the emerging technology involves the integration of the emerging TIS into the incumbent energy system in terms of applications and infrastructure. This process is likely to result in a number of unexpected practical problems, often leading to resistance by (potential) users.
- The maturity of a technology offers possibilities, most importantly the option of actually applying it in a market context. On the other hand, technological maturity suggests that the potential for further development is limited; this means that it is becoming more difficult to push the TIS forward by making promises of future improvement. This barrier has, for example, compromised the support for 1G biofuels and also the support for ANG technology in the Netherlands.
- The involvement of powerful selectors is critical at this stage. Often these can only be drawn in when external developments push in the right direction. In the case studies, typical external triggers were decisions by the EU or by foreign car manufacturers. This implies a weakness in the sense that the expansion of the *System Building Motor* is beyond the control of enactors that drive it, or on a more positive note, that stimulating the *System Building Motor* requires the competence to deal with exogenous developments in a constructive way.
- Another barrier is that the TIS which has so far been dominated by enactors, may now be 'captured' by selectors with an interest in maintaining the status quo of the incumbent system.

Impacts on TIS structure
The following structural impacts are typical for the *System Building Motor*:

- A main impact of the *System Building Motor* is that more selectors are drawn into the TIS. In most cases, this resulted in the national government becoming an integral part of the government structure of the TIS.
- The *System Building Motor* also attracts large incumbent firms. For the energy sector, these firms typically control important supply-side structures, such as refineries, but especially demand-side structures, such as firms with access to mass markets. The surge of incumbents also involves non-energy companies, such as building contractors.
- The enactors and selectors form strong networks that, stimulated by adequate regulation, induce the further development of the TIS.
- A related impact is the development of technological infrastructures. The *System Building Motor* typically transforms local and regional developments into national developments. This was observed in the ANG case. Obviously, these developments are matched by institutional arrangements, like the setting up of standards and licensing procedures.
- Another impact is the formation of a market for the emerging technology. This usually takes the form of specific amendments in tax legislation or mandates for the obligatory use of particular fuels. Through the setting up of these formal institutions, the emerging technology may be able to compete with conventional technologies. This is a very important step as it paves the way for the next motor to emerge.

9.3.4 The Market Motor
The *Market Motor* is characterised by a strong contribution to *Entrepreneurial Activities* [F1], *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4], *Resource Mobilisation* [F6] and *Market Formation* [F5]. All system functions are strongly fulfilled except for the *Support from Advocacy Coalitions* [F7], which is not as important for this motor. The main reason is that *Market Formation* [F5] is no longer an issue of politics; a market environment has been created as the result of formal regulations.[218] Instead, *Market Formation* [F5] is taken up as part of regular business activities, i.e., marketing and promotion strategies that are directly linked to *Entrepreneurial Activities* [F1].

The event sequence constituting the *Market Motor* starts with the setting up of institutional structures that directly facilitate a commercial demand for the emerging technology [F5]. Once such structures are firmly in place, this leads to high expectations [F4] and increasing availability of resources [F6]. This leads to the opening up of possibilities for new entrants to adopt the emerging technology [F1]. The newly entered firms are likely to make large investments, for example in infrastructure [F6], and they may also develop marketing strategies, thereby increasing demand for the emerging technology further [F5].

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[218] Note that it is hard to define *Market Formation* [F5] as an event within the dynamic of this motor; after all, it is considered as a set of institutional rules which are already put in place. Nevertheless, the impact of these rules on all system functions is so important that we consider it useful to 'count' them as events (with long duration) contributing to 'F5'.

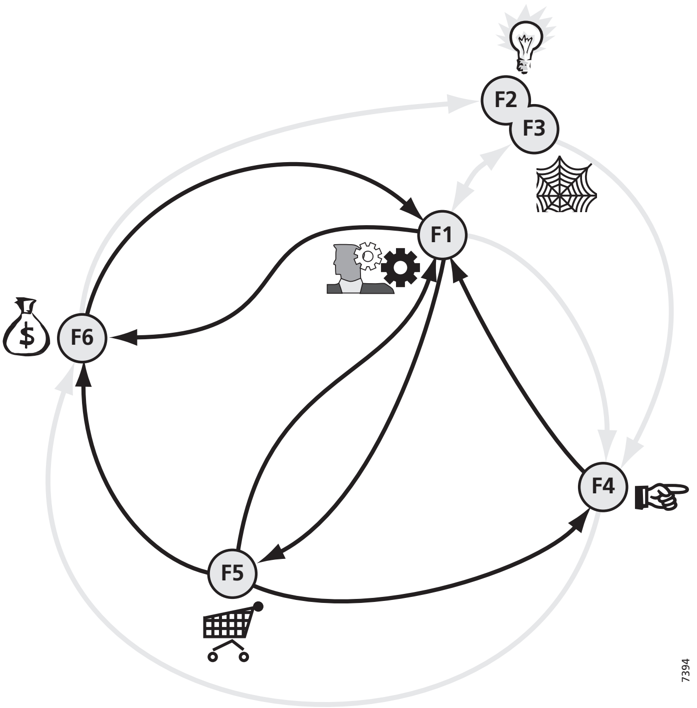


Figure 9.4 The Market Motor.

Note that the *Market Motor* drastically reduces the friction associated with the lobbying activities [F7] that are characteristic of the *Entrepreneurial Motor* and the *System Building Motor*. Figure 9.4 provides a graphical representation of the *Market Motor*. The bold arrows indicate the core relations that make its dynamics stand apart from the other motors. These are primarily the arrows connecting [F5] to [F1] to [F5, F6] to [F4, F6] to [F1]. The loop [F1] to [F6] to [F1] also provides a strong feedback. With the absence of the need for lobby activities [F7] a simple mutual relation between investments and opportunities conceived by firms (entrepreneurs but increasingly also banks, governments and other incumbents) has emerged.

The figure also shows that *Knowledge Development* [F2], *Knowledge Diffusion* [F3] and *Guidance of the Search* [F4] remain part of the dynamics. These system functions constitute important feedback loops that have already been explained as part of the other three motors.

Note that the *Market Motor*, as considered here, does not usually involve niche market dynamics. The fundamental idea of a *Market Motor* is that it expands and penetrates into the incumbent energy system. Obviously, niche market dynamics could in principle develop into a *Market Motor*, but the niche markets as identified in the case studies typically involved small application domains that were not likely to expand into the incumbent energy system.

Examples

The *Market Motor* was observed in the BF cases and in the ANG case. In all these cases this motor emerged only after a long and often troublesome trajectory, typically taking 20-30 years). For the Dutch BF case, the *Market Motor* was observed when the EU biofuels directive was translated into a national market creation policy [F5]. This took the form of a generic tax exemption in 2006, which was replaced by an obligatory blending scheme in 2007. The market environment that resulted meant a sudden boost to demand for biofuels, leading various firms, encouraged by high expectations [F4], to enter the TIS and start investing in the commercial production of 1G biofuels [F1, F6]. Where successful, this led to high expectations [F4] and more entries and investments of firms [F1, F6]. This especially concerned firms related to the oil industry that were involved in the import and distribution of biofuels from countries where production systems were more developed, such as Brazil or Germany. In this respect, it could be argued that the *Market Motor* did not induce developments within the Dutch BFTIS as much as could have been the case if the preceding *System Building Motor* had developed further. It should also be stressed that, even with market creation policies in place, the biofuels trajectory was still characterised by fundamental uncertainties because of the biofuels controversy; this hampered the *Market Motor*. In fact, it was still largely affected by *Support from Advocacy Coalitions*, positive as well as negative [F7, -F7].

In the Swedish BFTIS, the market creation policies were more sophisticated as they targeted not only the oil industry (as is the case with the scheme of obligatory use) but also (private) end-users, for example by establishing 'green' parking zones and by stimulating the use of flexi-fuel cars [F5]. The result was that a larger variety of actors, not just incumbent industries, could reap the benefits of an emerging biofuels market [F4]. This market perspective proved valuable for the deployment of commercial activities around 1G biofuels [F1, F6] but also for the support of R&D and demonstration of 2G biofuels [F1, F2, F3].

In the ANG case the *Market Motor* emerged by 2008 after the introduction of special tax conditions led to the creation of a market for NGVs [F5]. The tax incentives resulted in high expectations [F4] and new businesses entering the TIS [F1], making large investments in marketing and infrastructure [F5, F6]. An important effect was the increasing involvement of end-users and fleet owners in the TIS [F1, F5]. Due to the recent nature of the events, the actual outcome of this development cannot be assessed yet.

Structural drivers and barriers

The *Market Motor* typically arises when the following structural drivers are present:

- The technology is reliable enough to be diffused throughout the incumbent energy system.
- There exists a solid basis for a commercial market environment constituted by formal institutions, i.e., national government regulations have been aligned to the emerging technology.
- The enactor group involves a growing variety of (new) actors covering all TIS components.
- A large group of selectors is closely linked to the enactors and supportive of the emerging technology, including incumbent firms, the national government and often the first end-users.
- The internal momentum, i.e., the intensity of the internal dynamics, of the TIS has developed to such an extent that external resistance can be overcome.

If these structural conditions are in place, this provides a basis for enactors and supportive selectors to target all system functions, especially *Entrepreneurial Activities* [F1], *Guidance of the Search* [F4] and *Resource Mobilisation* [F6].

The following weaknesses were observed:

- The role of private end-users is often neglected, by governments and industries alike, when considering the diffusion of energy technology. This tends to hold back developments. This has been shown as part of the comparison between the Dutch and Swedish BFTISs. The ANG case also showed that the lack of user involvement hampered the development of technological infrastructures, and vice versa.
- The rapid diffusion of a radically new technology suddenly confronts many new actors with its potentially disruptive effects. Market diffusion tends to raise resistance among selectors that have previously been uninvolved. This was the case for the BF trajectory in the Netherlands where even today the controversy undermines the legitimacy of the technology, despite strong *Market Formation* policies.
- As a response to the diffusion into the incumbent energy system, actors within the incumbent energy system may attempt to encapsulate the emerging technology in order to control its disruptive potential. This was the case, for example, in the Dutch BFTIS where market creation policies were developed in such a way that oil companies could largely control the diffusion process. The result was that new entrants were excluded from this development and were unable to exploit this business opportunity.

Impacts on TIS structure

The following impacts may be expected:

- A first impact of the *Market Motor* is that, if markets are sufficiently established, they become part of economic routines, meaning that businesses' strategies are increasingly determined by pricing mechanisms.
- A second impact, related to this, is that TIS development is no longer dependent on the capricious outcomes of time-consuming lobbying and policy decisions.
- A third impact is the massive deployment of infrastructure and the inclusion of end-users.
- Finally, and most importantly, the *Market Motor* may be considered as the dynamic that forces a TIS out of its formative stage into a stage of widespread market expansion; see Chapter 2.

9.3.5 Motors of Decline

As was discussed in Chapter 2, motors of sustainable innovation are forms of cumulative causation (or virtuous cycles) that result in a build-up of system structures over time. However, cumulative causation may also result in a breakdown of structures, or a vicious cycle. Such vicious cycles may be termed motors of decline.

Note that motors of decline are not structural barriers that block motors of innovation; those are discussed above. Rather, they are event sequences that constitute an accelerated breakdown of TIS structures. Not many instances were observed that indicated such a breakdown of TIS structures. Also, for the instances in which they were observed, the event sequences were rather chaotic. For this reason no clear interaction patterns have been identified. The examples observed are nevertheless discussed below:

Examples

Motors of decline were observed in the BG case and in the ANG case. For the ANG case the breakdown started in the late 1980s. When the liberalisation of the energy sector started to put pressure on gas companies, these utilities, which had supported the development of ANG technology for years, stopped developing new projects or abandoned the use of ANG technology altogether [-F1]. This resulted in a spread of negative expectations [-F4], and since this affected potential ANG adopters it became increasingly difficult to obtain support for new experiments [-F1]. This subsequently led to a stagnation in *Knowledge Development* [F2] and *Knowledge Diffusion* [F3] as well. The result was that the diffusion of NGVs actually reversed over the course of time.

In the BG case the downward spiral was even more severe. Up to the late 1990s BG technology was considered an ideal solution to a set of problems [F4]. On top of this, it was communicated as a 'proven' technology [F4]. The problems arose when numerous demonstrations kept failing to fulfil these promises, thereby effectively reclassifying the technology as unreliable and immature [-F4]. On top of this, the national government introduced a new emission regime which turned out to be a barrier for BG installations (even if the technology would be working properly) [-F4]. Under pressure of ongoing liberalisation policies in the late 1990s, the TIS began to break down even further as discouraged energy companies [-F4] stopped venturing into BG projects altogether [-F1]. What this example shows is that if a cumulative build-up of promises and expectations is not backed up with results but, instead, followed by a series of interrelated disappointments, a motor of decline may emerge.

In the HyF case and the biofuels case, breakdown dynamics were also observed, for MCFC and for 1G biofuels technologies respectively. Interestingly, in these cases, the actors involved managed to adjust to worsening conditions by gradually shifting the course of the TIS in a new technological direction. For the MCFC trajectory, developments had been boosted by the *STP Motor*. However, the promised results did not materialise in the form of successful demonstrations. Instead, studies and demonstrations consistently showed that this technology could not compete in any market that was conceivable at the time [-F4]. For that reason, support was gradually shifted to other technological options which came with fresh technological promises. Strictly speaking this is not a motor of decline but a controlled (and partial) phase-out [-F1, -F4, -F6].

In the BF case, no motors of decline or phase-outs were observed. However, the case does suggest a powerful internal dynamic which has not been beneficial for the TIS. This relates to the controversy that emerged on the desirability of 1G biofuels. The development of the TIS was hampered by a continuous clash between opposing advocates of both technology options [F4, F7]/[-F4, -F7]. The advocates of 2G biofuels actually managed to make the national government exclude 1G biofuels from support [-F4, -F7]. It would be going too far to label this dynamic as a motor of decline. After all, the TIS did not collapse, and 1G biofuels did not collapse either. And, in fact, the biofuels controversy has recently contributed to the build-up of important structures that should guarantee the sustainability of 1G biofuels. Perhaps this dynamic may be regarded as a dialectic motor, in the vein of Poole et al. (2000) and Van de Ven et al. (1999). The outcome of the dialectic motor is determined by a clash of opposites. This clash either results in the breakdown of one opposite, or in the emergence of a system with new features in which the opposites are somehow combined. In fact, an argument can be made for supporting a combination of 1G and 2G biofuels as part of one TIS. After all, 2G biofuel technologies may benefit from the TIS structures – including a policy environment, the presence of supportive selectors, and powerful prospective visions – that would develop as the result of a successful diffusion of 1G biofuel technologies.

Structural drivers and barriers

Like motors of innovation, the dynamics of decline are associated with structural drivers and barriers. In the observed cases the structural conditions that typically led to a collapse included:

- The presence of overstretched expectations, usually built up by a group of enactors.
- The enactors are supported by a small and not very diverse base of selectors.
- The range of technologies involved and the range of institutions supporting the emerging technology is narrow.
- There is increasing distrust among selectors as the result of disappointing outcomes.
- Selectors are subject to a shifting institutional environment leading them to reject the technology in favour of other priorities. This happened in the ANG case, where liberalisation policies induced a series of mergers that changed the selectors' cognitive rules, such that innovative experiments went out of favour.

These conditions provide an ideal breeding ground for a system breakdown. It usually takes a number of triggering events to shock the TIS into a downwards spiral. An example would be the failure of a large demonstration project contributing to negative expectations. If *Guidance of the Search* [-F4] and *Entrepreneurial Activities* [-F1] are sufficiently affected, a collapse may result.

In terms of barriers, it may be useful to think of structures that buffer the mechanism of a collapsing TIS. The following buffering conditions may apply:

- Motors of decline typically emerge where TIS structures are narrow. If a TIS has a broader structural basis, including various enactors, selectors and technologies, it will be more capable of adjusting to external shocks. This was observed in the Dutch BF case and in the HF case where a system collapse was prevented due to internal reorientations towards a different set of technologies and a different set of selectors.
- Another buffer may be the presence of market niches. The case studies show that where TISs were in decline, market niches typically survived the downturn and provided important support to TIS build-up once the collapse had stopped.

Impacts on TIS structure

The following impacts may be expected from a motor of decline:

- The impact of a motor of decline on TIS structures is clearly the deterioration of the TIS in all kinds of ways. This affects especially the involvement of selectors but also of technologies, infrastructure and important institutions. With respect to the latter, it should be stressed that a most crucial impact is the breakdown of the prospective structure that has been developed by

enactors. After all, as technological promises are broken, the set of cognitive rules is bound to change. This is not something that can be changed easily as it is based on trust.
- What remains is a small group of enactors willing to sustain activities at all cost. Often the enactors serve to consolidate the knowledge base of the TIS.
- Often a small number of niche markets is present, these may provide a basis for the development of new projects when better conditions arise. This has happened in the ANG case and to some extent in the Dutch biofuels case.

9.3.6 Combinations of Motors

The possibility exists that more than one motor arises within a single TIS. This may happen when a TIS involves the simultaneous development of multiple (sub-) technologies with very different structural characteristics. This was observed in the Dutch and Swedish BF cases where different motors emerged around 1G and 2G biofuels respectively. The 1G biofuels trajectory was driven by a *Market Motor* at the time when the 2G biofuels trajectory was driven by an *Entrepreneurial Motor*. Based on the insights derived from these case studies it can be said that motors may collide but that they may also complement each other. The following empirical observations support this claim:

- The *STP Motor* that drives a 2G technology may be reinforced if an *Entrepreneurial Motor* or a *Market Motor* around a 1G technology develops positive spin-offs in the form of TIS structures beneficial to both technologies. This happened when 1G biofuels were framed as a stepping-stone technology by actors in the Swedish BFTIS. Also, the promise of a market for 1G biofuels was beneficial to 2G biofuels as well, since this reduced uncertainties among potential selectors.
- Vice versa, the *Entrepreneurial Motor* and the *System Building Motor* may benefit from the legitimation provided by the idea that a future 2G technology may improve the technological performance of 1G technologies.

In the other cases the different motors of innovation all developed sequentially. In the HyF case multiple technologies were developing but the dynamics could nevertheless be understood as part of a single 'unified' development.

9.4 A Succession Model of Innovation

Four motors of sustainable innovation have been singled out. All have been related to structural factors, both in terms of structural drivers and barriers; and in terms of impacts on structure (a summary is provided in Chapter 10). In this section, an attempt will be made to integrate these results into an overarching perspective on the dynamics of TIS build-up. This perspective is based on the idea that the four motors identified are related to each other in the sense that one motor is likely to build upon another. In this section this argument is developed by proposing a 'model of innovation' which offers insights into the nature of the build-up processes that characterise the formative stage of a sustainable energy TIS.

During the identification of each motor it was pointed out that some of the motors followed each other. In general, it turns out that the immature TISs are less prone to develop anything other than an *STP Motor*. Only when a TIS was developed enough to generate opportunities for firms did the *Entrepreneurial Motor* emerge. A *System Building Motor* was observed as being a transformation of

Table 9.2 Motors of sustainable innovation.

Time period:	1970	1975	1980	1985	1990	1995	2000	2005	2008
BG			STP	STP	STP	STP/E	E	D	D
Biofuels 1G Netherlands					E	E	0/E	E	M
Biofuels 2G Netherlands					0	STP	STP/E	E	E
Biofuels 1G Sweden			E	E	SB	SB	SB	M	M
Biofuels 2G Sweden			0	0	STP	E/STP	E/STP	SB	SB
HyF	D	D	STP	STP	STP	STP	E	E	SB
ANG	E	E	E	D	D	E	SB	SB	M

STP: Science & Technology Push motor, E: Entrepreneurial Motor, SB: System Building Motor, M: Market Motor, D: Decline, 0: Dynamics are weak or absent.

the *Entrepreneurial Motor*. And finally, the *Market Motor* was typically developed from structures shaped by a *System Building Motor*.

In general, there was a relation between the motors observed and the maturity of the TIS in terms of actors involved and in terms of technology and institutions. A systematic overview of the sequence is presented in Table 9.2. The case studies did not reveal a single example of this order being reversed. Even after periods of standstill or decline, TIS dynamics continued to unfold following the motor which was last active. Important exceptions to this were TISs where new technological options were emerging within the system, for example in the case of 2G biofuels, where the *STP Motor*, based on 2G technologies, replaced an *Entrepreneurial Motor* based on 1G technologies.

At first sight, the idea of motors unfolding according to a fixed sequence seems a discomforting confirmation of the famous linear model of innovation. Therefore, it should be stressed that the idea of a staged development is not synonymous with a linear development. For one thing, the mechanisms underlying each motor, even the *STP Motor*, is clearly non-linear, involving a variety of system functions that are connected through multiple feedback loops. The non-linear nature of TIS dynamics is also reflected in the outcomes, in the sense that TISs do not *necessarily* move through these stages. A TIS may very well collapse and not develop any further.

The idea of a progressive sequence of motors is in line with the concept of cumulative causation, which is based on the principle that a change to a system will call forth supporting changes, which move the system even further in the direction of the first change (Myrdal, 1957). As the fulfilment of system functions leads, via lasting impacts on TIS structures, to the increased intensity of system functions, so, on a higher level, motors of innovation cause TISs to develop into more complete (and more complex) structural configurations which are prone to yield more advanced motors of innovation in turn. In other words, in a TIS with *Motor A*, a more developed *Motor B* may emerge but only if *Motor A* establishes sufficient structural changes that pave the way for the transformation of *Motor A* into *Motor B*.

However, motors of innovation do not automatically emerge. It was observed that the rise of each motor was mirrored by conscious efforts, typically by groups of enactors supported by selectors. These actors had to continuously maintain and develop a variety of TIS structures in order to sustain the motor. At each point in the cycle of a motor, actors have the possibility to deviate from it. In fact, the enactors and selectors will have to deviate from the cycle if it is eventually to transform into something else.

The existence of a motor does make for a positive force that supports the further build-up of a TIS by enactors, selectors and other structural drivers. But this does not guarantee that a TIS will expand indefinitely. It was shown that each motor is also associated with 'built-in' barriers that reside in the TIS structures. Also, structural drivers and barriers are subject to external influences which are impossible to predict. In this way the dynamics of motors depend for a large part on luck and opportunity. However, when structural barriers are sufficiently outweighed by structural drivers, a motor of innovation will be sustained and is likely to expand. Given that the right structural conditions emerge, a motor may transform into another motor, one that is more encompassing in terms of underlying system functions.

This follow-up is crucial since, with each successive step, a TIS overcomes structural barriers that are inherent to its current dynamics. Only when a *Market Motor* arises can a TIS be considered as mature and therefore devoid of inherent barriers associated with the formative stage.

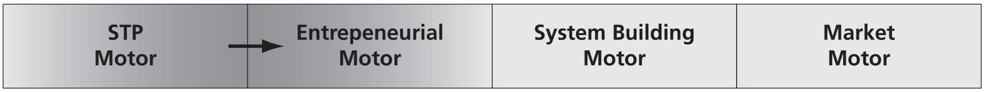
9.5 Implications for practitioners

The Succession Model of Innovation provides a heuristic basis for the evaluation of TIS dynamics that characterise the formative stage. In this section evaluative insights of the model will be presented and strategic lessons will be drawn from them. Examples from the various case studies are provided in order to indicate successful strategies.

The evaluative insights are based on understanding the dynamics of different motors of innovation. The evaluative insights will be connected to the different steps of the Succession Model, based on the idea that motors of innovation should be supported in order to develop and expand. Particular attention is given to the structural conditions required for a shift from one motor to the other.

The section is organised according to three 'succession steps'; the shift from the *STP Motor* to the *Entrepreneurial Motor*, the shift from the *Entrepreneurial Motor* to the *System Building Motor* and the shift from the *System Building Motor* to the *Market Motor*. The strategic lessons are tailored separately for enactors (typically entrepreneurs, technology developers, research institutes, NGOs) and selectors (typically policy makers, technology end-users, large firms).

9.5.1 Sustaining and transforming the STP Motor



The prime barrier of the *STP Motor* is poor technological performance and severe uncertainties with respect to the emerging technology's future development. The prime driver is a small and dedicated group of enactors, typically research institutes and technology developers willing to support this technology. At this point the following strategic issues are of relevance:

Promising technology

The *STP Motor* is driven by a technological promise communicated by enactors. In order to feed its dynamics, it is important that this promise is kept alive. Case studies show that this can be done by conducting successful research and communicating the positive results to selectors, particularly governments and potential technology adopters. It can also be effective to strengthen the promise by referring to external developments, for example by relating the emerging technology to urgent policy issues, such as environmental, economical and/or social problems. If enactors manage to keep up the flow of promises, the *STP Motor* tends to expand. The resulting advice is:

- *Enactors (particularly research institutes and technology developers) should develop a strategy for the management of expectations. By making promises, they reduce uncertainty in the TIS, thereby strengthening the prospective structures of the TIS.*

The *STP Motor* can only be sustained when a powerful selector chooses to stand behind the promises of enactors. At this stage, the most likely actor to take this role is a government. If enactors succeed in drawing in the national government, they typically gain access to financial and institutional support. The *STP Motor* tends to expand if this selector shapes formal institutions to support the emerging technology. This is a powerful way of further reducing uncertainty. The resulting advice is:

- *Selectors should establish formal structures to back up the promises of enactors. This can be done by setting up government R&D programmes.*

A good example is the way that enactors within the HyF TIS managed to start up the *STP Motor* and keep it running by pointing out how technological breakthroughs abroad would lead to the country lagging behind in terms of innovation and economic development. Policy makers bought into this promise and established the NOB support programme which was kept in place to sustain an *STP Motor* for 18 years.

Demonstrating technology

The *STP Motor* tends to become stuck in the production of feasibility studies and laboratory trials. The expansion of the motor demands more tangible outcomes than that. This may be realised through the setting up of pilots and demonstration projects in cooperation with launching customers. Such demonstrations serve as a collective reality check, which serves to reduce uncertainty. The resulting advice is:

- *Enactors should focus on developing tangible outcomes which support their original promises and make selectors believe in the future of the emerging technology.*

There is catch to this, as companies typically do not easily occupy the role of technology adopters before the technology has been proven, especially not when there are large investments involved. In this situation, usually governments or utilities have to support the first projects. The resulting advice is:

- *Selectors (in this case particularly governments or utilities) should support, or even execute, pilots and demonstration projects and, in the process, draw in other selectors, particularly launching customers.*

The case studies indicate that this is a particularly difficult step which requires effort, patience and luck. Often, demonstrations did not get off the ground as a result of the disappointing outcomes of feasibility studies. However, if successful, technology demonstrations have drawn in a multitude of enactors and selectors, thereby starting an *Entrepreneurial Motor*, for example in the HyF and BG case. In the latter case, energy utilities connected to the incumbent TIS played an important role as selectors.

Creating variety

Demonstration projects often fail to produce positive outcomes. There are often unexpected technological problems. Also, since demonstrations typically take a few years to develop, meanwhile the (prospected) market typically changes as the result of external (technological or institutional) developments. Despite the fact that these results can be considered a positive learning experience, there is a risk that the negative results start to undermine the promises that drive the *STP Motor*. In order to avoid this, it is important that enactors and selectors develop a flexible approach to supporting the *STP Motor*. They can do this by supporting a multitude of demonstrations which involve a variety of technological options. Such a portfolio strategy requires a lot of investment but, in the face of fundamental uncertainty, it is necessary to take such an approach. The resulting advice is:

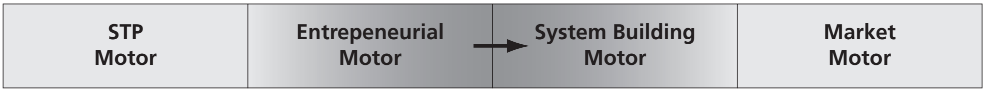
- *Enactors and selectors should make sure that they support a variety of demonstration projects involving multiple technologies and multiple enactors, i.e., they should spread resources across options and follow a port-folio strategy.*

Since selectors have access to more resources, they should have fewer problems with this. Enactors may adopt this approach as well, for example by cooperating with each other and by pooling resources. The national government may facilitate this by setting up insurance models through which the failure of one project is covered by the successes of another.

- *Selectors should cover at least some of the financial risks of enactors venturing into innovative projects. Thereby they make sure that risk-taking is no longer perceived as an extreme hazard but as an opportunity.*

The portfolio strategy increases the overall chances of successful outcomes. Moreover, this strategy makes it possible to learn from mistakes. If demonstrations are successful, for instance, if they back up promises with hard facts, this provides a boost to the *STP Motor* and may even result in a shift to the *Entrepreneurial Motor*. A positive example was observed in the HyF case where ECN supported numerous demonstration projects, all involving a different set of enactors, within the NOB programme. Despite the disappointing outcomes of the MCFC demonstrations, numerous other technologies were being developed that provided a source of continuity for the *STP Motor*.

9.5.2 Sustaining and transforming the Entrepreneurial Motor



Consider a TIS that has developed to such an extent that an *Entrepreneurial Motor* is emerging. The *Entrepreneurial Motor* arose because an enactor group – consisting of research institutes, technology developers and technology adopters – saw opportunities to develop commercial applications for the emerging technology. These enactors draw on the knowledge-base established earlier, possibly through an *STP Motor*. Also, the first linkages have been established between supply-side and demand-side enactors. In this respect, important weaknesses associated with the *STP Motor* have been overcome. However, with a new motor comes a new set of built-in weaknesses. At this point the following strategic issues are of relevance:

Societal needs

The main driver of the *Entrepreneurial Motor* is the availability of a relatively mature technology and a group of enactors willing to support the emerging technology. To sustain the motor, this group is to expand. It typically does this by further increasing the number of practical and commercially oriented projects. In the more developed TISs these projects are adoption experiments which contribute to the fulfilment of an actual societal need. The resulting advice is:

- *Enactors (particularly entrepreneurs, technology developers and technology adopters) should attempt to identify societal needs and develop practice-oriented projects connected to this need.*

To achieve this, enactors need to draw in selector support. In the more successful TISs the enactors manage to do this by lobbying for resources. The argument may be that the emerging technology contributes to a sustainable energy system but more creative legitimation strategies are often powerful ways to convince selectors. The lobby may be directed at the national government but another route is to mobilise support from local governments and utility companies. This works especially well when sustainability issues affect the societal responsibility of these selectors. In that sense, they are often the end-users of the energy technology. The lobby may also be directed at firms but at this stage this is often not effective without some form of support from government actors, due to technological unreliability and uncertain returns on investment.

- *Enactors (especially entrepreneurs, technology developers and technology adopters) should lobby for support from selectors, especially from the national government. Enactors which enjoy no support, or even resistance, from the national government may find it effective to draw in local governments (regions, provinces) or utility companies (public transport, energy producers).*

If the enactors are able to demonstrate that the emerging technology holds a promising solution to a problem, then successful projects will draw in more firms and eventually, the activities of all firms combined will result in the further development of the technology through learning-by-doing. For the *Entrepreneurial Motor* to develop, it is important that, besides removing technological bottlenecks, a policy environment is shaped that settles practical issues related to basic infrastructure, licensing procedures, safety standards and the like. After all, the performance of a technology depends on the institutions that surround it. The alignment of the policy environment to the emerging technology further reduces uncertainty in the field. The latter issue is very important where government selectors are concerned.

- *Selectors (especially governments) should shape a policy environment which provides continuous and reliable support for enactors.*

A positive example of these strategies was observed in the ANG case, where a powerful *Entrepreneurial Motor* emerged when a variety of enactors managed to draw local governments, energy companies and car dealers into the TIS. An interesting feature of this case was that, after some time, actors that started out as selectors started behaving like enactors. Conversely, in the BG case, the *Entrepreneurial Motor* was stopped after a while because, despite numerous attempts, the emerging technology did not result in useful applications. Eventually, the institutional environment was actually changed to select against BG technology.

Coordination and advocacy

Given that the TIS is only just emerging, it suffers from a lack of coordination and direction. In an early stage this usually is not a problem but as the field expands it becomes critical to establish networks. To sustain the *Entrepreneurial Motor*, enactors should link up with each other and establish network structures in the form of knowledge platforms, policy networks, branch organisations, public-private partnerships etc. This way, the enactors will be able to co-operate more. Intermediaries – including public agencies but also NGOs – can play an important role in managing cooperation. The resulting advice is:

- *Enactors (particularly technology developers and adopters) should develop networks in order to coordinate the direction of technology development.*

From the perspective of selectors it makes sense to play a role in the formation of these intermediaries as they are important platforms for giving direction to the field, for example by setting R&D agendas. Because they typically relate to multiple enactors, selectors may also play an important role as conflict managers.

- *Selectors (particularly national governments but also incumbent industries) should consider that, by entering the TIS and taking on the role of an intermediary, they take an opportunity to shape TIS development. They have the power to coordinate and to manage conflicts.*

Besides providing a structural basis for coordinating the activities of enactors, networks should also be considered as crucial organisations for articulating a political voice. This relates to the still weak link between the enactor group and potential selectors that are not yet part of the TIS, and resisting its development. If enactors also organise themselves in a political sense, they speak with one voice towards selectors.

- *Enactors (particularly technology developers and technology adopters) should develop networks that may facilitate their lobbying for institutional support from governments and/or other selectors.*

A bad example was provided in the BF case where various enactors and selectors sent out opposing signals to the national government. The government's attitude towards the enactors varied between ignoring them altogether, and giving them what they want. This ad hoc support has not been very effective as it did little to reduce the uncertainty in the field. A remarkable feature of the BF case was that potential intermediaries, environmental organisations, either took the role of enactors or as selectors resisting the TIS. A good example was observed in the ANG case, where enactors united to speak with one voice to the government, and the government in turn developed specific support programmes. Due to the concerted action of associations and advocacy coalitions, the *Entrepreneurial Motor* could expand.

Niche markets

A severe structural barrier that hampers the *Entrepreneurial Motor* is the lack of a market environment, or rather the lack of any market perspective in the near future. To some extent niche markets may play an important role to overcome this. After all, niche markets provide the opportunity to prove that the emerging technology actually works. Moreover, niche markets offer a structural basis for improving the technology and its embedding in society. In the more developed TISs, end-users may also be involved. In short, niche markets provide a stable and relatively cheap basis for practical experimentation. The resulting advice is:

- *Enactors and selectors should identify niche markets and exploit them as much as possible.*

On a more critical note it should be stressed that niche markets do not typically expand. They do provide for a fruitful learning environment but they are usually too small to allow for large cost reductions as the result of scale economies. From the perspective of a selector, the ideal situation would be that niche markets gradually expand as the costs of the emerging technology are reduced and other, larger, niche markets are reached. No doubt, this is possible but it should be considered a chance process and not something on which to base a strategy. The resulting advice is:

- *Selectors consider niche markets as opportunities for demonstration; they should not be conceived as the basis of a deliberate strategy to scale up the TIS.*

Interestingly, though, niche markets have proven to be a source of continuity for the *Entrepreneurial Motor*, as they typically survive long periods of decline by preserving a basic level of activities. This is important since it may provide a kick-start to the build-up process that emerges when the TIS starts to expand again. The resulting advice is:

- *Enactors and selectors may consider niche markets as a hedge that provides resilience and continuity when a TIS is subjected to a lengthened breakdown.*

The best examples of a positive effect from niche markets are from the BF and ANG cases. In the BF case, enactors kept using biodiesel in boats even when the TIS was largely excluding 1G biofuels from support. The adoption experiments were an important source of inspiration for the start-up of 1G activities across the country, even years later. In the ANG case, niche applications, like refuse lorries and forklifts, have been important sources of positive expectations as well. Moreover, they survived the dramatic liberalisation breakdown in the 1990s. In none of the cases did market niches expand to substitute parts of the incumbent energy sector. Moreover, in all of the cases, such market niches were still dependent on government subsidies.

9.5.3 Sustaining and transforming the System Building Motor

Given that the structural barriers of the *Entrepreneurial Motor* are overcome, a *System Building Motor* may emerge. This *System Building Motor* is especially driven by a concerted involvement of enactors and selectors. The selectors typically involve a number of incumbent firms and sometimes the national government. This development is cumulative in the sense that it is based on progress in the emerging technology and the build-up of technological and institutional structures that are (usually) the product of other motors. With these conditions in place, the main goal should now become to sustain the *System Building Motor* in order to make it expand and eventually to shift to a *Market Motor*. A new set of strategic issues becomes relevant:

Politics of market formation

To sustain the dynamics of the *System Building Motor*, enactors and supporting selectors should flock together and draw in even more selectors. This implies the expansion of existing networks into the incumbent system. This expansion is necessary because the further development of the emerging technology asks for up-scaling, which means that large investments are required. The lobby should aim for the adjustment or creation of institutions that massively induce TIS developments, especially by creating a market.

- *Enactors and supportive selectors should flock together and form political coalitions with the aim to draw in support from passive or even resistant selectors. They should aim for support policies that provide for a general and long-term stimulation of a market for the emerging technology.*

Whether the *System Building Motor* develops further is the outcome of a negotiation process, typically on the level of national politics. This process may be influenced by enactors and supporting selectors by increasing the visibility of the technology. In the ideal situation they are able to ground political claims on positive performance figures as realised by actual applications of the emerging technology. In this situation the involvement of end-users is an important quality for a TIS. The more that promises are backed up by 'real outcomes', the easier it is to draw in the selectors and to force them to shape formal institutions necessary for a market to emerge.

- *Enactors and selectors should increase the visibility of an emerging technology. This may be done by stimulating technology adoption among a limited group of private end-users.*

A good example is provincial governments enforcing the application of natural gas or biofuels in public transport concessions. Another possibility is to issue more localised policies such as lease contracts for NGVs and 'green' parking zones as was observed in the ANG case and in the Swedish BF case.

Imagining utopia

For the *System Building Motor* to develop, the technology should be mature in terms of reliability, safety and other basic performance characteristics. If not, the increased visibility of the technology may very well backfire on itself. However, paradoxical as it may seem, the increased performance of an emerging technology typically results in major drawbacks, since actors will be confronted with the inevitable downsides to its use. To sustain the *System Building Motor* it is crucial that these signals are taken seriously; not as resistance to be broken but as outcomes of a learning-by-using process in which end-users have a chance to improve the emerging technology.

- *Enactors and selectors should be aware that emerging technologies, even if they are reliable and offer benefits, will always have downsides. The downsides should be taken as a starting point for further technological and institutional improvements, and not be ignored or downplayed.*

Enactors typically go out of their way to develop a utopian imagery that works as a powerful prospective structure. As long as the technology is situated in laboratories, testing grounds and market niches, this works well to draw in enactors and selectors, as long as promises are occasionally backed up by successful outcomes in the form of more prototypes and larger demonstrations. The unavoidable downsides to a technology can then be considered as accidental features to be overcome through further improvements. However, if an emerging technology is on the brink of mass diffusion, it loses its ethereal quality; downsides are then increasingly conceived as real and essential to that technology. Selectors, even formally passive ones, will organise themselves and point to these downsides, thereby constructing dystopian prospective structures. In reality, neither the utopian nor the dystopian view should be fully embraced. The dystopian view is typically premature as, after all, the emerging technology is still (relatively) maladapted to the incumbent system and may improve as the incumbent system is adjusted. The utopian view is misleading as well, simply because there are no perfect solutions to the complex sustainability problems that society is currently facing.

- *Enactors and selectors should avoid developing or adopting the utopian-dystopian imagery. Such views may drive a TIS but they tend to backfire as soon as selectors realise that they are based on nothing but dreams (or nightmares).*

A good example of utopian imagery gone wrong can be found in the BF case, where enactors had promoted 1G biofuels for a long time without taking seriously the downsides in terms of land-use and CO_2 reduction. This utopian view on biofuels could easily be criticised by opponents, in this case mostly environmental organisations. The result was a flight forward in the direction of 2G biofuels, of which the outcome was still uncertain, and a troublesome development for 1G biofuels. The tragedy is that the efforts of these organisations would be better spent on battling the expansion of carbon-based energy technologies.

Lock-in

There is a risk that choices made by the expanding group of enactors and selectors leads to the untimely entrenchment of the TIS. After all, as developments are increasingly embedded in formal institutional structures, it becomes difficult to respond to shifting external circumstances. Even if the technology turns out to be unsustainable or undesirable, the TIS may keep developing. This risk of early lock-in should be taken seriously but it should be considered relative to the risk of continuing to proceed with investing in the incumbent TIS. Moreover, the idea of an early lock-in points to a notion of optimality that resonates with the utopian-dystopian imagery sketched above. The vision of a sustainable energy technology is a powerful one but also a dangerously utopian one, which may easily backfire on real technologies that can make a difference. After all, for every real technology, one can always think of a better alternative that is still on the drawing board. This issue is especially relevant for selectors. The resulting advice is:

- *Selectors should be aware of the fact that the best can be the enemy of the good. In their evaluations they should benchmark emerging technologies not to each other but to fossil energy technologies (and even then they should take into account hidden costs and benefits).*

The inducement of changes to the incumbent energy system requires that new technologies are actually diffused and implemented instead of just being developed in R&D labs. It is important to be aware of the fact that, as part of the *System Building Motor*, the TIS is becoming highly dependent on decisions taken by selectors that are involved in the incumbent TIS. This includes firms, like energy producers and oil companies, but also the national government, including all its ministries, becoming an integral part of the TIS. The succession to the *Market Motor* depends on negotiations with these actors, and these will include a multitude of interests, which are certainly not just related to sustainable energy. At this stage, the more successful TISs are actually those that have managed to establish some degree of lock-in. The challenge of negotiation is then to frame the emerging technology, not as being either optimal or suboptimal, but as a solution to a currently pressing political problem.

- *Enactors and selectors should organise themselves into advocacy coalitions in order to influence the political process by framing the emerging technology as part of a solution to an actual societal problem.*

A good example is the ANG case where, because of pressing problems related to local air quality, a market was created through policy support. Despite important deficiencies in the mass implementation of natural gas in the energy system – after all, it is a fossil fuel – supporters of ANG technology focused political attention on short-term issues. Moreover, they argued that ANG should be considered as a bridging technology. A similar development was observed in the BF case, especially in Sweden, where 1G biofuels were increasingly presented as a bridging technology to be considered as a first step towards the utilisation, later, of 2G biofuels.

9.5.4 Towards a take-off

It should have become clear by now that it takes a lot of time and effort to enhance the structure of the TIS sufficiently for a *Market Motor* to emerge. Once a *Market Motor* is established, the TIS may be considered to leave the formative stage.

Based on the case studies presented in this book, it is not possible to provide any well-founded advice on how the *Market Motor* should be sustained but it is expected that this requires little more than keeping the institutions built up in place, be it that support schemes should be adjusted to important new insights and phased out if the technology matures and requires no specific support.

10 Conclusion, discussion and reflection

This chapter begins, in Section 10.1, with a short reiteration of the answers to the three main research questions. Section 10.2 provides a theoretical discussion of these results. Section 10.3 contains a reflection on the internal and external validity of the results. In Section 10.4, recommendations are given for further research. The chapter concludes in Section 10.5 with a recapitulation and an outlook.

10.1 Main results

The idea followed throughout this book is that sustainable energy technologies develop within the context of systems made up by networks of actors, institutions and (related) technologies. These Technological Innovation Systems (TISs) do not come into existence overnight but are the result of a build-up process. If sustainable energy technologies are to be diffused into society, multiple TISs need to develop and expand into the incumbent energy system. This book has provided theoretical insights that support a better understanding of this build-up process.

In the first three chapters of this book a theoretical and methodological framework was introduced which conceptualised TIS development in terms of seven system functions. These involve *Entrepreneurial Activities* [F1], *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4], *Market Formation* [F5], *Resource Mobilisation* [F6] and *Support from Advocacy Coalitions* [F7] (Hekkert et al., 2007; Negro, 2007). The system functions are types of activities necessary for a TIS to develop. They may also be considered as criteria to be used for evaluating the performance of a TIS in the formative stage. This is important since, in the formative stage of technology development, available data for output measures, such as market diffusion, environmental or techno-economic features, are usually absent or invalid. The *Functions of Innovation Systems Approach* made it possible to analyse and evaluate the development of TISs in dynamic terms.

The concept of cumulative causation was adopted as a basis for understanding how the build-up of a TIS may undergo an acceleration as the result of positive feedback loops, i.e., virtuous cycles (Jacobsson and Bergek, 2004). The main contribution of this study was to identify forms of cumulative causation, or motors of sustainable innovation as they have been called, in order to contribute to the theoretical understanding of TIS development in the formative stage. With this idea in mind, the historical build-up of TISs was studied for five formative TISs, all involving sustainable energy technologies. Based on these studies the three research main questions of this book were answered. The remainder of this section provides a summary of the answers to each of these questions.

10.1.1 Research question 1

Which motors of sustainable innovation can be identified within the domain of emerging sustainable energy technologies?

Four different motors of sustainable innovation were identified. Each of the motors was characterised by particular interactions between system functions. Each motor was observed in more than one case study.

The STP Motor

The *Science and Technology Push (STP) Motor* is dominated by *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4] and *Resource Mobilisation* [F6]. All the other system functions are either absent or relatively weak.

The dynamic of the *STP Motor* involves an event sequence consisting of positive expectations and/or research outcomes [F4] leading to the setting up of government- supported R&D programmes [F4] and, directly linked to it, the allocation of financial resources to the emerging technology [F6]. This results in a surge in science activities in the form of basic research and feasibility studies [F2], and also conferences, workshops and other meetings [F3]. In the next step, or in parallel, firms are approached by government actors and research institutes to participate, as technology developers and launching customers, in projects aimed at the realisation of pilots and demonstrations [F1]. The willingness of these firms to participate in such risky projects depends particularly on the outcomes of the feasibility studies [F4]. With positive outcomes, firms may invest, thereby contributing to the expansion of the R&D programme.

The Entrepreneurial Motor

The *Entrepreneurial Motor* is partly similar to the *STP Motor*. Its dynamics are also characterised by a strong fulfilment of *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4] and *Resource Mobilisation* [F6]. What sets the *Entrepreneurial Motor* apart from the *STP Motor* is the particularly important role of *Support from Advocacy Coalitions* [F7] and *Entrepreneurial Activities* [F1].

The event sequence that characterises this motor starts with firms, utilities and/or local governments entering the TIS and initiating innovative projects [F1], usually adoption experiments or demonstrations, because they see opportunities for commercial or societal gain in the future [F4]. Given the pre-commercial status of the emerging technology, the actors then require resources to cover part of their costs and to compensate the financial risks they take. For this, they lobby the national government [F7]. If all goes well, the resources are granted in the form of project-specific subsidies [F6]. Depending on the funding, the projects are started [F1]. The outcome, positive or negative, feeds back into the dynamic as it provides the incentive for other actors to initiate projects, or refrain from doing so [F4]. Often, the *Entrepreneurial Motor* is strengthened through the presence of niche markets [F5].

The System Building Motor

In the *System Building Motor* the set of dominant system functions is similar to those of the *Entrepreneurial Motor* but it includes a more important role of *Market Formation* [F5]. The main difference lies in the connection between *Support from Advocacy Coalitions* [F7] on the one hand, and *Market Formation* [F5] and *Guidance of the Search* [F4] on the other.

These connections are established through entrepreneurs that organise themselves increasingly in networks and manage to draw in new actors [F1], including local governments, intermediaries and interest groups. From this powerful basis, they lobby the government [F7], not for project-specific support, but for policies aiming to mobilise resources or develop regulations beneficial to the emerging technological field as a whole [F4, F6]. Most importantly, their aim is to enforce the creation of a mass market [F5] for the emerging technology.

The Market Motor

The *Market Motor* is characterised by a strong contribution to *Entrepreneurial Activities* [F1], *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4], *Resource Mobilisation* [F6] and *Market Formation* [F5]. All system functions are strongly fulfilled except for the *Support from Advocacy Coalitions* [F7]. The latter is not as important for the dynamics of this motor because *Market Formation* [F5] is no longer a political issue; a market environment has been created as the result of formal regulations. Instead, *Market Formation* [F5] is taken up as part of regular business activities, i.e. marketing activities connected to *Entrepreneurial Activities* [F1].

The event sequence which constitutes the *Market Motor* starts with the setting up of institutional structures that directly facilitate a commercial demand for an emerging technology [F5]. Once such structures are firmly in place, this leads to high expectations [F4] and increasing availability of resources [F6]. This leads to the opening up possibilities for new entrants to adopt the emerging technology [F1]. The newly entered firms are likely to make large investments, for example in infrastructure [F6], and they may also develop marketing strategies [F5], thereby increasing demand for the emerging technology further.

10.1.2 Research question 2

Can the rise, retention (and decline) of motors of sustainable innovation be explained in terms of TIS structures (actors, institutions, technologies, networks) and external influences and to what extent do these motors, in their turn, impact on TIS structures?

The TIS is a configuration of structural factors: actors, institutions, technologies and networks. System functions, and their dynamics emerge from this configuration and in turn rearrange it. In other words, there exists a mutual relation between the structure of a TIS and the motors of innovation realised through that structure. The second research question of this book points to the importance of understanding this mutual relation between structural factors and motors of innovation.

For each motor of innovation, a set of structural drivers, barriers and impacts was identified. Structural drivers and barriers indicate the conditions that support or hamper the initial emergence and retention of a motor. The structural impacts indicate the effects of the motor on the TIS structures. A summary of these results is provided in Table 10.1. All the motors were coupled to developments external to the respective TIS as well. These involved policies (environmental regulations, liberalisation policies, EU subsidies), economic trends (oil prices), technological developments (the biofuels debate), etc. The internal TIS structures, including dominant strategies taken by enactors and selectors, determined the specific impact of these developments on the dynamics.

Some motors of innovation are more powerful than others in terms of structural drivers, structural barriers and structural impacts. In this respect it could be argued that policy makers

Table 10.1 Overview of motors of innovation as related to structural drivers, barriers and impacts.

	STP Motor	Entrepreneurial Motor	System Building Motor	Market Motor
Enactors	There is a small enactor group, typically consisting of research institutes, technology developers and sometimes governments.	An enactor group has grown in number and variety. Enactors are primarily aiming to develop practical and commercially oriented projects.	The enactor group is large and covers a broad variety of actors. The enactors are increasingly organised in networks.	The enactor group is large and develops nationwide activities. It typically includes incumbent firms as well as national government actors (e.g. ministries, provinces).
Selectors	Selectors are practically absent. Drawing in one or more selectors is the prime objective of enactors at this stage. The first selectors to enter the TIS are often governments.	Selectors have become more active under the influence of enactors, serving as institution builders and launching customers, especially when the first demonstrations have delivered positive results.	A large group of selectors, including incumbent firms, support the efforts of enactors. They are increasingly organised in networks. At the same time the resistance of other selectors increases.	The supportive selector group is large and closely involved with the cause of the enactors.
Institutions	Institutions are poorly aligned to the emerging technology. The main driver is the presence of a technological promise as communicated by enactors. As the motor is sustained, more formal institutions complement this promise in the form of R&D policy programmes aiming for pilots and demonstration projects.	Alignment to the emerging technology is still poor. Prospective structures are most important, especially if related to the urgency of (local) environmental issues as conceived by selectors. Additional institutional support comes mainly in the form of project-specific government subsidies.	Institutions are more aligned to the emerging technology. The most important institutions are policies that facilitate the exchange of knowledge and the shaping of political coalitions.	Institutions are aligned to the emerging technology. The main driver is formed by market creation policies.
Technology	The technology is unknown, unreliable and costly, but is holding a promise for the future.	The technology is still unreliable and costly but sufficiently improved to allow for practical applications.	The technology is reliable and beyond the stage of demonstration but is usually still costly.	The technology is reliable but is usually still costly. Costs may decrease rapidly as the result of mass production.
Impacts	• Build-up of a shared vision. • Build-up of knowledge structure. • Build-up of supply-side structures.	• Build-up of demand-side structures • Build-up of intermediary structures and networks. • Formal institutions are adjusted (safety standards, licensing procedures, etc.). • The technology is improved.	• Enactors and particularly selectors are drawn into the TIS in large numbers. • Build-up of political networks in the form of coalitions and platforms. • Build-up of government structures in the form of market creation policies. • Incumbents increasingly become part of the TIS.	• Technologies and institutions are increasingly linked to the incumbent energy sector. • The costs of technology decrease rapidly as the result of mass production.

and entrepreneurs should always strive for a *Market Motor* to emerge. However, more powerful motors typically arise only in TISs that are already quite developed. This is because these motors arise from structures that were built up through the impact of less powerful motors. A logical step, based on this idea, was to construct an overarching framework – the Succession Model of Innovation – in which the relations between the various motors of innovation become clear. The Succession Model suggests that motors of innovation cause TISs to develop into more complete (and more complex) structural configurations which are prone to yield more advanced motors of innovation in turn. This framework was based on the empirically grounded observation that each motor typically (though not necessarily) follows another less advanced motor, with possibly as a final result the *Market Motor*.

10.1.3 Research question 3

Based on the motors of sustainable innovation, as identified, how can TISs in the formative stage be evaluated?

The Succession Model may be considered as a heuristic basis for the evaluation of TISs in dynamic terms. This evaluation is based on the idea that the best way to support a formative TIS is to create the (structural) conditions for motors of innovation to emerge. Once a motor is developing it may be supported with policies or strategies. Each motor of innovation is characterised by particular drivers and barriers. If these drivers are supported and if the barriers are overcome, a shift may result from one motor of innovation to another, more advanced one. The following evaluative insights were drawn from the Succession Model:[219]

- The first insight is that, underlying each motor, there is a group of enactors that supports the dominant system functions of that motor. Depending on the motor, this group has a different composition. For example, the *STP Motor* is developed by a limited number of enactors, whereas more advanced motors, e.g. the *System Building Motor* or the *Market Motor*, were driven by a large and heterogeneous group of enactors. Enactors may support each motor by drawing new enactors into the TIS. In weaker motors, the enactor group often mainly consists of scientists and policy makers, but for more advanced motors to emerge it should be dominated by firms.

- The second insight is that enactors cannot sustain any motor without the support of selectors. The *STP Motor* and the *Entrepreneurial Motor* are typically supported by selectors related to the government. The *System Building Motor* and the *Market Motor* are driven by a larger variety of selectors including firms. The implication is that for more advanced motors to emerge and develop, enactors should draw in as many selectors as possible. (In the more advanced motors, selectors are also drawn in by other selectors.)

- For a TIS to shift to another, more advanced motor, enactors need to draw in enactors and selectors from outside the TIS. A third insight is that this may be done by relying on promises and expectations based on visions and long-term developments. In other words, enactors should build up prospective structures. For more advanced motors to emerge, these

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[219] This section provides merely general insights. A more elaborate answer on research question 3, dealing also with strategic lessons for enactors and selectors, can be found in Section 9.5.

prospective structures should be backed up by technological structures, for example prototypes and practical applications. Also, promises and technological accomplishments should be supplemented by formal institutional structures that, eventually, embed the emerging technology in the incumbent system. If enactors consequently fail to keep their promises a TIS may collapse.

- The fourth insight is about linkages being shaped between enactors and selectors. In order to succeed, enactors and supportive selectors need to pack together. For more advanced motors to emerge and develop, networks need to be developed that support a broader variety of system functions.

- The fifth insight relates to the build-up of technological and institutional structures. In terms of impact, each motor of innovation results in the further build-up of TIS structures. The *STP Motor* typically develops knowledge structures and supply-side structures; the *Entrepreneurial Motor* contributes primarily to demand-side structures and intermediary structures; and the *System Building Motor* and the *Market Motor* are particularly prone to develop government structures. It should be stressed that this does not mean that a TIS always starts with an *STP Motor*. Rather, it suggests that it only makes sense to build up a demand-side if a developed supply-side already exists. After all, if a (to some extent) developed technology does not yet exist, it is unlikely that there will be many customers.

- A sixth insight is that motors of innovation are affected by external factors but that the effect of these factors on motors is highly dependent on internal TIS structures. For example, enactors and selectors are often opportunistic in framing the positive or negative outcomes of foreign R&D. Likewise, the external effect of sustainability issues is internalised through promises and expectations as experienced and communicated by enactors and selectors in the TIS. Also, TIS actors often depend on industries and governments external to the TIS, either for the supply of technology or for legislative support (EU level). This is mirrored by the internal networks and institutional structures of the TIS which involve relationships with foreign actors. The implication is that, in order to support motors of innovation, enactors and selectors should be opportunistic with respect to external developments. This holds for all motors of innovation and it is absolutely critical for the weaker motors, i.e., the *STP Motor* and the *Entrepreneurial Motors*.

- A seventh, and final, insight is that if in a single TIS multiple technological options are available with very different characteristics, these may involve separate technological trajectories. It is possible to bundle these trajectories into a single development, thereby even combining different motors of innovation, but the differences may also be the source of conflict and stagnation. In order to further develop a TIS, enactors and selectors should attempt to support as many technological trajectories as possible within a TIS. Such a portfolio strategy requires a lot of investments but, in the face of fundamental uncertainty, it is necessary to take such an approach.

10.2 Theoretical discussion

This section contains a reflection on the main results and discusses their importance within the light of existing theoretical literature. Seven contributions are highlighted:

- A first contribution of this book is a replication of earlier studies. Each of the case studies in this book pointed out that the set of system functions as developed in the literature (Bergek, 2002; Hekkert et al., 2007; Negro, 2007) is a useful set of 'variables' for conducting historical research on TISs in the formative stage. It turned out that insights in the build-up of a TIS can be derived by tracking the fulfilment of system functions over time. Moreover, this development could be understood in terms of virtuous and vicious cycles by identifying interactions between system functions. This book has contributed to the TIS literature by successfully demonstrating the usefulness of the *Functions of Innovation Systems Approach* in a variety of empirical contexts.

- A second contribution of this book relates to the use of the process approach as developed by Poole et al. (2000). By using the process approach, and the methodologies associated with it, it was possible to conceive of system functions not so much as states of a system but as flows of activity. Inspired by this idea, the system functions were conceived as categories of events which, based on interpretation, could be integrated in a narrative of event sequences. By systematically going through the event data, it was possible to track the system functions, both on the micro-level of event sequences and on the system level of the TIS. This led to a detailed historical account that could not have been established with any other method. The theoretical literature on technological trajectories and innovation processes, including IS studies but also SNM and MLM studies, could certainly benefit from adopting the process approach.

- A third contribution of this book is that it develops the concept of cumulative causation further than other studies in the field of evolutionary economics have done. Based on detailed databases, it was possible to combine insights from multiple case studies and develop generalised forms of cumulative causation. In previous studies, cumulative causation was considered mainly as a concept for the identification of case-specific virtuous and vicious cycles; see, for example, Jacobsson and Bergek (2004). These studies have provided important insights but they have not made clear whether similar cycles exist in other TISs. By generalising from case-specific findings, this book provided a more theoretical understanding of cumulative causation.

- A fourth contribution is that this book has pointed out how motors of innovation were embedded in the structural configuration of a developing TIS. A framework was developed which related the rise, retention (and decline) of each motor to typical structural features of TISs. In this respect, the structural configuration of a TIS was considered as a context that conditions the possibility of system functions emerging. As motors of innovation unfold, this context is reshaped: actors are drawn in, network structures are formed, institutions are adjusted or created and technologies are developed. Thereby motors typically improve the structural conditions on which they are based, making it possible for other, more advanced, motors to arise. In TIS studies conducted so far, this intricate relation between structures and system functions has not been conceptualised as clearly.

- A fifth contribution is related to the analysis of TIS structures. An actor concept based on the work of Garud and Ahlstrom (1997) was introduced. This concept distinguished between enactors and selectors. It was possible to understand the actions taken by particular actors by taking into account their position/role in the TIS. Previous studies did not distinguish between these actor roles and therefore were unable to clearly point out why particular actors are more likely to behave like prime movers than others. Also, the enactor-selector distinction made it possible to explain the typical effects of structural factors on motors of innovation. An important example is how the expansion of motors of innovation could be explained by pointing out how a group of enactors managed to draw selectors into the TIS by referring to the presence of (other) TIS structures, for example, support schemes, networks, widely shared positive expectations. This way the actor concept provided a theoretical basis for understanding how a TIS may develop and gradually become an integrated part of the incumbent energy system. Previous studies have not addressed this development as clearly yet; this holds for TIS studies but also for most SNM studies.

- The sixth contribution is to consider technological features as part of the structural configuration of the TIS. So far innovation system analyses take technological features into account only as far as knowledge flows and economic factors are concerned. This conception neglects the material features of technology. By taking into account the material dimension of technology it was possible to identify important drivers and barriers that could not have been identified otherwise. For example it was shown that the development of biomass gasification technology was severely hampered by technological bottlenecks, not (merely) by bad policy. The exclusive focus on knowledge flows is a feature inherited from the NIS approach that may suit the analysis of a whole nation but it is not appropriate for studying emerging TISs where the material characteristics of technologies are important potential drivers and barriers. Fixing this issue brings the TIS approach closer to the literature on SNM or Large Technological Systems.

- The seventh, and perhaps most important, contribution is that a conceptual framework was developed in which the various motors of innovation were placed into an overarching perspective. This Succession Model of Innovation provided a basis for the evaluation of TISs by explaining how the development of a TIS typically involves a sequence of successive motors, with the *Market Motor* as a final stage. This idea is reminiscent of Utterback's conception of a staged development in industrial dynamics, where a 'fluid phase' is succeeded by a 'transitional phase' and a 'specific phase' (Utterback, 1994) (p. 90-102); other scholars have come up with stage models as well (Kline and Rosenberg, 1986; Rotmans, 2003). Compared with this literature, the contribution of this book is that each of the motors of innovation is constituted by a mechanism of interacting system functions. Moreover, the motors of innovation are embedded in a conceptual framework that indicates structural drivers and barriers. This strong connection of the Succession Model to structural factors makes it suitable as an evaluative basis for entrepreneurs, policy makers and other practitioners aspiring to influence the course of TIS development.

10.3 Reflections on method

The methodological backbone of the studies presented in this book is the event history analysis. In this section, the usefulness of this method is discussed by reflecting on the internal and external validity of the research outcomes. The internal validity refers to the meaningfulness and relevance of the concepts used and to the quality of the inferences through which relations between the concepts were established. The external validity refers to the applicability of the results in other cases, and, more broadly, in other contexts.

10.3.1 Internal validity

All the important concepts of this study were operationalised and measured according to the method of event history analysis. This method is based on the systematic collection of events in a database. The overview provided by the database allows for the clustering of events in types. The construction of event types is an iterative process that is guided by the system functions as defined in the theoretical literature. This way, the method involves a combination of inductive and deductive reasoning. The implication is that the system functions were not taken for granted but continuously checked against raw empirical data. The flexibility of the approach secures the construct validity of the seven system functions. In other words, the approach 'guarantees' that they are a meaningful set of categories for the analysis and evaluation of TIS dynamics.

By mapping events over time, it was possible to track the historical fulfilment of each of the system functions. Moreover, because events are related to each other in time, it was possible to reconstruct event sequences, and thereby the interactions between system functions. In short, the event data made it possible to establish a detailed empirical foundation for the identification of system functions and for the main theoretical constructs of this study: the motors of sustainable innovation.

Note that in most studies this type of insight is developed from the collection and interpretation of archive material and/or interview data. These methods are useful but they do not (easily) allow for a systematic measurement over time. The event history analysis reduces both the author's bias and the retrospective bias of interviewees to a minimum (see Negro (2007) for a more elaborate justification of the event history analysis).

Another advantage of the event history analysis is that it offers a standardised measurement scheme, which makes it easier to replicate the approach across case studies. This is especially important if single case study results are to be subjected to systematic comparisons.

There is no such thing as a perfect method. The following methodological problems were encountered:

- The first problem is that the availability and the quality of event data varied over time. For the more recent periods it was easier to collect data from archives, especially those containing digitalised media. A solution to this problem was to complement the primary dataset of events with historical accounts from secondary literature. Also, more information from interviews was used. A drawback is that this makes it more difficult to conduct reliable quantitative analyses. This issue was particularly encountered for the HyF case and the ANG case.

- The second problem is that the availability and quality of data sources varied across the case studies. For TISs that involved visible technologies, for example because of political attention, a lot of data was available. For TISs that drew less media attention, data was limited, especially where newspapers and popular journals were considered. A solution to this problem was, again, to rely more on secondary literature and interviews.

- A third problem is that, even where sufficient empirical data was available, not all system functions could be easily quantified in terms of events. This was particularly the case with the *Market Formation* [F5] and *Resource Mobilisation* [F6] functions. In order to quantify these system functions it would be sensible to trace the allocation of financial budgets over time. Unfortunately this data is hard to find, especially at a disaggregated level of analysis. The solution taken in this book was to avoid quantitative analysis and instead present the contribution to these system functions in terms of key events, e.g. the allocation of subsidies and other budgets to particular projects.

- A fourth problem is that it is not straightforward to determine which information from the literature should actually count as events. Literature reports are full of information, including things that happened, things that people said, reflections of the author, things that happened in the past and scenarios about the possible future. From all this information clear-cut events had to be separated. This was a complicated exercise of interpretation, and reinterpretation. It would be practically impossible to codify all the choices made during this process but, in the end, the operationalisation scheme resulting from this iterative exercise should be valid. In order to account for this, the events in the databases were checked by other researchers. For the first two case studies (BG and BF cases) this was done systematically; for the other cases, the operationalisation schemes turned out to be quite similar in the first place and were therefore checked by other researchers using small samples.

- A fifth problem is related to the fact that with each additional case study, the theoretical insights became more developed and the operationalisation schemes became more refined. In the BG and BF cases the concept of a motor was barely developed, whereas the HyF and ANG cases actually resulted in the formulation of motors of innovation in similar terms as presented in the synthesis. Also with respect to the structural analysis, more recent case studies were conceptually more developed. During the cross-case comparison, the basis for the construction of the typology of motors of innovation, the insights from recent case studies may have weighed more heavily. To compensate for this bias the synthesis was supported with examples from *all* the case studies.

- A sixth problem is related to the construction of motors of innovation based on the identification of event sequences. It should be stressed that the identification of event sequences, and the construction of virtuous cycles, made it necessary to filter out a lot of noise in the data. After all, events do not all follow up on each other in neat sequences. The narratives constructed as part of the case studies should therefore be considered as stylised simplifications of reality and not be interpreted as literal accounts of what happened. As suggested by Poole et al. (2000), the narratives should be regarded as interpretation schemes which can be used to understand a variety of stories that are all somehow related. It is expected that the narratives as presented here serve to show 'generative mechanisms' more or less generally at work within TISs around sustainable emerging energy technologies.

- A seventh issue is that the evaluation of TIS development, as based on events, was essentially a synthesis of judgments from various sources. These judgements were partly based on historical accounts, partly on hindsight judgements on the basis of 'present-day' interviews and partly on the theoretically-guided opinion of the researcher. The analysis did not systematically analyse all these various sources of judgement and may therefore contain subjective biases. To overcome this problem, the analysis focused on drivers and barriers of dynamics and withheld normative statements with respect to the outcome of particular projects or the desirability of particular technologies.

10.3.2 External validity

The Succession Model of Innovation and the typology of motors was based on dynamics observed in five case studies related to the Dutch and Swedish energy systems. Despite this limited empirical basis it is expected that, to some extent, the results are also valid for TIS dynamics in other countries and in other sustainable energy systems. (Note that the results are not expected to be valid beyond the domain of sustainable energy technologies.) The following arguments support this claim:

Each motor of innovation was observed in multiple case studies. Based on these observations it can be stated for each motor of innovation, that it can develop within the context of different technologies, different institutional backgrounds and different historical periods. This, at least, suggests that motors of innovation are not specific to one country, to one technological field or to a particular historical period. Apparently, the original idea of Poole, to 'elucidate generative mechanisms applicable to a broad range of complex and disparate cases that share a common developmental process' (Poole et al., 2000) has worked. The narrative approach has made it possible to capture similar developments in 'disparate cases'; various technologies, various time periods, two countries. Even if other TISs were not subject to similar dynamics, the abstract nature of the motors may still serve as a benchmark for comparison.

Whether the Succession Model of Innovation is valid outside the studied domains is less evident. However, the general idea behind this model is in line with theoretical notions like path-dependency and the technology lifecycle (see Chapter 1). In this respect, the Succession Model may be regarded as an enrichment and a specification of existing evolutionary economic theories. It is an enrichment in the sense that the Succession Model incorporates a broader set of structures (particularly the actor concept and the societal dimensions are more prominent). It is a specification because the Succession Model focuses specifically on sustainable energy technologies.

Despite the theoretical support for the Succession Model, it should be stressed that the evidence collected does not confirm the completeness of the typology presented here; indeed, this would be impossible with any research design. The implication is that other motors of innovation may exist and that other follow-ups may be possible. Nevertheless, these 'unobserved motors' may be grasped in terms of interactions between system functions as well. Therefore, if additional motors (or new variations) are identified, it may very well be possible to relate them to the typology presented in this book. In this respect, the Succession Model of Innovation should be considered as a first tentative step towards the formation of a tested conceptual framework.

In the end, a generalisation of the results from this book requires further research.

10.4 Further research

Based on the issues discussed above a number of recommendations for further research are suggested.

10.4.1 Further theory building through replication

Recently, the TIS concept and the Functions of Innovation Systems Approach have been adopted by an increasing number of scholars. Nevertheless, the number of empirical studies conducted is still limited. A first recommendation is therefore to replicate the studies presented in this book. This way the results may be confirmed, refined or even rejected. The event history analysis method provides a powerful basis for conducting case studies in such a way that they can be compared. The following research avenues are of particular interest:

- More case studies should be conducted on sustainable energy technologies. These should involve technology comparisons and country comparisons. By focusing on the identification of motors of innovation, such studies serve to confirm the external validity of the framework, as established in this book, in the domain of sustainable energy technologies.

- The studies presented in this book revealed virtuous cycles but not a lot of vicious cycles; and where they did occur they were typically short lasting and chaotic. Nevertheless, insights in the dynamics of system breakdown are just as crucial for the analysis and evaluation of TISs. It may be a good idea specifically to study TISs that have shown a prolonged period of vicious dynamics in the past.

- The TIS approach may be applied to other technological fields, either within the domain of sustainable development or outside it. The outcomes of these studies would make it possible to explore to what extent the typology of motors of innovation may be generalisable to other domains. More importantly such studies serve to increase our understanding of the differences between sustainable innovation and non-sustainable innovation.

- An elaborate study of the market expansion stage that is initiated after a take-off may provide important insights as well. It is expected that the dynamics will be very different in this stage and that the set of system functions may have to be adjusted to conceptualise them accurately.

10.4.2 Theoretical refinement

There are numerous refinements that can be made to the theoretical approach as developed in this book. The studies presented were specifically aimed to provide a better understanding of interactions between system functions. This required the analytical scope to be broad. A downside is that the details of various activities and structures underlying these interactions were somewhat lost. By focusing more on the development of specific activities or structures, it will be possible to contribute to a richer insight into the nature of particular system functions. The following research avenues are particularly relevant:

- It was observed that for the majority of motors, the *Entrepreneurial Activities* function was the pivot. These often involved practically-oriented demonstrations and adoption experiments. It may be fruitful to study more specifically the development of such projects against the background of a developing TIS. In that case, the management of projects is made central and the TIS structures are analysed as the conditions that drive or hamper the projects. The enactor-selector concept may serve to relate the strategies taken within the project to the configuration of a TIS.

- The *Guidance of the Search* function as conceptualised in this book covers a broad variety of activities, including expectations, promises and policy directives. It would be useful to split up this category and attempt to construct a more fine-grained division.[220] These activities may then be related to the enactors-selectors scheme in order to establish a 'management of expectations' theory. Such research is currently being undertaken by Bakker and Van Lente (2008).

- Another system function that should be subjected to a more refined analysis is the *Support from Advocacy Coalitions* function. It was shown that political activities have played a crucial role in the expansion of a TIS but the actual organisations that performed these lobbies have not been studied in detail. It would be interesting to find out more about how and why these organisations operate in a certain way. This would involve linking up the TIS concept more with ideas from political science; cf. Sabatier (1988; 1998).

10.4.3 Improvements to method

For all the research avenues suggested above, the event history analysis provides a fruitful basis for the systematic analysis of events. This method may be refined by taking up the following suggestions:

- So far the event history analysis has mainly been developed as a tool for the construction and analysis of narratives. However, given that the method allows for a quantitative mapping of events, it should be possible to develop formal models of motors of innovation. This could be done by complementing the narrative approach with statistical techniques as developed by Poole et al. (2000). See, for example, how Chappin (2008) has demonstrated how learning processes can be conceptualised and modelled in terms of dual feedback loops.

- Another way to develop formal theories about motors of innovation is to use agent-based modelling; see Alkemade (2004). These models are based on simulations of activities undertaken by groups of heterogeneous actors. By providing each actor with a set of rules it becomes possible to study how particular strategies on the micro-level result in dynamics on the macro level of a system. With actor-based modelling it would be possible to see if the enactors-selectors scheme is a valid way of linking structural factors to dynamics.

10.4.4 Policy and practice

Future research may also contribute to the development of more sophisticated evaluation and policy models:

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[220] For the other system functions an analysis may also benefit from applying a more fine-grained division of activities. The event typology developed in this book may serve as a heuristic guide to such a sub-division of system functions.

- So far the method of evaluating a TIS has mainly been based on discussions with experts. It would be useful to develop a more systematic approach to the evaluation of TISs for example by formulating a clear set of milestones, or process goals, related to each motor of innovation; see Bergek et al. (2008a) for a similar idea. This may be established on the basis of a benchmark study that takes into account a lot of different TISs from various nations and technological fields.

- Based on the outcomes of this study it should be possible to develop a set of systemic policy instruments that specifically aim to induce motors of innovation. Such research would be in line with the work done by Smits and Kuhlmann (2004).

10.5 Recapitulation and outlook

This section provides a recapitulation of the most important conclusions of this book and ends with a short outlook.

Recapitulation

The objective of this book was to contribute to a theoretical understanding that allows for the analysis and evaluation of dynamics of technological trajectories around emerging sustainable energy technologies. Although a lot of work remains to be done, this main objective has been achieved. A conceptual framework and methodology has been developed that enabled studying the interactions between system functions in a diverse set of formative TISs. As a result, four typical virtuous cycles – or motors of innovation – were identified: a *Science and Technology Push Motor*, an *Entrepreneurial Motor*, a *System Building Motor* and a *Market Motor*.

These motors were observed to play an important role in the build-up of Technological Innovation Systems around emerging sustainable energy technologies in the Netherlands and in Sweden. Where these motors emerged, they reorganised the structural configuration of the TIS. In some cases motors expanded and grew into the incumbent energy system, thereby linking up to it and reforming parts of it. This was especially the case for the *System Building Motor* and the *Market Motor*.

The creation of a sustainable energy system is about removing structural barriers and about creating structural drivers necessary for the motors of innovation to emerge. It was pointed out, in a variety of case studies, that this requires continuous efforts by governments, firms and other actors. It was also shown that institutions and technologies have to be adjusted or even created in order for the motors to develop further. It cannot be expected that all barriers will be removed at once, or that the strongest driver of all, 'the market', will be formed overnight. Rather, a step-by-step approach should be taken by which a TIS is gradually built up over time. This step-by-step approach was labelled the Succession Model of Innovation.

According to the Succession Model, the four motors may be regarded as stages in the development of a formative TIS. It turned out that the immature TISs were less prone to develop anything other than an *STP Motor*. Only when a TIS was developed enough to generate short-term opportunities for firms did the *Entrepreneurial Motor* emerge. A *System Building Motor* was observed as being a transformation of the *Entrepreneurial Motor*. Finally, the *Market Motor* was typically developed from structures shaped by a *System Building Motor*. In general, there was a relation between the motors observed and the maturity of the TIS in terms of actors involved and in terms of technology and institutions. The most powerful motors arose if a TIS was supported by a large variety of actors, institutions and technologies, preferably integrated into networks.

The build-up of a TIS was shown to be a troublesome process, characterised by uncertainty and adversity but also by luck and opportunity. The studies presented in this book indicated that once a motor emerged, this process was accelerated. A small but dedicated group of actors was often able to succeed in inducing a 'primitive' motor of innovation with the power to reshape a first set of structural drivers and barriers. Once this was realised, inducing a more advanced motor became possible as a new set of actors became more able and willing to follow up on earlier achievements, benefiting from the initial structural reinforcements in a cumulative fashion.

The Succession Model was used as a basis for formulating strategic lessons directed at policy makers and other practitioners that aspire to understand and influence the development of emerging energy technologies. These recommendations specified which interventions could be taken to support particular motors of innovation, and thereby to further the development of a TIS from one stage of development to another.

Outlook

With the increasing urgency of sustainability issues, it is hoped that actors, including governments, firms and NGOs, become aware of the fact that they actually share a common ground: the need to reform, or even overthrow, the incumbent energy system and to support a variety of emerging sustainable energy technologies. If these actors develop the strategies suggested in this book, they will be able to induce the motors of innovation that foster the build-up of a TIS.

There are numerous sustainable energy technologies, many of which are currently on the verge of take-off. The TISs around wind energy, solar energy, biomass energy and numerous energy-saving technologies all harbour the potential to make an energy transition happen. It is hoped that the ideas developed in this book contribute to the development of a variety of sustainable energy TISs and to the realisation of a sustainable energy system in the near future.

The ultimate claim of this book is that, with the right policies and strategies, proper awareness of future needs and long-term commitment of actors from the public and private sphere, it is possible to make this hope become reality.

Summary

Introduction

Modern societies are encountering environmental and political problems in the sphere of energy supply. Combustion of fossil fuels causes numerous environmental problems and the dependence on oil- and gas-exporting countries creates political tensions. One possible way to deal with this is to develop and use sustainable energy technologies. However, more than 30 years of development in sustainable energy technologies have resulted in little more than a drop in the ocean compared with the dominance of fossil energy technologies. From 1973 to 2005 the share of renewables has increased by a meagre 1.7% points (IEA, 2007a). If sustainable energy technologies are to achieve dominance over fossil technologies within, say, a generation, this trend needs to be 'shifted'.

Underneath the trend of slowly diffusing renewables lies a world of companies, consumers, governments, scientists and other technologies, all interrelated. This has been described well by Unruh (2000), who provides an overview of the causes underlying what he calls carbon lock-in. Unruh explains how, over the past few decades, an energy (and transport) system has evolved into an interlinked complex of actors, technologies and institutions. This complex continuously provides positive reinforcements – in the form of scale economies, accumulation of knowledge and technology, network externalities and habits – to the further development of fossil energy technologies. In order for sustainable energy technologies to prosper, these forces of inertia that prevail in the incumbent energy system have to be broken, implying a reorganisation of the structures that lie at the basis of modern capitalist societies.

This poses a problem, but a reason for optimism is that, historically, large transitions are known to occur. From an overview of historical transitions by Grübler et al. (1999) it becomes clear that transitions are characterised by a relatively long period of gestation, followed by a rapid take-off. If such a take-off should occur, a sustainable energy system could be realised within a generation. This book starts from the position that it is possible and desirable to intervene in the course of such a sustainable energy transition.

Transitions involve massively complex processes developing over a long period of time, across a broad extent of societal structures. A broad perspective is needed in order to make sense of transitions, but this can only be attained gradually through a solid understanding of the underlying processes, the micro and meso activities that form the core of a possible sustainable energy transition. In this book, technological innovations, around sustainable energy technologies are considered as being such core processes.

The innovation studies literature stresses that technological innovation can be understood as the development of a set of interlinked technologies and institutions being shaped through the activities of actors. In the course of time, the outcomes of these activities result in an accumulation of structures. With these structures in place, the innovation process typically gains more direction and speed (Jacobsson and Bergek, 2004). Once a technological innovation in the field of sustainable energy takes off, it is expected to replace or rearrange important structures that support incumbent energy technologies, thereby possibly establishing a contribution to a sustainable energy transition.

From a historical perspective, the development of a technological innovation can be considered as a technological trajectory. The course of technological trajectories can be influenced, but to do so in a sensible way is far from trivial, since emerging technologies are characterised by fundamental uncertainties (Meijer, 2008). After all, the performance of a technological artefact is determined by the structures in which it is embedded. For an emerging, or 'fluid', technology, the alignment with its surrounding structures is weak, hence its current performance is bound to be poor (Christensen, 1998). In fact, the whole meaning of performance is unclear, since the normative framework from which judgement derives is linked to the incumbent structures which are supposed to change in the future.

There is thus a situation where, on the one hand, technological trajectories around sustainable energy technologies harbour the potential to contribute to a transition, but on the other hand, due to the uncertainty surrounding the technologies involved, there is hardly a basis for support. Indeed, policy makers and other practitioners have been struggling to develop suitable support policies and strategies. Strategic insight is needed into how emerging sustainable energy technologies are shaped and how this process can be influenced.

The general objective of this book is to contribute to a theoretical understanding that allows for the analysis and evaluation of the dynamics of technological trajectories, focusing on emerging sustainable energy technologies contributing (or expected to contribute) to a sustainable energy transition.

In order to achieve this objective, the Technological Innovation Systems approach is adopted and further developed. The idea behind this theory is that technologies develop within the context of a system which consists of actors, institutions, technologies and the interrelations between them (Carlsson et al., 2002b). This Technological Innovation System (TIS) does not come into existence overnight but is formed during a build-up process. The TIS literature stresses that technologies will pass through a so-called formative stage before they can be subjected to a market environment (Jacobsson and Bergek, 2004). During this formative stage actors are drawn in, networks are formed and institutions are designed. These structures are increasingly aligned to the emerging technology.

A TIS approach may focus on these *structures* and their effects, but it may also focus on the *processes* underlying the formation of the system (Jacobsson et al., 2004). This is done by studying a set of seven key activities or 'system functions' (Hekkert et al., 2007; Negro, 2007). A description of the system functions is provided in Table S.1. It is expected that by mapping the fulfilment of system functions over time a better understanding of the formative stage will be developed.

The main contribution of this book revolves around the idea that the TIS approach is essentially a growth model based on the notion of cumulative causation (Jacobsson and Bergek, 2004; Myrdal, 1957). This idea implies that the build-up of a TIS may accelerate due to system functions interacting and reinforcing each other over time. Such a rapid build-up is exactly what is needed to establish the diffusion of sustainable energy technologies. The idea of analysing interactions between system functions is not new. However, so far, no attempt has been made to generalise results based on this idea. In order to gain a better understanding of transitions, it is important to do so because there is never just one TIS that needs support, but many, all potentially contributing to a single transition.

In this book, dynamics are mapped for a variety of TISs in order to come up with a typology of dynamics. The assumption is that multiple forms of cumulative causation may occur; these variations will be called motors of sustainable innovation. The following research questions are answered:

RQ1: Which motors of sustainable innovation can be identified within the domain of emerging sustainable energy technologies?

RQ2: Can the rise, retention (and decline) of motors of sustainable innovation be explained in terms of TIS structures (actors, institutions, technologies, networks) and external influences, and to what extent do these motors, in their turn, impact on TIS structures?

RQ3: Based on the motors, as identified, how can TISs in the formative stage be evaluated?

The three research questions are answered by studying the historical development of a number of different TISs around emerging sustainable energy technologies in the Netherlands (4) and Sweden (1). For each TIS, motors of sustainable innovation are identified, as well as structural factors related to the motors. Based on the results, evaluative insights are presented. The results are compared across the cases and synthesised into a typology.

Part I: Theory and Method

The first part of this book (Chapters 2 and 3) contains the outline of theoretical and methodological ideas that are used in the case studies. The theoretical outline consists of an elaborate discussion of the innovation systems literature, including a detailed explanation of the concepts related to the TIS, both in terms of *structures* and *processes*. The methodological part focuses on how to measure the build-up of a TIS. The most important theoretical concepts are the following:

TIS Structures

Structural factors represent the static aspect of the TIS, meaning that they involve elements that are relatively stable over time. Three basic categories are distinguished; actors, institutions and technologies:

- The actor category involves any organisation contributing (with its knowledge and competences) to the emerging technology in focus, either directly as a developer or adopter of technology, or indirectly as a regulator, financer, etc. An important distinction is made between so-called enactors and selectors (Garud and Ahlstrom, 1997). Enactors are actors that are closely involved in the development of a particular technology and fundamentally dependent on its success, whereas selectors are actors that are engaged at a distance, for example because they have the possibility to choose between those options.

- Institutions are 'the rules of the game' (North, 1990) (p. 3), such as laws, regulations, norms. They also involve cognitive rules, i.e., search heuristics, promises and expectations. In terms of intervention, institutional factors are of key importance, as they are often the main target of government policies and business strategies.

- Technological factors consist of artefacts and the technological infrastructures in which they are integrated. The techno-economic workings of such artefacts, including cost structures, safety, reliability, effects of up-scaling etc., are of crucial importance to understanding technological change.

Structural factors are merely elements, or building blocks. In an actual TIS, structural factors are intricately linked to each other. If structural factors form a dense configuration they may be called a network. Network structures are crucial forms of organisation that facilitate the exchange of knowledge across disparate actors. On a higher level, all structural factors combined may form one big network that, provided that it is a more or less coherent whole, constitutes a system configuration.

TIS Processes

The purpose of this book is to analyse TIS dynamics. Therefore the focus will be on processes, or system functions. The idea behind the so-called Functions of Innovation Systems approach is to consider the TIS as being a system with a purpose which is to be served through the fulfilment of a set of system functions. System functions are (types of) activities that are necessary for the build-up of a TIS. In this respect, it is important to mention that each system function can be fulfilled in various ways; each system function encompasses a variety of activities. With this conceptualisation it is also possible to consider activities that contribute negatively as the fulfilment of a system functions. Obviously, these negative contributions imply a (partial) breakdown of the TIS.

The earlier mentioned idea of cumulative causation suggests that system functions may reinforce each other over time. Indeed, a positive interaction between system functions is considered necessary for TIS build-up to occur. The fulfilment of system functions could result in a virtuous cycle, constituted by positive feedback loops. For example, the successful realisation of a research project, contributing to *Knowledge Development* [F2], may result in high expectations, contributing to *Guidance of the Search* [F4], among policy makers, which may, subsequently, trigger the start-up of a subsidy programme, contributing to *Resource Mobilisation* [F6], which induces even more research activities; *Knowledge Development* [F2], *Guidance of the Search* [F4], etc. (see Table S.1). System functions may also reinforce each other 'downwards'. In that case a sequence may result in conflicting developments or even in a vicious cycle.

In order to understand the process of TIS build-up it is important to know under what conditions virtuous or vicious cycles occur. Moreover, such dynamics have important implications for intervention strategies. An ambitious goal would be to actively shape a virtuous cycle and to support it, thereby inducing a dynamic so powerful that it will, eventually, undermine the incumbent system. This may be impossible to be realised by a single entrepreneur or even by a government. On the other hand, the concept suggests that once a cycle emerges, targeting any one of the system functions involved in the cycle will affect many others, thereby amplifying interventions throughout the TIS.

The example provided above is rather simple and it is expected that, in reality, more complex forms of cumulative causation exist, forms which involve many system functions displaying multiple feedback loops. However, an important assumption in this book is that there is a limit to the number of patterns that historically occurs. If this is indeed the case, then it makes sense to construct a typology of forms of cumulative causation that may occur in the formative stage of a TIS. These forms will be called motors of sustainable innovation.

The relation between process and structure

Motors are not independent of the structures of a TIS. On the contrary, motors emerge from a configuration of structural factors and in turn rearrange that configuration. This means that:

- It is to be expected that structural factors determine, for a large part, the fulfilment of system functions and the rise of motors. These involve enactors, selectors, institutions being present and the nature of technologies. External factors are important as well.

- Motors may in turn impact TIS structures. This way, they feed back into the TIS configuration that made it possible for them to develop in the first place. These impacts may be a combination of new (types of) enactors or selectors being drawn in, the setting up of institutions, improvements made to technologies, etc.

Method

Each case study should result in the identification of structures and system functions within the TIS. In order to realise this, a systematic methodological approach is taken, namely the event history analysis as developed by Poole (2000) and Van de Ven (1990; 1999). This method offers the possibility to operationalise and measure system functions by relating them to events. Examples of such events are studies carried out, conferences organised, plants constructed, policy measures issued, etc.

Based on literature surveys and interviews, a database was constructed for each case study, containing events. The identification of events was an inductive exercise during which the conceptual framework of system functions was applied as a heuristic tool, in the sense that, with the definitions of system functions in mind, it became easier to interpret the available information. The database provided an insight in the content of events and overview of their chronology. Based on this overview, the events were clustered into types that corresponded to the seven system functions (see Table S.1).

The development of individual system functions over time was measured by tracking the number of events per year for each system function. The interaction between system functions was measured by tracking (causal) sequences of events, like in the example of a virtuous cycle given above. These patterns were interpreted as elements of a narrative. This narrative, made up of storylines related to the system functions and their interactions, was validated by means of interviews with 'field experts'. The narrative provided the basis for all further analysis.

The event history analysis makes it possible to identify motors of sustainable innovation in terms of event sequences that recur over time. The method also allows for the analysis of structures that relate to these motors, either as underlying causes of change (drivers and barriers), or as targets of change (impacts).

Part II Case Studies

The second part of this book contains five case studies each of which provides an analysis of the development of a particular TIS (Chapter 4-8). The focus is on the dynamics of TIS build-up in terms of motors of sustainable innovation. The analyses are translated into evaluative insights and implications for practitioners. These case studies also provide the building blocks for the typology of motors. In the following, the content of the case studies is discussed without explaining the characteristics of the motors identified; these are discussed as part of the typology presented in Part III.

Biomass gasification in the Netherlands

The biomass gasification case (Chapter 4) involves the Dutch TIS around biomass gasification technology as it developed from 1980 to 2004. This involves the production, diffusion and utilisation of a technology for the conversion of biomass to syngas. This is supposed to enable efficient, clean and flexible bio-energy production.

The dynamics of the Biomass Gasification TIS (BGTIS) are characterised by a relatively long period of build-up, followed by a rapid decline. The build-up began slowly in the 1980s within a community of scientists and engineers that had so far been developing coal gasifiers. In the 1990s, biomass gasification came to be regarded as an enabling technology for the creation of a sustainable energy production system. This technological promise was largely fed by scientists, technology developers and policy makers. The effect was that numerous small firms entered the BGTIS to develop their own projects. However, gasification technology posed far more technical problems than originally expected. By 1998, the 'hype' came to an end and was followed by a sudden decline.

The focus of this study is on identifying system functions and relating them to drivers and barriers within (and outside) the system. The concept of a motor is not explicitly addressed. Nevertheless, a number of virtuous and vicious cycles are identified which will turn out to be in line with motors as identified in the other case studies.

Biofuels in the Netherlands

The second case study (Chapter 5) involves the Dutch TIS around (liquid) biofuels. The focus is on the production, diffusion and utilisation of liquid biomass-based fuels in the mobility domain from 1990 to 2005. Various biofuels options exist, but, in general, two types can be distinguished: first-generation (1G) and second-generation (2G) biofuels.

The dynamics of the Biofuels TIS (BFTIS) are characterised by a conflict over the desirability of 1G versus 2G biofuel technologies. The first BFTIS developments, involving 1G biofuels, started in the 1990s when farmers, small firms and local governments led small biofuels experiments. In the late 1990s, scientists and environmental organisations began advocating against 1G biofuels. The argument was that they were costly, inefficient and unsustainable. Instead, they argued, support should be given to 2G biofuels. The result was that the national government focused support on 2G biofuels. From the late 1990s until 2002 the BFTIS was dominated by activities around 2G biofuels. In 2004-2005 this changed as, despite the ongoing controversy around 1G biofuels, the EU decided to set a target for a minimum of 10% biofuels implementation by 2010. What followed was a surge in activity related to both 1G and 2G biofuels. However, the conflict raged on as scientists and environmentalists increased their opposition to biofuels in general, 1G and 2G alike.

The study reveals three motors of sustainable innovation that supported the development of biofuels in the Netherlands: an *Entrepreneurial Motor*, a *Science and Technology Push (STP) Motor* and a *Market Motor*. A number of drivers and barriers are indicated as well. Specifically, it is pointed out that the conflict has posed a barrier for development of biofuels as the actors involved, failed to join forces for what is arguably a common cause, namely the development of the BFTIS.

Biofuels in Sweden

The perspective on TIS dynamics around biofuels is broadened by comparing the developments in the Dutch BFTIS with the Swedish BFTIS (Chapter 6). The development of the Swedish BFTIS is characterised by a gradual build-up. The developments started in the 1980s when projects were initiated by the SSEU, a public-private partnership. In the 1990s, dynamics expanded under the influence of government policies directed at both 1G and 2G biofuels. Developments were legitimated on the basis of local environmental issues. By the end of the 1990s, advocates managed to shape niche markets that supported the use of 'flexi-fuel cars', thereby inducing the adoption of biofuels among end-users. Despite the presence of 2G advocates criticising the diffusion of 1G biofuels, the overall strategy of actors was to join forces and plead for general support. The result was that, from 2000 on, market creation measures were introduced by the government.

The study reveals various forms of cumulative causation. The comparative perspective reveals similarities and differences from which important lessons are derived for influencing and improving such dynamics. The analysis shows, for example, that developments in the Swedish TIS were particularly strong as the result of system functions being developed in parallel.

Hydrogen and fuel cell technologies in the Netherlands

The fourth case study is about the Dutch TIS around Hydrogen and Fuel cell technologies (from 1980 to 2007 (Chapter 7). This case involves the development, diffusion and utilisation of fuel cells and the hydrogen storage and distribution infrastructure needed to support them. The utilisation of fuel cells is expected to result in efficiency gains and emission reductions. Moreover, this technology harbours the possibility of opening up the automotive energy system to renewables other than biomass.

For the Hydrogen and Fuel Cells TIS (HyFIS), the dynamics involved multiple waves of activities. The first wave emerged in the 1970s – against the background of the oil crisis – when the Molten Carbonate Fuel Cell (MCFC) emerged as a viable option to increase the efficiency of power production. The MCFC was advocated by scientists and engineers and picked up by the national government. The result was, in the early 1980s, the setting up of a development programme. From the 1980s to the early 1990s, the HyFIS was dominated by activities unfolding from this programme. The programme did not succeed in realising demonstration plants, as the organisations involved encountered difficulties in finding launching customers. By 1998 the programme came to a halt. At the very same time, a second wave of activities emerged which was triggered by improvements in the performance of other HyF technologies, especially the Proton Exchange Membrane Fuel Cell (PEMFC). The PEMFC connected the HyFIS to a new application domain – (electric) vehicles. After a reorientation to the PEMFC, rising oil prices, climate change issues and local air quality issues provided a sense of urgency, which caused the HyFIS to receive support from a variety of actors. From 2005 on, a variety of demonstrations was realised, with ever more visible results.

Two motors of sustainable innovation are identified in this case study: a *Science and Technology Push (STP) Motor*, and an *Entrepreneurial Motor*. This study centres particularly on the identification of structures that explain the rise of motors. The impact of the motors on these structures is also addressed.

Automotive natural gas in the Netherlands

The fifth case study is about the Dutch TIS around 'Automotive' Natural Gas (Chapter 8) which involves the production, diffusion and utilisation of natural gas for automotive purposes from 1970 to 2007. This technology offers advantages in the form of reduced emission of CO_2 and especially of particle matter.

The dynamics related to the Automotive Natural Gas TIS (ANGTIS) are characterised by an early build-up in the 1970s, followed by a breakdown in the 1980s and then, again, a build-up from 2000 to 2007. The early build-up was induced by the oil crisis, which led gas companies and other utilities to experiment with alternative fuels for their fleets. This involved a growing number of adoption experiments supported by the national government and by the EU. The breakdown of the ANGTIS began in the 1980s when the oil price decreased and the urgent need for alternative fuels disappeared. Also, the adoption experiments were unsuccessful in terms of costs and reliability. The result was a collapse of the ANGTIS. From 2000 on, developments started accelerating again as the result of tightened EU air quality regulations which urged local governments to adopt automotive natural gas technology. In 2004, these developments expanded as natural gas advocates organised themselves in platforms and began lobbying the national government for support. The ambition was to broaden out the NG infrastructure, so far regional in character, to cover the whole nation. These activities provoked resistance, especially within the national government but also among incumbent industries. The result was a political battle which resulted, by 2006-2007, in a positive outcome for the natural gas advocates: a policy package that aims for the creation of a market for natural gas vehicles.

Three motors of sustainable innovation were identified; the *Entrepreneurial Motor*, the *System Building Motor* and a *Market Motor*. Like the previous case, the analysis reveals motors as well as structural drivers, barriers and impacts.

Part III Synthesis

In the third part of this book the insights from the case studies are combined in order to establish an integrated perspective on motors of sustainable innovation. By doing so the three main research questions are answered (Chapters 9 and 10). Subsequently, the relevance and validity of these answers is discussed (Chapter 10).

Answers to the research questions

The first research question concerns the various forms of cumulative causation, or motors of sustainable innovation, identified. Based on the results of the case studies, four different motors are identified. Each is characterised by particular interactions between system functions:

The STP Motor

The *Science and Technology Push (STP) Motor* is dominated by *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4] and *Resource Mobilisation* [F6]. All the other system functions are either absent or relatively weak.

The dynamic of the STP Motor involves an event sequence consisting of positive expectations and/or research outcomes [F4] leading to the setting up of government- supported R&D programmes [F4] and, directly linked to it, the allocation of financial resources to the emerging technology [F6]. This results in a surge in science activities in the form of basic research and feasibility studies [F2], and also conferences, workshops and other meetings [F3]. In the next step, or in parallel, firms are approached by government actors and research institutes to participate, as technology developers and launching customers, in projects for the realisation of pilots and demonstrations [F1]. The willingness of these firms to participate in such risky projects depends particularly on the outcomes of the feasibility studies [F4]. With positive outcomes, firms may invest, thereby contributing to the expansion of the R&D programme.

The Entrepreneurial Motor

The *Entrepreneurial Motor* is partly similar to the *STP Motor*. Its dynamics are also characterised by a strong fulfilment of *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4] and *Resource Mobilisation* [F6]. What sets the *Entrepreneurial Motor* apart from the *STP Motor* is the particularly important role of *Support from Advocacy Coalitions* [F7] and *Entrepreneurial Activities* [F1].

The event sequence that characterises this motor commences with firms, utilities and/or local governments entering the TIS and initiating innovative projects [F1], usually adoption experiments or demonstrations, because they see opportunities for commercial or societal gain in the future [F4]. Given the pre-commercial status of the emerging technology, the actors lobby in order to obtain resources to cover part of their costs and to compensate the financial risks they take [F7]. If the lobby activities are successful, then the resources are granted in the form of project- specific subsidies [F6]. Depending on the funding, the projects are started [F1]. The outcome, positive or negative, feeds back into the dynamic as it provides the incentive for other actors to initiate projects, or refrain from doing so [F4]. The *Entrepreneurial Motor* may be strengthened through the presence of niche markets [F5].

The System Building Motor

In the *System Building Motor* the set of dominant system functions is similar to those of the *Entrepreneurial Motor* but it includes a more important role of *Market Formation* [F5]. The main difference lies in the connection between *Support from Advocacy Coalitions* [F7], on the one hand, and *Market Formation* [F5] and *Guidance of the Search* [F4] on the other.

These connections are established through entrepreneurs that organise themselves increasingly in networks and manage to draw in new actors [F1], including local governments, intermediaries and interest groups. From this powerful basis, they lobby the government [F7], not for project-specific support, but for policies to mobilise resources or develop regulations beneficial to the emerging technological field as a whole [F4, F6]. Most importantly, their aim is to enforce the creation of a mass market [F5] for the emerging technology.

The Market Motor

The *Market Motor* is characterised by a strong contribution to *Entrepreneurial Activities* [F1], *Knowledge Development* [F2], *Knowledge Diffusion* [F3], *Guidance of the Search* [F4], *Resource Mobilisation* [F6] and *Market Formation* [F5]. All system functions are strongly fulfilled except for the *Support from Advocacy Coalitions* [F7]. The latter is not as important for the dynamics of this motor because *Market Formation* [F5] is no longer a political issue; a market environment has been created as the result of formal regulations. Instead, *Market Formation* [F5] is taken up as part of regular business activities, i.e., marketing activities connected to *Entrepreneurial Activities* [F1].

The event sequence which constitutes the *Market Motor* starts with the setting up of institutional structures that directly facilitate a commercial demand for an emerging technology [F5]. Once such structures are in place, this leads to high expectations [F4] and increasing availability of resources [F6]. This leads to the opening up of possibilities for new entrants to adopt the emerging technology [F1]. The newly entered firms are likely to make large investments, for example in infrastructure [F6], and they may develop marketing strategies [F5], thereby increasing demand for the emerging technology further.

The second research question of this book points to the importance of understanding the mutual relation between structural factors and motors. In order to answer this question, a typical set of structural drivers, barriers and impacts is identified for each motor. An important result from this analysis is that, in a formative TIS, a first primitive motor, for example, a *STP Motor* or an *Entrepreneurial Motor*, typically emerges as the result of a small but dedicated group of enactors. If these enactors manage to improve the institutions and technologies, more enactors and even selectors may be drawn in. All the motors are coupled to developments external to the respective TIS as well. These involve policies, economic trends (e.g. oil prices) and technological developments. However, the internal TIS structures, for example, strategies taken by enactors and selectors, largely determine the specific impact of these developments on the specific development of motors.

Based on the case studies, it is argued that motors play an important role in the build-up of a TIS. Where motors emerged, they reorganised the structural configuration of a TIS. In some cases the motors expanded and grew into the incumbent energy system, thereby linking up to it and reforming parts of it. This was especially the case for the *System Building Motor* and the *Market Motor*.

This means that some motors of sustainable innovation are more powerful than others. In this respect it could be argued that policy makers and entrepreneurs should always strive for a *System Building Motor* or a *Market Motor* to emerge. However, more powerful motors arise only in TISs that are already quite developed. This is because these motors arise from structures built up through the impact of less powerful motors.

A logical step, based on this idea, was to construct an overarching framework – the Succession Model of Innovation – in which the relations between the various motors of sustainable innovation become clear. The Succession Model suggests that motors cause TISs to develop into more complete (and more complex) structural configurations which are prone to yield more advanced motors in turn. According to the Succession Model, the four motors may be regarded as stages in the development of a formative TIS. It turned out that the immature TISs were less prone to develop something other than an *STP Motor*. Only when a TIS was developed enough to generate short-term opportunities for firms did the *Entrepreneurial Motor* emerge. A *System Building Motor* was observed as being a transformation of the *Entrepreneurial Motor*. And finally, the *Market Motor* was typically developed from structures shaped by a *System Building Motor*. In general, there was a relation between the motors observed and the maturity of the TIS in terms of actors involved and in terms of technology and institutions. The most powerful motors arose if a TIS was supported by a large variety of actors, institutions and technologies, preferably integrated into networks.

Relating to the third research question, the Succession Model was applied as a heuristic basis for the evaluation of TISs in dynamic terms. The idea is that the best way to support a formative TIS is to create the (structural) conditions for motors to emerge. Once a motor is developing it may be supported with policies or strategies. Each motor is characterised by particular drivers and barriers. If these drivers are supported and if the barriers are overcome, a shift may result from one motor of innovation to another, more advanced one. With this in mind, the Succession Model is used as a basis for formulating strategic lessons directed at policy makers and other practitioners that aspire to understand and influence the development of emerging energy technologies. These recommendations specify which interventions may be taken to support particular motors, and thereby to further the development of a TIS from one stage of development to another.

Concluding remarks

The objective of this book is to contribute to a theoretical understanding that allows for the analysis and evaluation of dynamics of technological trajectories around emerging sustainable energy technologies. The idea followed throughout this book is that sustainable energy technologies develop within the context of a TIS. This book provides insights that support a better understanding of this build-up process, especially for TISs in the formative stage.

If sustainable energy technologies are to be diffused into society, multiple TISs need to develop and expand into the incumbent energy system. There are numerous sustainable energy technologies, many of which are currently on the verge of a take-off. The TISs around wind energy, solar energy, biomass energy and numerous energy-saving technologies all harbour the potential to make an energy transition happen. It is hoped that the ideas developed in this book will contribute to the development of a variety of sustainable energy TISs and to the realisation of a sustainable energy system in the near future.

The ultimate claim of this book is that, with the right policies and strategies, proper awareness of future needs and long-term commitment of actors from the public and private sphere, it is possible to make this hope become reality.

Table S.1 Functions of technological innovation systems.

System Function	Description	Event types associated
F1. Entrepreneurial Activities	At the core of any innovation system are the entrepreneurs. These risk takers exploit business opportunities and perform the innovative commercial experiments.	Projects with a commercial aim, demonstrations, portfolio expansions
F2. Knowledge Development	Technological research and development (R&D) are a source of variation in the system and are therefore prerequisites for innovation processes to occur.	Studies, laboratory trials, pilots
F3. Knowledge Diffusion	The typical organisational structure of an emergent innovation system is the knowledge network, primarily facilitating information exchange.	Conferences, workshops, alliances
F4. Guidance of the Search	This system function represents the selection processes necessary to facilitate a convergence in development.	Expectations, promises, policy targets, standards, research outcomes
F5. Market Formation	New technologies often cannot outperform established ones. In order to stimulate innovation it is necessary to facilitate the creation of (niche) markets, where new technologies have a possibility to grow.	Market regulations, tax exemptions
F6. Resource Mobilisation	Financial, material and human factors are necessary inputs for all innovation system developments.	Subsidies, investments
F7. Support from Advocacy Coalitions	The emergence of a new technology often leads to resistance from established actors. In order for an innovation system to develop, actors need to raise a political lobby that counteracts this inertia, and supports the new technology.	Lobbies, Advice

Samenvatting

Introduction

Moderne samenlevingen hebben te kampen met problemen die gerelateerd zijn aan de productie en levering van energie. Verbranding van fossiele brandstoffen veroorzaakt diverse milieuproblemen en afhankelijkheid van olie en gas leidt tot geopolitieke spanningen. Eén manier om tot een oplossing te komen, is door ontwikkeling en implementatie van duurzame energietechnologieën. Echter ondanks 30 jaar ontwikkeling op dit gebied is het aandeel van dergelijke technologieën nog altijd marginaal vergeleken met de dominantie van fossiele energietechnologieën. Het aandeel duurzame energie is van 1973 tot 2005 slechts toegenomen met 1,7% (IEA, 2007a). Willen duurzame energietechnologieën binnen overzienbare tijd een substantiële rol kunnen spelen in het energiesysteem, dan moet deze trend worden 'omgebogen'.

Onderliggend aan deze trend van langzaam diffunderende 'renewables' ligt een wereld van bedrijven, consumenten, overheden, wetenschappers en technologieën. Deze wereld wordt treffend beschreven door Unruh (2000) die een overzicht geeft van de diverse oorzaken van wat hij 'carbon lock-in' noemt. Unruh legt uit dat er zich gedurende de afgelopen decennia een energie- en transportsysteem heeft ontwikkeld dat bestaat uit een complex van actoren, instituties en technologieën. Dit complex zorgt ervoor – door middel van schaalvoordelen, kennisaccumulatie, netwerkeffecten en ingesleten gedragingen – dat de positie van fossiele energietechnologieën voortdurend wordt versterkt. Wil de ontwikkeling van duurzame energietechnologieën van de grond kunnen komen, dan zullen deze inerte krachten in het gevestigde energiesysteem moeten worden doorbroken. Dit impliceert een reorganisatie van de structuren die aan de basis liggen van moderne kapitalistische samenlevingen.

Een aanleiding voor optimisme is dat de geschiedenis laat zien dat dergelijke grootschalige transities zich zo nu en dan wel degelijk voordoen. Een overzicht van transities, geschetst door Grübler et al. (1999), maakt duidelijk dat transities worden gekarakteriseerd door een relatief lange periode van gestatie, gevolgd door een periode van versnelling. Als een dergelijke versnelling zich voor het energiesysteem zou voordoen dan zou een volledige verduurzaming kunnen worden gerealiseerd binnen het tijdsbestek van een generatie. Dit boek start vanuit het vertrekpunt dat het mogelijk en zelfs wenselijk is om een dergelijke duurzame energietransitie tot op zeker hoogte te sturen of te beïnvloeden.

Een transitie moet worden gezien als een complex geheel van verweven processen die zich ontvouwen over een lange historische periode. Om transities te kunnen begrijpen, is het daarom noodzakelijk een breed perspectief te hanteren. Alvorens hiertoe te komen is het van belang om te focussen op de onderliggende processen; op de micro- en meso-activiteiten die de kern vormen van een duurzame energietransitie. In dit boek worden technologische innovaties rond duurzame energietechnologieën beschouwd als dergelijke kernprocessen.

Volgens de innovatieliteratuur kan een technologische innovatie worden opgevat als de ontwikkeling van een verzameling onderling afhankelijke technologieën en instituties; dit alles gevormd door de activiteiten van actoren. De uitkomst van dit proces is een accumulatie van structuren. Als deze structuren voldoende ontwikkeld zijn, dan zal het innovatieproces een meer specifieke richting krijgen en mogelijk versnellen (Jacobsson en Bergek, 2004). Zodra een technologische innovatie op het gebied van duurzame energie in een versnelling komt, kan men verwachten dat de inerte structuren die gevestigde energietechnologieën ondersteunen, worden doorbroken en vervangen. Op deze wijze kan technologische innovatie bijdragen aan een duurzame energietransitie.

Vanuit historisch perspectief kan een technologische innovatie worden opgevat als een technologisch traject. De richting van een technologisch traject kan worden beïnvloed. Dit is echter alles behalve triviaal omdat emergente technologieën worden gekarakteriseerd door zogenaamde fundamentele onzekerheden (Meijer, 2008). Immers, de prestaties van een technologisch artefact worden bepaald door de structuren waarin het artefact is ingebed. Een emergente technologie is fluïde. Dat wil zeggen dat de vorm niet vast ligt en dat de koppeling met omringende structuren zwak is; dit maakt dat prestaties meestal ondermaats zijn (Christensen, 1998). Het is vaak zelfs onduidelijk welke betekenis moet worden gehecht aan het idee van een prestatie; het normatieve kader van waaruit deze beoordeling moet plaatsvinden is immers ofwel afwezig, ofwel sterk gekoppeld aan gevestigde structuren die nu juist het probleem vormen waarvoor de emergente technologie een oplossing moet bieden.

Er is dus een situatie waarbij het aan de ene kant duidelijk is dat technologische trajecten rond duurzame energietechnologieën een belangrijke bijdrage kunnen leveren aan een duurzame energietransitie, maar waarbij het aan de andere kant moeilijk blijkt om deze trajecten op een zinnige manier te beïnvloeden. Het is om deze reden dat beleidsmakers en andere praktijkmensen al sinds jaar en dag worstelen om een geschikte aanpak te ontwikkelen. Er is dus een behoefte aan inzicht in de wijze waarop emergente duurzame energietechnologieën worden gevormd en in de wijze waarop dit proces kan worden beïnvloed.

Het algemene doel van dit boek is om bij te dragen aan theoretische inzichten op basis waarvan het mogelijk wordt de dynamiek van technologische trajecten te analyseren en te evalueren. Hierbij is de focus op emergente duurzame energietechnologieën waarvan verwacht wordt dat ze bij kunnen dragen aan een duurzame energietransitie.

Om dit doel te bereiken wordt een begrippenkader ontwikkeld op basis van de Technologische InnovatieSysteem benadering. Het basisidee in deze benadering is dat technologieën worden ontwikkeld binnen de context van een systeem van actoren, instituties en technologieën (Carlsson et al., 2002b). Dit Technologisch InnovatieSysteem (TIS) is er niet van vandaag op morgen, maar moet geleidelijk worden opgebouwd. De TIS-literatuur benadrukt dat gedurende dit opbouwproces emergente technologieën door een zogenaamde 'formatieve fase' gaan. Gedurende deze fase worden steeds meer actoren aangetrokken, instituties ontworpen (denk aan regelgeving) en netwerken gevormd. Gelijktijdig raakt de technologie steeds meer ingebed in deze structuren.

Eén mogelijkheid van een TIS-benadering is te focussen op dergelijk structuren en hun effecten op de technologie. Een ander mogelijkheid is te focussen op de processen die bepalend zijn voor de vorming van het systeem (Jacobsson et al., 2004). Dit wordt wel gedaan door een verzameling van zeven sleutelactiviteiten in kaart te brengen, ook wel systeemfuncties genoemd (Hekkert et al., 2007; Negro, 2007). Een beschrijving van de zeven systeemfuncties is te vinden in Tabel S.2. Het is de verwachting dat door het volgen over de tijd van de vervulling van deze systeemfuncties, een begrip kan worden verkregen van TIS-dynamiek in de formatieve fase.

De belangrijkste bijdrage van dit boek draait om het idee dat de TIS-benadering in essentie een groeimodel is dat is gebaseerd op de notie van cumulatieve veroorzaking (Jacobsson and Bergek, 2004; Myrdal, 1957). Dit betreft het idee dat de opbouw van een TIS een versnelling kan ondergaan als gevolg van systeemfuncties die elkaar wederzijds versterken. Het is de positieve terugkoppeling tussen systeemfuncties die voor de opbouw kan zorgen die nodig is voor de snelle diffusie van een duurzame energietechnologie. Het idee om interacties tussen systeemfuncties te onderzoeken is niet nieuw. Maar tot nu toe is er geen poging gedaan om de bevindingen die gedaan zijn op basis van dit idee te generaliseren. Omwille van een beter begrip van transitieprocessen is het wel van belang om dit te doen. Immers, er is niet één TIS maar er zijn er vele die ondersteuning behoeven en elk van hen bezit de potentie om een bijdrage te leveren aan een duurzame energietransitie.

In dit boek zal voor verschillende TIS'en de dynamiek in de formatieve fase in kaart worden gebracht met als doel een typologie te construeren over vormen van dynamiek die in het algemeen voorkomen. Een aanname hierbij is dat er zich verschillende vormen van cumulatieve veroorzaking kunnen voordoen. Deze variaties zullen motoren van duurzame innovatie worden genoemd. De volgende drie onderzoeksvragen worden beantwoord:

RQ1: Welke motoren van duurzame innovatie kunnen worden geïdentificeerd in het domein van emergente duurzame energietechnologieën?

RQ2: Kan de vorming, de retentie (en ondergang) van motors van duurzame innovatie worden verklaard in termen van structuren (actoren, instituties, technologieën, netwerken) en externe invloeden, en tot op welke hoogte beïnvloeden deze motoren op hun beurt deze structuren?

RQ3: Hoe kunnen TIS'en in de formatieve fase worden geëvalueerd op basis van de motoren?

De drie onderzoeksvragen worden beantwoord door de historische ontwikkeling van verschillende TIS'en rond emergente duurzame energietechnologieën te bestuderen in Nederland (n=4) en Zweden (n=1) (zie hieronder). Voor iedere TIS worden motoren van duurzame innovatie geïdentificeerd en worden structuren blootgelegd en gerelateerd aan deze motoren. Gebaseerd op deze resultaten worden evaluatieve inzichten gepresenteerd. Uiteindelijk worden de resultaten over verschillende cases heen vergeleken en verwerkt tot een typologie die de synthese vormt van dit boek.

Deel I Theorie en Methode

Het eerste deel van dit boek (Hoofdstuk 2 en 3) bevat een uiteenzetting van de theoretische en methodologische ideeën die worden gebruikt voor de casestudies. Het theoretische onderdeel bevat een discussie van de literatuur over innovatiesystemen, inclusief een gedetailleerde uitleg van alle concepten die gerelateerd zijn aan het TIS, zowel waar het gaat om *structuren* als om *processen*. Het methodische onderdeel is toegespitst op de wijze waarop de opbouw van een TIS concreet kan worden gemeten. De belangrijkste theoretische concepten zijn de volgende:

TIS-structuren

Structurele factoren representeren het statische aspect van een TIS. Het gaat hier om elementen die tot op zekere hoogte stabiel zijn in de tijd. Er worden drie basiscategorieën onderscheiden: actoren, instituties en technologieën.

- De actor-categorie betreft iedere organisatie die bijdraagt (bijvoorbeeld met kennis en vaardigheden) aan de emergente technologie in kwestie, ofwel direct als ontwikkelaar of gebruiker, ofwel indirect als overheid, financier, etcetera. Er wordt verder onderscheid gemaakt tussen zogenaamde 'enactors' en 'selectors' (Garud en Ahlstrom, 1997). Enactors zijn actoren die nauw betrokken zijn bij de ontwikkeling van een technologie; zij zijn voor hun voortbestaan volledig afhankelijk van het succes van de emergente technologie. Selectors zijn op afstand betrokken en hebben doorgaans de mogelijkheid om tussen verschillende technologische opties te kiezen.

- Instituties zijn de spelregels waaraan actoren zich (moeten) houden. Denk aan wetgeving, regulering, sociale normen. Instituties omvatten ook cognitieve regels zoals heuristieken, verwachtingen en beloften. In het licht van een interventie is deze categorie zeer belangrijk omdat de genoemde elementen vaak het onderwerp zijn van overheidsbeleid en bedrijfsstrategieën.

- Technologische factoren omvatten technische artefacten en de technologische infrastructuur waarin deze zijn geïntegreerd. De techno-economische werking van artefacten, dat wil zeggen de kostenstructuur, veiligheid, betrouwbaarheid, opschalingsmogelijkheden, etcetera, zijn van cruciaal belang voor een goed begrip van technologische ontwikkeling.

Structurele factoren zijn slechts de bouwstenen van het systeem. In een feitelijk bestaand TIS zullen deze elementen met elkaar verwevenzijn. In het bijzondere geval dat verschillende elementen een dichte configuratie vormen, kunnen zij een netwerk genoemd worden. Deze netwerken zijn cruciale vormen van organisatie, onder andere omdat zij de uitwisseling en recombinatie van kennis tussen verschillende actoren mogelijk maken. Op een hoger aggregatieniveau zullen alle netwerken samen één groot netwerk vormen. Indien dit netwerk voldoende coherent is spreken we van een systeemconfiguratie.

TIS-processen

Het doel van dit boek is inzicht te verkrijgen in TIS-dynamiek ligt de focus op processen, of systeemfuncties. Het idee achter de zogenaamde Functies van Innovatiesystemen Benadering is om het TIS te beschouwen als een systeem met een doel; een doel dat gediend wordt door de vervulling van een verzameling systeemfuncties. Systeemfuncties zijn (type) activiteiten die noodzakelijk zijn voor de opbouw van een TIS. Het is van belang om in dit licht op te merken dat iedere systeemfunctie op uiteenlopende wijze kan worden vervuld; iedere systeemfunctie omvat een variatie van activiteiten. Deze opvatting laat ruimte voor de mogelijkheid om ook activiteiten die negatief bijdragen te beschouwen als 'vervulling' van een systeemfunctie. Deze negatieve bijdragen kunnen worden gezien als een (gedeeltelijke) afbraak van het TIS.

Het idee van cumulatieve veroorzaking impliceert dat systeemfuncties elkaar kunnen versterken over de tijd. Een positieve interactie tussen systeemfuncties is zelfs noodzakelijk voor de opbouw van een TIS. Deze interactie kan leiden tot het ontstaan van een virtueuze cyclus. Bijvoorbeeld: de succesvolle realisatie van een onderzoeksproject, bijdragend aan *Kennisontwikkeling* [F2], kan resulteren in grote verwachtingen, bijdragend aan *Richtinggeving* [F4] onder beleidsmakers; dit kan dan resulteren in het ontwerpen van een subsidieregeling, bijdragend aan *Mobiliseren van Middelen* [F6], die op zijn beurt weer leidt tot meer onderzoeksactiviteiten die bijdragen aan *Kennisontwikkeling* [F2], *Richtinggeving* [F4], etcetera (zie Tabel S.2). Systeemfuncties kunnen elkaar ook neerwaarts versterken. In dat geval is er sprake van conflicterende ontwikkelingen, stagnatie of zelfs een vicieuze cyclus.

Om het proces van TIS-opbouw goed te kunnen begrijpen, is het belangrijk te weten onder welke omstandigheden zich virtueuze of vicieuze cycli voordoen. Bovendien is het, in het licht van een mogelijke interventiestrategie, nuttig om te weten op welke wijze dergelijke processen kunnen worden opgeroepen, of op zijn minst ondersteund. De dynamiek die ontstaat kan enorm krachtig zijn en heeft de potentie om gevestigde structuren te ondermijnen. Het is misschien onmogelijk dat een dergelijke ontwikkeling in gang wordt gezet door een enkele ondernemer, of zelfs door een overheid. Aan de andere kant suggereert de theorie dat zodra een cyclus ontstaat, een interventie op één van de activiteiten alle andere activiteiten zal bevorderen. Een enkele goedgeplaatste interventie kan op die manier het TIS enorm versterken.

Het voorbeeld hierboven is simpel en het is te verwachten dat er zich in werkelijkheid meer complexe vormen van cumulatieve veroorzaking zullen voordoen; vormen die een groter aantal systeemfuncties omvatten en meer dan één terugkoppelingsmechanisme. Een belangrijke aanname in dit boek is echter dat er een beperkte verzameling is aan dynamische patronen die zich in werkelijkheid voordoen in een opkomend TIS. Als dit inderdaad het geval is, dan is het nuttig om een typologie te construeren van vormen van cumulatieve veroorzaking die zich kunnen voordoen in de formatieve fase van een TIS. Deze vormen worden motoren van duurzame innovatie genoemd.

De relatie tussen proces en structuur

Motoren kunnen niet los worden gezien van de TIS-structuur. Een motor ontstaat binnen een configuratie van TIS structuren. Omgekeerd wordt deze configuratie wederkerig beïnvloed door de motor. Dit betekent het volgende:

- Het is te verwachten dat structurele factoren grotendeels bepalen hoe verschillende systeemfuncties worden vervuld en hoe deze elkaar versterken en motoren vormen. Hierbij gaat het om aanwezige enactors en selectors, de instituties en de aard van de technologieën in het systeem. Externe factoren zijn ook van belang.

- Motoren zullen omgekeerd de TIS structuren beïnvloeden. Hiermee werken ze in op de configuratie die hun ontstaan in eerste instantie mogelijk maakte. Bij deze invloed kan gedacht worden aan nieuwe enactors of selectors die toetreden tot het systeem, instituties die worden opgezet en aanpassingen die worden gedaan aan de beschikbare technologieën, etcetera.

Methode

Iedere casestudie moet resulteren in de identificatie van structuren en systeemfuncties binnen het TIS in kwestie. Om dit te bewerkstelligen, wordt gebruik gemaakt van een systematische benadering, de zogenaamde 'event history analysis' (Poole, 2000; Van de Ven, 1990; 1999). Deze methode biedt de mogelijkheid om systeemfuncties te operationaliseren en te meten in termen van gebeurtenissen die zich in de tijd voordoen. Voorbeelden van gebeurtenissen zijn studies, conferenties, fabrieken die gebouwd worden, beleidsmaatregelen die geïntroduceerd worden, etcetera.

Gebaseerd op literatuurstudies en interviews is voor iedere casestudie een database opgezet waarin zoveel mogelijk gebeurtenissen zijn vastgelegd. De identificatie van gebeurtenissen moet worden gezien als een inductieve excercitie waarbij het conceptuele kader, met name gevormd door de zeven systeemfuncties, als heuristiek geldt. Dit betekent dat de systeemfuncties als theoretische concepten leidend waren voor het selecteren van relevante informatie en voor het interpreteren daarvan. De database gaf uiteindelijk inzicht in de inhoud van alle gebeurtenissen en overzicht van de chronologie. Op basis van dit overzicht was het mogelijk om gebeurtenissen te clusteren in typen. Deze typen zijn weer als indicatoren gekoppeld aan de zeven systeemfuncties (zie Tabel S.2).

De ontwikkeling van individuele systeemfuncties over de tijd kon worden gemeten door per systeemfunctie voor ieder jaar het aantal gebeurtenissen op te tellen. De interactie tussen de systeemfuncties kon worden gemeten door de relaties tussen de gebeurtenissen te traceren. De gebeurtenissen konden op deze wijze in sequenties worden geplaatst, zoals in het boven gegeven voorbeeld van de virtueuze cyclus. Deze patronen zijn geïnterpreteerd als elementen van een narratief. Dit narratief, bestaande uit verhaallijnen die sterk gerelateerd zijn aan de systeemfuncties en hun interacties, is gevalideerd aan de hand van interviews met verschillende experts op het gebied van de desbetreffende case. Dit narratief vormde de basis voor alle verdere analyses.

De 'event history analysis' biedt de mogelijkheid tot het identificeren van motoren van duurzame innovatie in termen van sequenties van gebeurtenissen die zich over de tijd herhalen. De methode biedt ook de mogelijkheid om structuren te analyseren die gerelateerd zijn aan deze motoren, ofwel als onderliggende oorzaak van verandering ('drivers' en 'barriers'), ofwel als onderwerp van verandering ('impacts').

Deel II Casestudies

Het tweede deel van dit boek beslaat de vijf casestudies (Hoofdstukken 4-8). Deze studies bevatten ieder een analyse van de ontwikkeling van een specifiek TIS. De nadruk ligt op het blootleggen van de dynamiek rond de opbouw van het TIS; het identificeren van motoren van duurzame innovatie is daarbij leidend. De analyseresultaten worden voor de verschillende studies ook vertaald naar evaluatieve inzichten en beleidsimplicaties. De casestudies moeten worden opgevat als de bouwstenen waarmee uiteindelijk in het laatste deel een typologie van motoren wordt geconstrueerd. In de volgende passage wordt iedere casestudie kort geïntroduceerd. De karakteristieken van de verschillende motoren worden niet uiteengezet; dit komt aan bod in Deel III.

Biomassavergassing in Nederland

De studie over biomassavergassing (Hoofdstuk 4) gaat over het Nederlandse TIS rond biomassavergassingstechnologie van 1980 tot 2004. Het gaat hier om de productie, diffusie en implementatie van een technologie voor de conversie van biomassa naar syngas. De conversie naar syngas maakt het mogelijk om op efficiënte, schone en flexibele wijze bio-energie te produceren.

De dynamiek van het BiomassaverGassingsTIS (BGTIS) wordt gekarakteriseerd door een langzame opbouw, gevolgd door een versnelling en direct daarna een snelle ineenstorting. De opbouw begon in de jaren '80 binnen een gemeenschap van wetenschappers en ingenieurs die tot dan toe ervaring hadden opgedaan met kolenvergassing. In de jaren'90 werd biomassavergassing steeds meer gezien als een sleuteltechnologie voor de realisatie van een duurzaam energiesysteem. Deze sterke belofte werd gevoed door wetenschappers, ingenieurs en beleidsmakers. Het gevolg was dat vele kleine ondernemingen toetraden tot het TIS en experimentele projecten begonnen uit te voeren. Niettemin bleek al snel dat biomassavergassingstechnologie vele onvoorziene problemen kende. De hype kwam rond 1998 aan een einde en werd gevolgd door een abrupte ineenstorting.

De nadruk in deze casestudie ligt op het identificeren van systeemfuncties en het relateren daarvan aan 'drivers' en 'barriers' binnen (en buiten) het TIS. Het concept van een motor komt hier niet expliciet aan de orde, maar er worden wel virtueuze en vicieuze cycli onthuld die overeenkomen met sommige van de motoren uit andere casestudies.

Biobrandstoffen in Nederland

De tweede casestudie (Hoofdstuk 5) gaat over het Nederlandse TIS rond biobrandstoffen in de periode 1990 tot 2005. De nadruk ligt op de productie, diffusie en implementatie van vloeibare biobrandstoffen in het mobiliteitsdomein. Er zijn verschillende type biobrandstof technologieën, maar er wordt vaak onderscheid gemaakt tussen biobrandstoffen van de eerste generatie (1G) en van de tweede generatie (2G).

De dynamiek van het BioBrandsoffen-TIS (BBTIS) wordt gekarakteriseerd door een conflict over de wenselijkheid van 1G versus 2G biobrandstoftechnologie. De vroege BBTIS-ontwikkelingen beginnen rond 1990 en betreffen experimenten met 1G-technologie, uitgevoerd door boeren, kleine ondernemers en lokale overheden. Later in de jaren '90 beginnen wetenschappers en milieuorganisaties te ageren tegen deze ontwikkelingen. Het argument is dat biobrandstoffen duur zijn, inefficiënt en bovendien niet duurzaam. In plaats van 1G-biobrandstoffen, zo beweren deze lobbyisten, moet worden ingezet op 2G-biobrandstoffen. Het gevolg is dat de nationale overheid met name de 2G-biobrandstoffen ondersteunt. Vanaf eind jaren '90 wordt het BBTIS enkele jaren gedomineerd door activiteiten rond 2G-biobrandstoffen. Dit verandert in 2004-2005 als de EU, ondanks de controverse rond 1G biobrandstoffen, besluit een beleidsrichtlijn af te kondigen met als doel om in 2010 een aandeel te realiseren van 10% biobrandstoffen in de transportvraag. Het gevolg is een toename in allerlei activiteiten, zowel rond 1G- als 2G-biobrandstoffen. Het conflict tussen aanhangers van beide technologische opties gaat intussen echter gewoon door. Wetenschappers en milieuactivisten nemen zelfs stelling tegen biobrandstoffen in het algemeen (1G en 2G).

Deze casestudie resulteert in de identificatie van drie motoren die de ontwikkelingen rond biobrandstoffen in Nederland hebben bevorderd: een *Ondernemersmotor*, een *Wetenschap en*

Technologiegedreven motor en een *Marktmotor*. Ook wordt een verzameling 'drivers' en 'barriers' geformuleerd. Hierbij wordt de biobrandstoffencontroverse genoemd als een belangrijke belemmering voor een gezonde ontwikkeling van het TIS. Actoren zijn door de conflictsituatie niet in staat gebleken om samen te werken en zich als groep te mobiliseren voor wat eigenlijk een gemeenschappelijk doel zou moeten zijn: de ontwikkeling van het BBTIS als geheel.

Biobrandstoffen in Zweden

Het perspectief op de dynamiek rond biobrandstoffen wordt verbreed door een vergelijking van het Nederlandse BBTIS met het Zweedse BBTIS (Hoofdstuk 6). De ontwikkeling van het Zweedse BBTIS wordt gekarakteriseerd door een geleidelijke opbouw. Aan het begin van de jaren '80 werden diverse toepassingsgerichte projecten geïnitieerd door een publiek-privaat samenwerkingsverband. In de jaren '90 breidde deze dynamiek zich uit onder invloed van diverse overheidsmaatregelen die gericht waren op ondersteuning van zowel 1G als 2G biobrandstoffen. Deze maatregelen werden gelegitimeerd op basis van lokale milieuproblemen. Aan het eind van de jaren '90 slaagden voorstanders van 1G-biobrandstoffen erin om nichemarkten te vormen die het gebruik van 'flexi-fuel'-voertuigen ondersteunden. Hierdoor werd de ontwikkeling van biobrandstoffen ook bevorderd onder eindgebruikers. Ondanks het feit dat voorstanders van 2G-biobrandstoffen ook hier de 1G-biobrandstoffen bekritiseerden, was er over het algemeen sprake van samenwerking tussen uiteenlopende actoren. Binnen deze samenwerkingsverbanden werd gepleit voor een algemeen overheidsbeleid ter bevordering van biobrandstoffen. Het gevolg was dat de Zweedse overheid vanaf 2000 een serie marktstimuleringsmaatregelen introduceerde.

Deze casestudie onthult verschillende vormen van cumulatieve veroorzaking. Op basis van het comparatieve perspectief worden verschillen en overeenkomsten getoond tussen Nederland en Zweden. Op basis hiervan worden enkele belangrijke lessen getrokken die van nut kunnen zijn voor praktijkmensen met de ambitie om de TIS-dynamiek positief te beïnvloeden. De analyse laat met name zien dat in het Zweedse TIS sterker werd aangestuurd op het gelijktijdig bevorderen van verschillende systeemfuncties.

Brandstofcellen en waterstoftechnologie in Nederland

De vierde casestudie gaat over het Nederlandse TIS rond brandstofcellen en waterstoftechnologieën van 1980 tot 2007 (Hoofdstuk 7). Deze studie betreft de ontwikkeling, diffusie en implementatie van brandstofcellen en van de waterstofopslag en -distributie infrastructuur die nodig is om deze technologieën van brandstof te voorzien. De verwachting is dat het gebruik van brandstofcellen kan resulteren in efficiëntievoordelen en emissiereducties. Bovendien herbergt de technologie de mogelijkheid om het mobiliteitssysteem te koppelen aan een gevarieerde schare (duurzame) energiebronnen.

De dynamiek van het Brandstofcellen en Waterstoftechnologie-TIS (BWTIS) wordt gekarakteriseerd door een opeenvolging van verschillende golven van activiteit. De eerste golf begon in de jaren '70 – tegen de achtergrond van de oliecrisis – toen de gesmolten carbonaatbrandstofcel (MCFC) een interessante optie bleek voor het efficiënter maken van de elektriciteitsproductie. De MCFC werd door wetenschappers en ingenieurs gepusht en al snel werd de technologie opgepikt door beleidsmakers op nationaal niveau. Het resultaat was dat begin jaren '80 een ontwikkelingsprogramma werd gestart. Tot in de vroege jaren '90 werd het BWTIS gedomineerd door activiteiten die voortvloeiden uit dit programma. Het programma resulteerde alleen niet in de beoogde realisatie van demonstratieprojecten. Een terugkerend probleem was de afwezigheid van 'launching customers'. In 1998 werd het programma stop gezet. Op dat zelfde moment ontstond een tweede golf van activiteit; deze golf werd geinitieerd door sterke verbeteringen in de prestaties van een geheel andere brandstofceltechnologie, de polymere brandstofcel (PEMFC). De PEMFC maakt het mogelijk dat het BWTIS wordt gekoppeld aan een nieuw toepassingsdomein, dat van elektrische voertuigen. Gedurende de reöriëntatie op de PEMFC-technologie wordt het BWTIS sterk gesteund door externe ontwikkelingen: stijgende olieprijzen, het klimaatprobleem en met name lokale een toenemende druk op de lokale luchtkwaliteit binnen gemeenten. Een gevarieerde schare aan actoren trad toe tot het systeem met als resultaat dat vanaf 2005 een grote hoeveelheid technologiedemonstraties werd gerealiseerd. Hierdoor werd deze opkomende technologie zichtbaarder dan ooit.

In deze casestudie worden twee motoren van duurzame innovatie geïdentificeerd: een *Wetenschap en Technologiegedreven motor* en een *Ondernemersmotor*. Deze studie focust meer dan de voorgaande studies op het blootleggen van structuren die bijdragen aan het ontstaan van de motoren. Daarnaast bevat deze studie een analyse van de impact van deze motoren op de TIS-structuren.

Aardgas als transportbrandstof in Nederland

De vijfde casestudie gaat over het Nederlandse TIS rond aardgas als transportbrandstof (Hoofdstuk 8). Dit betreft de productie, diffusie en implementatie van aardgas als transportbrandstof in de periode 1970-2007. De verwachting is dat aardgas voordelen biedt in de vorm van emissiereducties van CO_2 en vooral fijnstof.

De dynamiek rond het Aardgas-TIS (ATIS) wordt gekarakteriseerd door een opbouw in de jaren '70, gevolgd door een periode van verval in de jaren '80. Vanaf 2000 wordt het systeem weer geleidelijk opgebouwd. De vroege opbouw werd geïnduceerd door de oliecrisis van de jaren '70, die er toe leidde dat gasproducenten en andere nutsbedrijven gingen experimenteren met alternatieve brandstoffen voor hun 'vlootvoertuigen'. Het ging hier om een groeiend aantal adoptie-experimenten, ondersteund door de nationale overheid en de EU. De ineenstorting van het ATIS begon in de jaren '90 op het moment dat de olieprijs sterk daalde en de behoefte aan alternatieve brandstoffen weer verdween. Het hielp ook niet dat gedurende de adoptie-experimenten bleek dat de jonge technologie niet altijd even betrouwbaar was en dat het rijden op aardgas hoge investerings- en onderhoudskosten met zich meebracht. Het gevolg was een vrijwel totale ineenstorting van het ATIS. Pas vanaf 2000 begonnen de ontwikkelingen weer. Dit keer als gevolg van een aangescherpt EU luchtkwaliteitsbeleid waar met name lokale overheden mee te maken hadden; de aardgastechnologie bleek voor veel gemeenten uitkomst te bieden. Het gevolg was dat hier en daar weer geëxperimenteerd werd met aardgasvoertuigen. Vanaf 2004 onderging deze ontwikkeling een versnelling doordat diverse 'aardgas aanhangers' de handen ineen sloegen en zich organiseerden in platformorganisaties die lobbyden voor een nationaal ondersteuningsbeleid. Het was de ambitie van deze goed georganiseerde actoren om een landelijke aardgasinfrastructuur uit te rollen. Deze activiteiten stuitten op verzet, met name binnen de nationale overheid, maar ook onder gevestigde industriën. Het gevolg was een politieke strijd die, in 2006-2007, resulteerde in een overwinning voor de aardgas-lobby. Sindsdien is er een serie beleidsmaatregelen afgekondigd met als doel een markt te stimuleren voor aardgasvoertuigen.

In deze casestudie worden drie motoren van duurzame innovatie geïdentificeerd; de *Ondernemersmotor*, de *Systeemmotor* en de *Martkmotor*. Net als in de voorgaande casestudie, focust de analyse zowel op motoren als op de structurele factoren die aan deze motoren ten grondslag liggen (en onderwerp zijn van verandering).

Deel III Synthese

In het derde deel van dit boek worden de inzichten uit de casestudies gecombineerd met als doel een geïntegreerd totaalbeeld te vormen over de verschillende motoren van duurzame innovatie die zich voordoen in de formatieve fase van een TIS. Op basis van dit totaalbeeld worden de drie eerder gestelde onderzoeksvragen beantwoord (Hoofdstuk 9 en 10). Vervolgens worden ook de relevantie en de geldigheid van deze antwoorden bediscussieerd (Hoofdstuk 10).

Antwoorden op de onderzoeksvragen

De eerste onderzoeksvraag betreft de diverse vormen van cumulatieve veroorzaking, of motoren van duurzame innovatie. Op basis van de casestudies zijn vier verschillende motoren geïdentificeerd. Iedere motor wordt gekarakteriseerd door interacties tussen de verschillende systeemfuncties:

De WT-motor

De *Wetenschap en Technologiegedreven motor* wordt gedomineerd door *Kennisontwikkeling* [F2], *Kennisdiffusie* [F3], *Richtinggeving aan het Zoekproces* [F4] en *Mobiliseren van Middelen* [F6]. Alle andere systeemfuncties zijn zwak of afwezig.

De dynamiek van deze motor wordt gekarakteriseerd door de volgende sequentie van gebeurtenissen: positieve verwachtingen en/of onderzoeksresultaten [F4] leiden tot overheidsgefinancierde R&D-programma's [F4] en, hieraan gerelateerd, tot de allocatie van financiële middelen [F6]. Dit heeft tot gevolg dat er een toename is in wetenschappelijke activiteiten in de vorm van fundamenteel onderzoek en haalbaarheidsstudies [F2] en tevens in de vorm van conferenties, workshops en andere ontmoetingen [F3]. In de volgende stap, of gelijktijdig, worden bedrijven benaderd door beleidsmakers en onderzoeksinstituten om te participeren in de ontwikkeling, ofwel als technologieontwikkelaars ofwel als 'launching customers' [F1]. Het doel is doorgaans om grote technologiedemonstraties op te zetten om te bewijzen dat de technologie marktrijp is. De bereidheid van het bedrijfsleven om deel te nemen in dergelijke risicovolle projecten hangt veelal af van de eerdere onderzoeksresultaten [F2, F4]. Bij voldoende hoge verwachtingen zullen bedrijven bereid worden gevonden te investeren en daarmee bijdragen aan de expansie van het R&D-programma [F4, F6], met nog meer onderzoeksactivitetien als gevolg [F2, F3].

De Ondernemersmotor

De *Ondernemersmotor* komt deels overeen met de *WT-motor*. De dynamiek wordt gekarakteriseerd door een sterke vervulling van *Kennisontwikkeling* [F2], *Kennisdiffusie* [F3], *Richtinggeving aan het Zoekproces* [F4], en *Mobiliseren van Middelen* [F6]. Wat de *Ondernemersmotor* onderscheidt van de *WT-motor* is de belangrijke aanvullende rol van *Ondersteuning door Belangengroepen* [F7] en *Ondernemersactiviteiten* [F1].

De gebeurtensissensequentie die karakteristiek is voor deze motor zier er als volgt uit: ondernemers, nutsbedrijven en/of lokale overheden treden toe tot het TIS en initiëren innovatieve experimenten met de nieuw technologie [F1]. Meestal gaat het om adoptie-experimenten en demonstratieprojecten. Deze partijen zien kansen voor commercieel succes ofwel voor een maatschappelijk goed [F4]. Omdat de technologie nog niet marktrijp is hebben de actoren meestal aanvullende middelen nodig om hun kosten en risico's te dekken. Om die reden lobbyen ze veelal richting de nationale overheid [F7]. Als dit goed gaat worden hun projecten gefinancierd, meestal met projectgerichte subsidies [F6]. Afhankelijk van deze steun worden de projecten gestart [F1]. De uitkomst van deze projecten kan succesvol of minder succesvol zijn [F4]. Hiermee ontstaat een terugkoppeling (positief of negatief) in het systeem. Immers, bij een positieve uitkomst zullen nieuwe actoren bereid zijn om projecten te initiëren [F1]. De Ondernemersmotor kan worden gesterkt door de aanwezigheid van nichemarkten [F5].

De Systeemmotor

De dominante systeemfuncties van de *Systeemmotor* zijn grotendeels dezelfde als in de *Ondernemersmotor*. Maar een belangrijk verschil ligt in het enorme belang van *Marktvorming* [F5]. Verder ligt er een verschil in de rol van *Ondersteuning door Belangengroepen* [F7] bij het aanjagen van *Richtinggeving aan het Zoekproces* [F4] en vooral *Marktvorming* [F5]. Deze rol wordt nu ingevuld door ondernemers die zich in toenemende mate organiseren in netwerken en platformorganisaties. Hun inspanningen leiden ertoe dat nieuwe actoren toetreden [F1] tot het systeem. Hieronder bevinden zich lokale overheden en bedrijven. Vanuit deze krachtige organisatorische basis lobbyen deze partijen voor ondersteuning vanuit de nationale overheid [F7]. Het betreft hier niet zozeer een vraag om projectspecifieke steun, maar een roep om beleid dat het veld als geheel vooruit helpt [F4, F6]. De hoogste inzet is beleid af te dwingen om een grootschalige markt te stimuleren voor deze emergente technologie [F5].

De Marktmotor

De *Marktmotor* wordt gekarakteriseerd door een sterke bijdrage van *Ondernemersactiviteiten* [F1], *Kennisontwikkeling* [F2], *Kennisdiffusie* [F3], *Richtinggeving aan het Zoekproces* [F4], *Mobiliseren van Middelen* [F6] en *Marktvorming* [F5]. Alle systeemfuncties zijn sterk vervuld behalve de *Ondersteuning door Belangengroepen* [F7]. Deze laatste activiteit is bij deze motor relatief van minder belang omdat *Marktvorming* [F5] niet langer een politiek obstakel vormt; er is al een marktomgeving tot stand gekomen als gevolg van overheidsregulering. De activiteiten die nog wel onder *Marktvorming* [F5] vallen zijn onderdeel van reguliere bedrijfsvoering, bijvoorbeeld marketing acties die voortkomen uit *Ondernemrsactiviteiten* [F1].

Een typische gebeurtenissensequentie behorende bij de *Marktmotor* begint met de totstandkoming van structuren die een commerciële marktvraag op gang brengen voor de emergente technologie [F5]. De aanwezigheid van deze structuren leidt tot grote verwachtingen [F4] en een toenemende beschikbaarheid van middelen [F6]. Dit resulteert erin dat er een toenemend aantal ondernemers toetreedt tot het systeem om de emergente technologie te gebruiken of verder te ontwikkelen [F1]. Deze commerciële spelers investeren massaal in de toekomst van de technologie, bijvoorbeeld door een uitgebreide infrastuctuur uit te rollen [F6]. Ze zetten daarbij ook in op verdergaande stimulering van de vraag middels allerlei specifieke marketingacties [F5].

De tweede onderzoeksvraag van dit boek duidt op het belang van een goed begrip van de wederkerige relatie tussen de structurele factoren van een TIS en de motoren. Om inzicht te bieden in deze complexe relatie wordt voor iedere motor onderzocht welke structuurfactoren ('drivers' en 'barriers') bepalend zijn geweest in de ontwikkeling en retentie van die motor. Ook wordt de invloed ('impact') van iedere motor op TIS-structuren geanalyseerd. Een belangrijk resultaat van deze analyse is dat, voor een TIS in de formatieve fase, een eerste primitieve motor, bijvoorbeeld een *WT-motor* of een *Ondernemersmotor*, veelal ontstaat door de inspanningen van een kleine toegewijde groep 'enactors'. Als deze 'enactors' erin slagen om verbeteringen aan te brengen in de technologische en institutionele structuur, dan kan dit ertoe leiden dat nog meer 'enactors', en zelfs 'selectors', toetreden tot het systeem. Alle motoren zijn ook gekoppeld aan TIS-externe invloeden. Dit betreft bijvoorbeeld EU-beleid, economische veranderingen (zoals olieprijzen) en ontwikkelingen rond alternatieve technologieën. Toch is het zo dat de interne TIS-structuren, bijvoorbeeld de strategieën die worden ontplooid door enactors, in belangrijke mate bepalen wat de precieze impact van de externe invloeden is op de ontwikkeling van motoren.

Op basis van de verschillende casestudies kunnen we stellen dat motoren een belangrijke rol spelen in de opbouw van een TIS. In alle gevallen waar motoren tot ontwikkeling kwamen was duidelijk te zien dat de structuren van een TIS aan verandering onderhevig waren. In sommige gevallen breidde de dynamiek van de motoren zich zodanig uit dat ze invloed hadden op de structuren van het gevestigde energiesysteem. Deze koppelingen met het gevestigde energiesysteem werden met name geobserveerd voor de *Systeemmotor* en de *Marktmotor*.

Dit betekent dat sommige motoren krachtiger zijn dan andere. Dit kan een argument zijn om te claimen dat beleidsmakers en ondernemers altijd moeten streven naar een *Systeemmotor* of een *Marktmotor*. Het probleem is echter dat dergelijke krachtige motoren zich met name voordoen in TIS'en die al relatief volwassen zijn. Deze motoren ontstaan namelijk vanuit structuren die eerder zijn opgebouwd onder de invloed van minder krachtige motoren.

Een logische stap op basis van dit idee, was om een overkoepelend kader te ontwikkelen – het Successieve Innovatiemodel – waarbinnen de relaties tussen de verschillende motoren van duurzame innovatie duidelijk worden. Het Successieve Innovatiemodel suggereert dat iedere motor ertoe bijdraagt dat een TIS zich verder ontwikkelt en daarbij completere (en complexere) structuren realiseert, die de condities vormen voor het ontstaan van meer geavanceerde motoren. Volgens het Successieve Innovatiemodel kunnen de vier motoren grofweg worden beschouwd als ontwikkelingsstadia binnen de formatieve fase van een TIS. Het is gebleken dat voor primitieve TIS'en nauwelijks te verwachten valt dat er zich iets anders voordoet dan een *WT-motor*. Slechts wanneer een TIS ontwikkeld genoeg is om op korte-termijn kansen te genereren voor bedrijven kan een *Ondernemersmotor* worden verwacht. De *Systeemmotor* deed zich met name voor als transformatie van de *Ondernemersmotor*. De *Marktmotor*, tenslotte, ontwikkelde zich veelal vanuit structuren die eerder waren opgebouwd door een *Systeemmotor*. In het algemeen blijkt er dus een relatie te bestaan tussen de geïdentificeerde motoren en het ontwikkelingsniveau van de TIS-structuren. De krachtigere motoren ontstonden daar waar het TIS werd gesteund door een grote varieteit aan actoren, instituties en technologieën, bij voorkeur in sterk geïntegreerd netwerken.

De derde onderzoeksvraag betreft de mogelijkheid tot evaluatie van een TIS. In dit licht is het Successieve Innovatiemodel toegepast als heuristiek. Het idee is dat een TIS in de formatieve fase het beste kan worden ondersteund door de structurele condities te scheppen, die er toe kunnen leiden dat er motoren ontstaan en tot ontwikkeling komen. Zodra er een motor is, kan beleid en strategie erop worden gericht dat deze dynamiek zich voortzet en uitbreidt. Iedere motor wordt gekarakteriseerd door bepaalde 'drivers' en 'barriers'. Als de drivers voldoende worden ondersteund en als de barriers worden overbrugd, dan kan zich een verschuiving voordoen in de dynamiek, zodanig dat de motor wordt overgenomen door een andere meer geavanceerde motor. Dit idee van motoren die elkaar opvolgen in successie vormt de basis voor het formuleren van strategische lessen gericht op beleidsmakers en praktijkmensen met de ambitie om de ontwikkeling van emergente duurzame energietechnologieën te begrijpen en te beïnvloeden. In de hieraan gerelateerde aanbevelingen wordt per motor een bepaalde interventiestrategie voorgesteld. Hiermee moet het mogelijk zijn om de ontwikkeling van een TIS te stimuleren over verschillende ontwikkelingsstadia.

Concluderend

Het doel van dit boek is om bij te dragen aan theoretische inzichten op basis waarvan het mogelijk wordt de dynamiek van technologische trajecten rond emergente energietechnologieën te analyseren en te evalueren. Het idee wordt uitgewerkt dat duurzame energietechnologieën tot ontwikkeling komen binnen de context van een TIS dat wordt opgebouwd. De inzichten gepresenteerd in dit boek moeten leiden tot inzicht in dit opbouwproces, in het bijzonder voor TIS'en in de formatieve fase.

Wil de diffusie van duurzame energietechnologieën in de samenleving op gang kunnen komen, dan zullen vele TIS'en tot ontwikkeling moeten komen. Bovendien zullen deze TIS'en zich moeten uitbreiden en onderdeel moeten worden van het gevestigde energiesysteem. Er zijn talloze duurzame energietechnologieën, waarvan er innmiddels velen op de rand van een versnelling verkeren. De TIS'en rond windenergie, zonne-energie, biomassa-energie en vele energiebesparingstechnologieën herbergen allen het potentieel om een energietransitie in gang te zetten. Het is te hopen dat de ideeën die ontwikkeld zijn in dit boek zullen bijdragen aan de verdere ontwikkeling van deze en andere duurzame energie-TIS'en en aan de realisatie van een duurzaam energiesysteem in de nabije toekomst.

De ultieme claim van dit boek is dat, met het juiste beleid, de geschikte strategieën, met voldoende bewustzijn van toekomstige behoeften en met een lange-termijn visie van actoren in de publieke en private sfeer, het mogelijk moet zijn om van deze hoop werkelijkheid te maken.

Table S.2 Functies van technologische innovatiesystemen

Systeemfunctie	Beschrijving	Type van gebeurtenissen
F1. Ondernemersactiviteiten	De kern van het TIS wordt gevormd door ondernemers. Het gaat hierbij om actoren die innovatieve projecten opzetten gericht op het exploiteren van (commerciële) kansen.	Commerciële projecten, demonstratieprojecten, portfolio-uitbreidingen
F2. Kennisontwikkeling	Onderzoek en ontwikkeling (R&D) vormen een belangrijke bron van variatie en zijn daarmee een voorwaarde voor het totstandkomen van innovaties.	Studies, laboratoriumexperimenten, pilots
F3. Kennisdiffusie	De typische organisatiestructuur van een TIS is het netwerk. Dit netwerk is met name van belang voor het faciliteren van kennisuitwisseling.	Conferenties, workshops, allianties
F4. Richtinggeving aan het Zoekproces	Deze systeemfunctie betreft de selectiedruk die noodzakelijk is om tot een ontwikkeling in een bepaalde richting te komen.	Verwachtingen, beloften, beleidsdoelen, standaarden, onderzoeksuitkomsten
F5. Marktvorming	Er is doorgaans nog geen marktvraag voor nieuwe technologieën. Om innovatie te stimuleren is het veelal noodzakelijk om op 'kunstmatige' wijze marktcondities te scheppen.	Marktstimuleringsbeleid, belastingvrijstellingen
F6. Mobiliseren van Middelen	Om alle andere ontikkelingen mogelijk maken moeten er voldoende financiële, materiële en menselijke 'resources' worden gemobiliseerd.	Subsidies, investeringen
F7. Ondersteuning door Belangengroepen	De ontwikkeling van een nieuwe technologie leidt doorgaans tot verzet onder gevestigde belangen. Voor een gezonde TIS-intwikkeling is het van belang dat actoren zich voldoende organiseren en deze weerstand omver werpen in politieke zin.	Lobbyactiviteiten, adviezen

Dankwoord/Acknowledgements

In de eerste plaats wil ik degenen bedanken die heel direct betrokken waren bij de inhoud van mijn promotieonderzoek. In het bijzonder dank ik Marko Hekkert voor zijn rol als eerste begeleider en uiteindelijk ook als eerste promotor. Marko, ik heb de afgelopen zes jaar onder jouw begeleiding veel geleerd. Niet alleen over het uitvoeren van onderzoek, maar ook over belangrijke zaken die hiermee verbonden zijn. Je hebt me laten zien dat onderzoek ook draait om het vormen van netwerken, het managen van verwachtingen en (af en toe) het bedrijven van politiek. Daarnaast wist je me aan te moedigen om me tot de 'essentie' te beperken en niet ingewikkeld te doen. Of dit laatste is gelukt …

Daarnaast een woord van dank voor Ruud Smits. Ruud, je wist me vaak te motiveren en je hebt me op beslissende momenten aangespoord om belangrijke keuzes te maken in het onderzoeksproces. En dankzij jou zal ik de 80/20-regel als een mij niet helemaal passende lijfspreuk met me meedragen voor de rest van mijn loopbaan.

Furthermore, I would like to thank Staffan Jacobsson for supporting me, especially during the final stages of my PhD trajectory. Staffan, you encouraged me on many occasions to be patient and to keep improving my texts. You inspired me to believe in the importance of my work. Thank you for inviting me to Chalmers University in 2006.

Verder bedank ik hier Koen Frenken. Koen, jij hebt aan het begin van mijn promotietraject een belangrijke rol gespeeld. Met je brede interesse en kennis op het gebied van innovatietheorie, evolutionaire economie, filosofie en vele aanverwante zaken was je voor mij een bron van inspiratie. Bedankt ook voor je scherpe commentaar op mijn eerste teksten.

Vervolgens ben ik dank verschuldigd aan de mensen met wie ik direct heb samengewerkt in het kader van diverse projecten gedurende mijn promotietraject, in het bijzonder: Simona Negro, Floortje Alkemade, Oscar van Vliet en Sylvia Breukers. I would also like to thank Karl Hillman and Björn Sandén for a fruitful cooperation on particular chapters of this book. Daarnaast een woord van dank voor Frank Geels, Johan Schot, Geert Verbong, Rob Raven, Frans Berkhout, Jo Wachelder en Els Rommes voor het leveren van nuttig commentaar op onderdelen van mijn werk.

Ook bedank ik alle mensen die mij informatie hebben gegeven of op andere wijze hebben bijgedragen aan mijn onderzoekingen 'in het veld'. Met name: Barend van Engelenburg, Elke van Thuijl, Ellart de Wit, Eric van den Heuvel, Erik Middelman, Erik de Nie, Esther Keijser, Frank Denys, Frank Witte, Frits van Drunen, Godert van Hardenbroek, Hein Aberson, Henk Barten, Henk Verbeek, Kas Hemmes, Martin Weissmann, Peter Aubert, Peter Bout, Remco Hoogma, Robert van den Hoed en Ronald Mallant.

Ik heb het geluk gehad om in een dynamische onderzoeksgroep te werken met enthousiaste mensen. Beste collega's, hartelijk dank voor de leuke en warme werkomgeving. In het bijzonder bedank ik Maryse (geinig!), Tessa (nooit, nooit, nooit, …), Rutger (twee differentiaalvergelijkingen), Klaas (het ideale energiegewicht), Laurens (020), Sjoerd (de keiharde realiteit), Wouter (Pittsburgh gangstah life); en natuurlijk de twee mensen met wie ik met plezier een kamer heb gedeeld: Simona (bedankt 'young princess' voor een supermooie tijd in het BG) en Rens (ik hoop dat je nu wel bij het raam mag zitten; I'm bringing it back!).

Mijn nieuwsgierigheid naar filosofische, sociologische en economische ideeën kon ik botvieren met Rik, Frank, Roderik, Mathijs en Laurens. Beste 'Young Schumpeterians', het was me een genoegen om me samen met jullie op lichtzinnige wijze te verdiepen in de werken van Schumpeter, Polanyi, Arthur en Marshall.

Dit proefschrift werd mede mogelijk gemaakt door financiële en institutionele ondersteuning van NWO/SenterNovem, het Copernicus Instituut, het KSI-netwerk (Knowledge network for System Innovations and Transitions) en de WTMC-onderzoeksschool (the Netherlands Graduate School of Science, Technology and Modern Culture). Ik dank 'WTMC' ook voor het vergoeden van een deel van de drukkosten van dit boek.

Vervolgens bedank ik hier mijn vrienden voor de belangrijke rol die zij de afgelopen jaren hebben gespeeld in mijn leven: Martin, Edward, Barbara (mooie fietstochtjes), Arno ('headshots' en 'airstrikes'), Ivan (het wegvagen van mijn risk-legertjes), Jochem (het is weer gelukt), Vincent (kopen voor duizend euro?), Fjalar ('this modern world hath need of thee'), Joop (flitspopper), Emile ('you will, you can'), Shapol en Arwen (voor de gezelligheid in Scheep 4 en dat jullie er zijn), Tinka (psst, de zwaluwen vliegen naar het oosten), Steven en Hugo (zenmeesters), Mathijs (voor het wegvagen van waardenkaders; let wel, je hebt nu een dialectisch moment in handen) en Walter (voor een mooie vriendschap die heel wat hoofdstukken van mijn leven beslaat). In het bijzonder bedank ik Lude voor het ontwerpen van het omslag van dit boek (en natuurlijk voor het halen van alle targets, inclusief de Obersalzberg).

Mijn dank gaat natuurlijk ook uit naar mijn ouders en zus voor de rotsvaste basis die zij me bieden. Pap, mam, Anouk, jullie liefde en zorg betekenen veel voor me. En, tenslotte, Ianthe, mijn lieve vriendin, ik hoop dat we nog lang en gelukkig samen door het leven zullen gaan. Met jou aan mijn zijde is alles licht en luchtig.

Roald Suurs

Utrecht, December 2008

Curriculum Vitae

Roald Suurs was born in ’s-Hertogenbosch, the Netherlands, on 9 January 1977. He completed his secondary education at the Ds. Pierson College in ‘s-Hertogenbosch in 1995. From 1995 to 2001 he studied Environmental Sciences[221] and Science & Policy[222] at Utrecht University. He graduated with Master’s degrees in Environmental Sciences and Science & Policy in 2000 and in 2001, respectively. During the final years of his studies he specialised in the chemistry of soils (partly at the Alterra Research Institute of Wageningen University) and in the techno-economics of biomass-based energy systems (partly at Lund University in Sweden). From 2002 to 2005 he studied Philosophy, first at the University of Nijmegen (2002) and then at the University of Utrecht (2003-2005). He obtained his Bachelor’s degree in Philosophy in 2005.

In 2002, Roald started working as a junior researcher at the Innovation Studies Group at Utrecht University. His research project focused on the analysis and evaluation of technological trajectories involving sustainable energy technologies. From 2003 to 2008, he worked on his PhD project, entitled ‘Motors of Sustainable Innovation. Towards a theory on the dynamics of technological innovation systems’. Aside from conducting research, Roald assisted in teaching courses on statistics and research methods. He also participated in contract research for the Environmental Planning Agency (MNP), in 2005, and for the Ministry of Economic Affairs and SenterNovem, in 2008.

Roald currently works as an assistant professor at the Department of Innovation and Environmental Sciences, Faculty of Geosciences, Utrecht University. The Department of Innovation and Environmental Sciences is part of the Copernicus Institute for Sustainable Development and Innovation.

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Motors of Sustainable Innovation

Modern societies are encountering environmental and political problems in the sphere of energy supply. One way to deal with this is to support the development of sustainable energy technologies. Since the development and diffusion of renewable energy has proved to be a very slow process, strategic insight is needed into how the emergence of these technologies takes place and how this process can be accelerated. The objective of this book is to gain insight into the dynamics of technological change with a focus on sustainable energy technologies.

As the theoretical starting point, the Technological Innovation Systems (TIS) framework is used. The TIS is a structure made up of actors, institutions and technologies, in which the development and diffusion of new technologies takes place. For the successful development of a technology, a TIS needs to be built up. This build-up is understood as the unfolding of key activities that take place within the TIS. The author develops the idea that the build-up of a TIS, especially in a formative stage, can accelerate due to positive interactions between these key activities. These positive interactions are called motors of sustainable innovation.

The development of motors of sustainable innovation is studied in several historical case studies situated in the Netherlands and Sweden (biomass gasification, biofuels, hydrogen fuel cells and automotive natural gas). Based on these studies, a typology of motors is constructed. Strategic lessons are drawn that specify which interventions can be taken to support particular motors.

Roald Suurs currently works as an assistant professor at the Department of Innovation and Environmental Sciences, Faculty of Geosciences, Utrecht University. The Department of Innovation and Environmental Sciences is part of the Copernicus Institute for Sustainable Development and Innovation. ■