The Formation of a Biofuels Innovation System: Lessons from The Netherlands

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July 25th 2007

Abstract

Supporting the development and diffusion of sustainable energy innovations has become a dominant topic on the political agenda of many countries. Providing this support remains difficult, since the processes constituting such innovation trajectories are poorly understood. To increase insight in such processes, this paper takes the development of biofuel technologies in the Dutch mobility sector as the topic of study. A feature to which we will draw special attention is the simultaneous development of two technology generations within the field: a first generation and a second generation of biofuels. We apply a Technological Innovation System (TIS) perspective to analyse and evaluate the dynamics of both technology groups. A TIS is a network, constituted by actors and institutions, that is constructed around a technology, as it develops. We analyse whether the actors in this network have succeeded in developing seven key processes, or System Functions, necessary for the development and diffusion of biofuel technologies. The System Functions will be traced through time and employed as performance criteria for 15 years of biofuel technology development in The Netherlands. From the results we draw lessons of relevance for scholars, policy makers and entrepreneurs that aspire to understand and influence emerging energy technologies.

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1. Introduction

Supporting the development and diffusion of sustainable energy innovations has become a dominant topic on the political agenda of many countries. However, providing this support remains a difficult task, since the processes constituting such innovation trajectories are, as yet, poorly understood (Coates, 2001). To increase insight in such processes, this paper takes the development of biofuel technologies in the mobility sector as the topic of study.

Various national governments have supported innovation trajectories around biofuels. Here we analyse and evaluate one such trajectory as it has developed in time, namely that of The Netherlands. The last fifteen years, Dutch governments and entrepreneurs have started various initiatives around biofuels (GAVE, 1999), yet still, diffusion is close to zero. As there are usually long lead times involved in bringing a new technology to the market, this could mean two things: either the Dutch have not sufficiently supported the emerging biofuel technologies, or they have done so, but the technologies are simply in a stage in which rapid diffusion is not expected to occur. In order to find out, we will analyse the development trajectory in detail.

A feature to which we will draw special attention is the simultaneous development of two technology generations within the field. A first generation (1G) of biofuels with limited performance in terms of CO2-reduction but already in a near-commercial stage of development, and a second generation (2G) of biofuels with high expected performances but in a pre-commercial stage. We will especially address the question to what extent developments differ between these technology groups, and how they benefited the overall biofuels development trajectory in The Netherlands.

The aim of the paper is to draw attention to the analysis and evaluation of the dynamics involved in the development of biofuels, and to provide results that contain lessons for entrepreneurs and policy makers, both in The Netherlands and other countries.

As a framework for our analysis we take up a Technological Innovation Systems (TIS) approach (Carlsson and Stankiewicz, 1991). The TIS is a social network, constituted by actors and institutions (rules of the game), that is constructed around a specific technology. The TIS literature stresses exactly the fact that most emerging technologies will have to pass through a so-called formative stage before they can be subjected to a market environment (Jacobsson & Bergek, 2004). So market diffusion is absent or insignificant, but during the formative stage actors are drawn in, institutions are designed and adjusted; in short, many processes unfold that, positively or negatively, will influence technology diffusion.

Following Bergek (2002) the build-up, or break-down, of these processes is conceptualised as the fulfilment of a set of System Functions. Examples are the emergence of Entrepreneurial Activities, Knowledge Development, and the Mobilisation of Resources (Hekkert et al., 2007); a complete overview will be given in the next section. The System Functions combined foster the emerging technology. In the ideal case, the TIS will develop and expand its influence, thereby propelling the emerging technology towards a stage of market diffusion.

The TIS framework matches our conceptual focus on a specific technological field. It has also proven its heuristic value for the evaluation of public and private intervention in relation to complex innovation processes (Smits & Den Hertog, 2006). However, a weakness of past innovation system studies is that they fail to address historical features in dynamic terms (Hekkert et al., 2007). As we aim to study an emerging TIS, in the process of shifting from a formative stage of emergence to a stage of market diffusion, dynamics are crucial for our understanding. Recent TIS literature suggests that such phenomena can be captured by pointing out positive (and negative) interactions between System Functions (Bergek, 2002; Jacobsson & Bergek, 2004; Hekkert et al., 2007). We will take such dynamics into account when analysing the Dutch developments around biofuel technologies. Also, as a special focus, we will breakdown the analysis of dynamics for 1G and 2G biofuels, point out the differences, and relate them to the overall build-up of the TIS. This leads us to the following research questions:

How did System Functions, and their dynamics, differ for 1G and 2G biofuel technologies, and how did this influence the formation of the Dutch biofuels TIS from 1990-2005?

Based on this analysis and evaluation we indicate to what extent government authorities and entrepreneurs have been effective in supporting TIS dynamics. From the results we draw theoretical and practical lessons, of relevance for scholars, policy makers and entrepreneurs that aspire to understand and influence emerging energy technologies.

The structure of the paper is as follows. In Chapter 2 the research design, including theory and method, is revealed. Chapter 3 provides the case study on the Dutch biofuels developments. In Chapter 4 we will evaluate and discuss the implications of our results. Chapter 5 concludes by recapitulating and drawing practical and theoretical lessons.

2. Research Design

Our theoretical approach is based on the work by Carlsson & Stankiewicz (1991), Bergek (2002), Jacobsson & Bergek (2004) and most recently Hekkert et al. (2007). The method we use is derived from Abell (1987) and Poole et al. (2000), and thoroughly illustrated by Hekkert et al. (2007), Suurs & Hekkert (2007) and Negro et al. (2006). Since there is already a lot of literature discussing our approach from a theoretical and methodical perspective, we will limit ourselves to a condensed account.

2.1 Theory

The TIS approach is part of a wider theoretical school, called the Innovation Systems (IS) approach (Freeman, 1995; Lundvall, 1992). The central idea behind the IS approach is that determinants of technological change are not (only) to be found in individual firms or in the R&D network, but also in a broader social environment in which the firm as well as the R&D system is embedded (Lundvall, 1992). From the 1980s IS studies have pointed out the great influence of this social structure on technological change and economic performance within nations, sectors or technological fields. The structure of an IS consists of actors, institutions and the network of relations through which these are connected (Carlsson et al., 2002). The TIS approach focuses on that structure that surrounds a specific technology. We follow this idea in defining the Dutch biofuels TIS as the network of actors and institutions, that directly support (or reject) the development and (eventually) the diffusion of biofuels, in the Netherlands.

The TIS approach serves as a heuristic tool to point out the actors, institutions and networks that influence technology development (Carlson & Stankiewicz, 1991; Jacobsson & Bergek, 2004). However, most TIS approaches have focused on just this, and as a result have neglected the shaping process itself. A main disadvantage of this is that dynamics are poorly conceptualised (Hekkert et al., 2007). To overcome this, recent studies have suggested augmenting the analysis of structure with an orientation on a limited set of key processes, called System Functions (Bergek 2002; Jacobsson & Bergek 2004). These System Functions are processes that foster the shaping and the diffusion of a technology. The premise is that a TIS should realise multiple System Functions. Each 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). These are presented in Table 1.

The System Functions are criteria for the evaluation of a TIS in a formative stage. As actors, institutions and networks are successfully arranged to realise a sufficiently high level of System Function activity, chances of technology diffusion will increase. It is also expected that System Functions need to be realised synchronically, as they need to complement and reinforce each other.

We prepare a basis for evaluation in two ways: (i) we expect the intensity of different System Functions to change through time, which should make it possible to find out what System Functions were sufficiently fulfilled and to what degree; (ii) we expect the System Functions to interact, possibly in such a way that it becomes possible to discern a positive feedback, or as Jacobsson & Bergek call it a cumulative causation. 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) to support even more research projects (Knowledge Development). Of course developments may also result in (un)fruitful conflict, or a standstill. By describing in detail the development and interactions of System Functions we provide an understanding of the dynamics of technological change.

Table 1: Innovation System Functions

System Function	**Definition**
F1: Entrepreneurial Activities	Entrepreneurs are at the core of a TIS. They perform the market-oriented experiments necessary to establish radical change. Entrepreneurs are usually private enterprises, yet they can also be public actors.
F2: Knowledge Development	Research and development of technological knowledge are prerequisites. This System Function is associated with the creation of variety in technological options. R&D activities are often performed by scientists, although contributions by other actors are possible as well.
F3: Knowledge Diffusion	The typical organisation structure of a TIS is the knowledge network that facilitates the exchange of information.
F4: Guidance of the Search	Often, within an emerging technological field, various technological options exist. This System Function represents the selection process necessary to facilitate a convergence in development. Guidance can take the institutional form of policy targets, but is often realised even more efficiently through the expectations of technological options as expressed by various actors.
F5: Market Formation	Often, new technologies cannot exceed incumbent technologies. In order to stimulate innovation, it is usually necessary to facilitate the creation of (niche) markets. This is especially the case in the energy sector, where external costs of fossil fuel-based technologies are often unaccounted for.
F6: Resource Mobilisation	Material and human factors are a necessary input for all TIS developments. Mobilisation can be triggered by venture capitalist investments, government support programmes, or entrepreneurial activities.
F7: Support from Advocacy Coalitions	The emergence of new technology often leads to resistance from established actors. In order for a TIS to develop, some actors must raise a political lobby counteracting this inertia. Often, this is done by NGOs or industrial interest groups.

2.2 Method

To measure the development of System Functions we propose an event history analysis (Abell, 1987; Poole et al., 2000). The empirical basis of such an analysis is the event. Each instance of change with respect to actors, institutions and 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. The selection of events is essentially an exercise of interpretation in which a large amount of data is surveyed and analysed.

In our case a search was carried out in Dutch periodicals from the period 1990-2005. The following keywords were used (translated from Dutch): bio(-)fuel, bio(-)ethanol, biodiesel, dme (dimethylether), fischer-tropsch, htu (hydrothermal upgrading), pure plant oil, ppo (pure plant oil). In total about 1100 events were retrieved to form the basis of our analysis. With the events a database was constructed. For this case we indicated whether events belonged to the 1G biofuels, the 2G biofuels, or the generic category.

The events can be clustered into types that correspond to the System Functions. This clustering exercise will yield different outcomes for each empirical study. For our case the outcome is presented in Table 2. The next step is to construct a narrative in which the events are interpreted and connected in a meaningful way. This is possible since the relations between the more influential events can be traced back by looking into the content.

Table 2: Event Types as Indicators of Innovation System Functions

System Function	**Event Types**
F1: Entrepreneurial Activities	Projects with a Commercial Aim, Demonstrations, Portfolio Expansions
F2: Knowledge Development	Studies, Lab Trials, Pilots
F3: Knowledge Diffusion	Conferences, Workshops, Alliances between actors
F4: Guidance of the Search	Expectations, Promises, Policy Targets, Standards, Research Outcomes
F5: Market Formation	Regulations constituting Niche Markets, Tax Exemptions
F6: Resource Mobilisation	Subsidy Programmes
F7: Support from Advocacy Coalitions	Lobbies, Advises

By relating event sequences to System Functions, we can point out how System Functions reinforce (or antagonise) each other through time. If such sequences carry on for some time, this indicates a feedback mechanism. In the ideal situation such a sequence will be cyclic, involving a repetition of a particular sequence of System Functions.

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

In the next section, we reconstruct the development of the Biofuels TIS (BIS) and refer to the various system functions as F1, F2, F3 etc., following Table 1. The narrative is chronologically organised, covering five episodes.

3. Dutch Biofuel Technology Developments

We have already mentioned that a remarkable feature of this case, is the appearance 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 beets, 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 – mainly forestry materials – is converted to 'biocrude', 'Fischer-Tropsch-diesel' or 'cellulosic bioethanol' (all synthetic substances). The 2G biofuels are currently in a pre-commercial stage of development. See Schubert (2006) for a condensed account of different types of biofuels.

It is currently expected that – in the long term – the 2G biofuels will offer a possibility for larger CO2-emission reductions at lower costs than 1G fuels. 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 near future. As will be shown, the dynamics of the Dutch BIS largely revolve around a clash of these two technology groups.

With respect to utilisation in vehicles, if biofuels are used in their pure form, significant vehicle changes are necessary; for blends, only minor changes are needed. The only exception to this is Fischer-Tropsch biodiesel, which can be applied in regular diesel engines.

3.1 Emerging Biofuel Technologies (1990-1994)

During the early 1990s, there is no political urgency of a sustainable energy system. Oil prices are low and the climate issue is barely mentioned in political arenas. The biofuels issue arises in Europe as an effect of the declining agricultural sector (NRC, 1991). With the production of non-food crops, the sector could be aligned with a new market. In 1992, within the context of this 'agrification' idea, Europe proposes to financially support biofuels (NRC, 1992a) by putting forward a scheme for generic tax exemptions. Also, 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; Trouw, 1992).

In The Netherlands, these developments are 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 busses. A number of actors is involved, among which the alcohol producer Nedalco (AD, 1992a). Another entrepreneurial project [F1] is started in the city of Rotterdam, this involves a trial [F2] where busses are fuelled with biodiesel. Funding is provided by the companies themselves and through European subsidies [F6]. These examples of Entrepreneurial Activities and Knowledge Development, are the first signs of a Dutch BIS taking shape. Technically, the outcomes are a success [F4] (Gelderlander, 1995). A less positive outcome [F4] is the low economic feasibility: under the present circumstances, biofuels cannot compete with fossil fuels.

Measures of national support are absent. This relates to the emergence of a controversy around the use of biofuels. The national 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 goes on until today. Regional actors emphasize the strategic and environmental value of biofuels, whereas scientists and environmentalists stress the meagre performance. The national government remains divided on the biofuels issue [F4] (AD, 1992c; ANP, 1993a; ANP, 1993b; Trouw, 1993;).

In this first episode, System Functions are beginning to develop, although they are mainly driven by external factors. There is no indication of feedback dynamics internal to the BIS. Note that in this episode 2G biofuels are not yet mentioned; in fact the term hasn't been invented yet.

3.2 First Niche Market (1995-1997)

From 1995 onwards the climate issue is gaining political interest and the concept of biomass is becoming important in the energy sector (DE, 1995; 1996). Against this background, a first series of projects starts which will turn out to contribute 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]. One important reason is the increase of regulative pressure with respect to surface water pollution [F4], as 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 province 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 – for two years – is provided [F5] (FD, 1995). A positive feedback now emerges as the province decides to adopt biodiesel for its fleet of service boats. The adoption experiment results in knowledge [F2] and, most importantly, it serves as an example to others in the field [F4]. Several other boating projects start [F1] and, once again, tax exemptions are demanded [F7], and issued [F5].

These (1G) biofuels technologies gain more attention due to the positive outcome of the trials. The positive dynamics revolve around a Support from Advocacy Coalitions and Resource Mobilisation by regional entrepreneurs. An important Market Formation factor is the presence of local regulations.

A critical downside is that, meanwhile, various impact assessments [F2] yield contradictory or negative results for 1G fuels [F4]. Studies show that 1G options are unsustainable. The national government still does not take a clear stance in the debate [F4]. Tax exemptions are issued [F5], yet on project-specific grounds, instead of on the basis of a general vision (VROM, 2006).

The story of struggling entrepreneurs also fits the role of Nedalco, an alcohol producer. Nedalco plans a business expansion [F1], starting with a trial production of bioethanol [F2] (FD, 1996). Together with other companies, plans are made for a pilot plant [F3], and the national government is asked to support this [F7]. Returns cannot cover the investments without a tax exemption (Nedalco, 2005). Nedalco succeeds to raise general attention to bioethanol [F4] (E&M, 1996). In the summer of 1997, Nedalco succeeds in persuading [F7] the national authorities to guarantee a ten year tax exemption [F5] for the annual production of 30 million litres of bioethanol. (Stem, 1998). However, the amount turns out insufficient to cover the investments (Nedalco, 2005). As a result, the project is discontinued [F1] and the plans remain a promise. Nevertheless, Nedalco's project is successful in the sense that they take a stance against the government's resistance to (1G) biofuels.

The Entrepreneurial Activities serve as a pivot in the unfolding of more positive dynamics. The event sequence is characterised by an initial impulse of multiple System Functions simultaneously, including Entrepreneurial Activities, Knowledge Development and Knowledge Diffusion. But the positive feedback especially depends on Guidance of the Search (public opinion, press releases) and Support from Advocacy Coalitions (especially their own lobbies). Note that 2G biofuels are still not mentioned.

3.3 Clash of Generations (1998-2000)

In 1998, the climate issue becomes more and more important. An international milestone is the signing of the Kyoto treaty by European member states in 1998. Furthermore, the automotive mobility sector is increasingly considered an important target for energy policy (E&M, 1998a; 1998b). A significant event during this episode is the initiation – by Novem – of a national programme for the assessment and support of gaseous and liquid CO2-neutral energy carriers: the GAVE programme (GAVE, 2005). GAVE manages to establish a breakthrough in the status quo, in three ways.

The first breakthrough is related to Guidance of the Search. Scarcity of biomass has been increasing as a result of growing demands for electricity production [F6] (Stromen, 1999), causing a fierce discourse on the use of biomass streams for transport vis-à-vis electricity purposes [F4] (VROM, 2006). However, an influential study (KEMA, 2000) [F2], authorised by GAVE [F4], designates that biofuel production could certainly be favourable, provided that production scales are sufficiently high [F4] (Stromen, 2001a). Moreover, a whole range of alternatives already exists for electricity production, whereas for transportation purposes, little has been achieved [F4]. With these arguments, GAVE turns to the responsible government ministries and puts the issue on the political agenda [F7] [F4] (GAVE, 2005).

The second breakthrough initiated by GAVE is the Knowledge Development around 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) [F2]. The advice is to exclusively support projects with which a CO2-reduction of at least 80% is guaranteed [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 advanced options (GAVE, 2005).

Thirdly, the programme serves as a catalyst, bundling and connecting (2G) activities that, until then, had been developed in relative isolation. Pivot of the unfolding dynamics are Guidance of the Search - promises made by entrepreneurs plus visibility, networks, and funding delivered by GAVE. Note that this involves Knowledge Development, Knowledge Diffusion, Resource Mobilisation and Support from Advocacy Coalitions as well. All these System Functions become tightly interrelated. As a result, GAVE strongly influences the BIS dynamics to come.

In this light it is worth mentioning that Nedalco - not part of GAVE - has shifted its attention in response to the attention for 2G biofuels [F1]. They initiate a highly innovative R&D project [F2] on the production of cellulose ethanol. Organisations involved are Wageningen University, TNO, and Shell [F3]. The project is partly funded by government subsidies [F6] (Nedalco, 2005).

To sum it up, the consistent promises of 2G technologies trigger fruitful BIS dynamics, largely supported by the Guidance of the Search given through the government's GAVE programme. Yet, the negative aspects of 1G biofuels are now further stressed. Also the BIS now strongly focuses on Resource Mobilisation and Knowledge Development. Apart from the 'boating niche', there are no market dynamics.

3.4 Technology Choices (2001-2002)

Besides the climate issue, the security of oil supply issue is gaining importance, especially since the 9-11 event. Sustainable mobility is now put firmly on the political agenda. Against this background, the work of GAVE continues (Stromen, 2001b). From 2001 to 2002, GAVE installs a subsidy scheme [F6] aimed at guiding entrepreneurs towards the realisation of demonstration-scale fuel chains [F4] (Stromen, 2001c; 2002; GAVE, 2003). The programme consists of two tenders for a total budget of approximately 2 million Euros. The first step is to stimulate the formation of coalitions [F3] and to support assessment research [F2]. The 80% CO2-reduction criterion still holds. As a result, all projects [F1] are directed at 2G options.

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

The next stage of the programme is to realise a commercial demonstration. By the end of 2002, possibilities are considered [F4], as both alliances are liable candidates and GAVE has a sum of 5 million Euros to offer [F6]. Unfortunately, both parties decide to discontinue [F1]. The main reason is that the building of a commercial-scale plant would cost far more than 10 million Euros, which would not be feasible without a flanking market stimulation programme, e.g. tax exemption measures [F5] (GAVE, 2002b; GAVE, 2005). The subsidy programme stops [F6].

Once again, the absence of Market Formation forms a critical barrier to BIS development (GAVE, 2005). From a technology perspective, the approach of GAVE has resulted in important successes. Still, a crucial System Function is left unaddressed; the exclusive orientation towards 2G biofuels will, as we shall see, results in the neglect of potentially powerful demand-side dynamics.

3.5 Paradigm Shifts (2003-2005)

In 2003 Europe decides on a biofuel directive demanding from its members to substitute a percentage of all transportation fuels, by biofuels (EU, 2003). With GAVE's subsidy programme terminated, and with the new task of implementing the directive, a reorientation of national policy is imminent (Stromen, 2003). In 2003 GAVE is issued with a priority task [F4]: the development of a market for biofuels [F5]. The 1G technologies are now increasingly perceived as a stepping stone towards future use of 2G fuels (EZ, 2006; GAVE, 2005).

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 bioethanol [F1] (Nedalco, 2005). However, despite the policy shift [F4], concrete tax measures are still not in effect [F5]. Once again, Nedalco pleas for a long-term tax exemption [F7]. The promise of 2G technologies serves as important leverage, as in the intermediate period, their venture in R&D on 2G ethanol has been extraordinary fruitful (GAVE, 2005; Nedalco, 2005). Still, the national government does not readily respond [F4] and the project is halted [F1].

Despite the absence of a supportive programme [F4], a variety of 1G initiatives is started from 2002 onwards [F1]. These are the first commercial experiments that target the supply side of the biofuels chain. The projects are supported by a large number of actors; amongst them are farmers, farmers' associations and local government authorities [F3]. Many of them are made shareholders [F6]. Also, biofuels are promoted to potential users [F4]. For these projects to financially work out, tax exemptions are requested [F7], and issued on project basis [F5] (SOS, 2005). By 2005, the first (1G) bio-diesel plant is built (Bizz, 2002a; 2002b; SOS, 2005). This successful outcome [F4] triggers a pattern of cumulative causation, as from 2002 numerous projects [F1] start all over the country, especially in rural areas. The first plant is an often used example [F4]. In 2004 numerous municipalities start to adopt bio-diesel for their car fleets [F1] (DvhN, 2004; 2005a; LC, 2004; PZC, 2004; RD, 2004).

Now multiple System Functions are being fulfilled. Remarkably, it is, again, regional authorities and entrepreneurs that take the BIS forward with their Entrepreneurial Activities. The perspective of Market Formation, offered through the EU directive, plays a pivotal role. National policy makers realise that their scheme has failed because Market Formation was completely neglected. In accordance with this GAVE now changes its role, from an R&D catalyser, to a facilitator of Knowledge Diffusion and Market Formation. In the process, the concept of bridging technologies – from 1G to 2G – has gained popularity. The 1G fuels are now explicitly regarded as a bridging option (EZ, 2006; GAVE, 2005).

4. Analysis and Evaluation

Having analysed the historical development of the Dutch BIS in detail, our main questions can now be addressed explicitly. How did the seven System Functions, and their dynamics, differ for 1G and 2G biofuels, and how did this affect the formation of the BIS? We will first address differences in the fulfilment of separate System Functions and then pay attention to the dynamics.

4.1 System Function Fulfilment for 1G and 2G Biofuels

The evidence from our case particularly suggests a strong role for Entrepreneurial Activities. In many ways the projects and experiments of the entrepreneurs and regional governments have been a prime mover, initiating positive feedback. This is true for 2G biofuels, but particularly for 1G Biofuels. An important difference is that for 2G biofuels, events were mainly driven by large companies, whereas for 1G, it was many small companies, farmers and regional governments that took the lead.

Knowledge Development and Knowledge Diffusion have been fulfilled to a high degree, for both technology groups. This is the case for 1G biofuels, but especially for 2G biofuels. This is not surprising as these technologies still require a lot of development. With respect to 1G biofuels the knowledge being developed was largely practical, and it was exchanged mostly within a community of practitioners operating in a market environment. The knowledge developed around 2G biofuels was more of a theoretical nature, i.e. research involving laboratory experiments and feasibility studies. A striking feature is the radical split up of the TIS in separate networks dedicated to 1G biofuels and 2G biofuels. Although, an important exception to this is Nedalco's network which entailed both 1G and 2G actors.

The most crucial System Function, with respect to the difference between 1G and 2G biofuels, is the Guidance of the Search. The 1G biofuels developments started out with little support, and a high degree of dissent, with respect to the expected merits. Government policies were absent, despite some ad hoc funding measures for specific projects. For 2G biofuels a positive Guidance of the Search started late (1998), in the form of the GAVE government programme, but because of its consistent nature, it succeeded in quickly pushing 2G biofuels in the picture for entrepreneurs, and especially policy makers. From that moment on 1G biofuels started to become marginalised, as GAVE did not support these technologies. Only recently, with the European biofuels directive, 1G biofuels gained credit again. The Dutch government, including GAVE authorities, now regard 1G biofuels as a stepping-stone towards 2G biofuels. Still, the debate continues until today.

With respect to Resource Mobilisation, events are correlated with the Guidance of the Search. The national government supported developments around 2G biofuels, providing a scheme that was meant to result in a commercial scale demonstration plant for 2G biofuels. Unfortunately, the resources provided were not sufficient to cover the costs of such a project. With respect to 1G biofuels, the national government financially supported some small projects, most notably the boating experiments and the Nedalco experiments with 1G biofuels. However there was never a clear subsidy scheme that provided financial means for the long term. For a large part, Resource Mobilisation was of course in the hands of regional governments, and smaller and larger companies like Nedalco or Shell. But since the investment climate remained unpredictable these actors did not invest as much as they could have.

Market Formation is the crucial System Function when it comes down to evaluating the biofuels development trajectory as a whole. Despite some exceptions - mainly the boating experiments which took place in a niche protected by surface water quality regulation - no serious developments has been observed. This holds for 1G biofuels and for 2G biofuels alike. The absence of a market has had severe consequences for both technology groups: the development of 2G biofuels did not continue because entrepreneurs lacked the financial certainty associated with a market environment. For 1G biofuel, in multiple cases technically successful projects have stopped because of poor economic pay-offs.

For Guidance of the Search, Resource Mobilisation and particularly Market Formation we have drawn a lot of attention to the role of the national government. The reason for this is that our case clearly shows how the national government fails to take a stand. Actions mainly resulted as a response to the positive and negative Support from Advocacy Coalitions as given by entrepreneurs, academics and even regional governments. This is a weakness since this reinforced the dividedness of the BIS, hampering the development of all other System Functions, and hence the further development of 1G and 2G biofuels. With respect to Support from Advocacy Coalitions, we should also mention that the private actors of the BIS could have made a difference themselves by cooperating more, joining forces and coming up with a clear univocal message to the government. This could have paved the way for a less segregated BIS where build-up dynamics, and not so much exclusion dynamics, are central.

4.2 Dynamics of Exclusion

System Functions should not be regarded as independent variables, or static criteria. Rather, they are processes that can reinforce each other. In fact they should reinforce each other, or otherwise there will be no build-up. We have demonstrated this by pointing out how sequences of events may result in positive feedback, i.e. cumulative causation.

Lets look at the observed occurrences of cumulative causation. The first example we found was constituted by boating companies, we observe that they started (1G) biofuels projects [F1] who lobbied [F7], successfully, for tax exemptions [F5], with which they setup trials [F2] that resulted in successful outcomes [F4]. As a result of this success more projects were started [F1], reinitiating the cycle. This positive feedback could continue because the effect of existing surface water regulation.

The second example, though less successful, was the 'cycle' which involved Nedalco's (1G) biofuels. This sequence was never finished since crucial System Functions were left unaddressed, namely Market Formation and Guidance of the Search.

The third example of cumulative causation is the GAVE-programme directed at 2G biofuels. This was more or less a top-down subsidy scheme [F4] [F6] which resulted in the setup of alliances [F3], a number of R&D projects [F2] with promising outcomes [F4]. Unfortunately, here also, the limiting factor was Market Formation.

Finally the fourth instance of cumulative causation is the boost of activities that was the result of the European biofuels directive. Here it was mainly the positive expectations [F4] of a future to-be-created biofuels market [F5], that triggered all kinds of market experiments [F1], especially in the field of 1G biofuels. The outcome of this most recent development is not entirely clear yet, but it in terms of the increase in the number of activities this is enormous.

So, given these stylised pieces of narrative, what are the strong points and what are the weak points of the Dutch biofuels trajectory, with respect to dynamics? We saw that a consistent Guidance of the Search, in combination with Knowledge Development and Diffusion, had a strong impact on the development of 2G biofuels. Still, a crucial weakness was the absence of Market Development. For 1G biofuels the absence of Market Development was also critical. However, the 1G biofuels suffered from the absence of Guidance of the Search as well. After all, the government's choice to exclude 1G biofuels from programmatic support marginalised these activities for some years. The most striking result from our study is the rather radical segregation of technology groups, especially as conceived by the national government, academics and large industries. The dynamics of exclusion that result from this, affect all the individual occurrences of cumulative causation mentioned above.

With this analysis in mind it may be surprising that, if we compare the two technology groups, nevertheless, the dynamics of 1G technologies seem to have been healthier. Looking at the occurrences of cumulative causation, the dynamics around 1G biofuels seem to be more fruitful. They are more diverse and, so far, they have been actively supported over and over again by a large variety of actors. With the European biofuel directive in place, these dynamics may very well provide a strong basis for further development of 1G and 2G biofuel technologies alike.

5. Conclusion

We have analysed and evaluated the dynamics of 1G and 2G biofuel technologies. To do this we adopted the Technological Innovation Systems (TIS) framework, which proved to be a powerful tool for determining factors that influence such processes. We analysed the build-up and interactions of System Functions over time. The theoretical framework, in combination with our event history analysis, proved useful in gaining insights in the dynamics of technological change. By distinguishing between 1G and 2G biofuel technologies we could point out interesting patterns that relate these dynamics to technological differences.

One conclusion is that the Dutch biofuels TIS was successful in facilitating Knowledge Development and Knowledge Diffusion, but did not succeed in facilitating Market Formation necessary for emerging technologies to gradually take shape. This is especially true for 2G biofuel technologies, which, despite government support, never got close to even a demonstration. For 1G biofuels, for which a technological niche already existed, we have seen that market dynamics can play an important role, even in the formative stage of TIS development.

Another main conclusion relates to the difference between 1G and 2G biofuels. The Dutch government effectively marginalised 1G developments, by exclusively targeting System Functions for 2G biofuels. This hampered potential dynamics, and as a result the TIS remained underdeveloped in terms of other System Functions, especially with respect to Market Formation. It seems plausible that this has also hampered the development of 2G biofuels. After all, they, for a large part, belong to the same system. Recently, under pressure from the European Commission, the Dutch government has left the logic of excluding 1G behind. Now, 1G fuels are regarded more and more as a possible stepping stone towards advanced technologies.

What practical lessons can be learned from this? Lets assume, as we have done throughout the paper, that we want these emerging technologies to develop further. For policy makers, the System Functions then offer 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 dynamics of cumulative causation could be closely monitored, and policy should be directed at accelerating these processes. Studies like ours provide information on the specific ways to do this. There are also implications for entrepreneurs that are active in an emerging technological field. Their chances of survival will improve when System Functions are fulfilled. They should be aware of TIS dynamics and their pivotal role in this. By running in packs, and organising themselves into an alliance, they are likely to be more influential, and more successful in innovating. Part of their resources should then be dedicated to the formation of a TIS.

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