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Abstract

Despite its worldwide success, the innovation systems approach is often criticised for being theoretically underdeveloped. This article aims to contribute to the conceptual and methodical basis of the (technological) innovation systems approach. We propose an alteration that improves the analysis of dynamics, especially with respect to emerging innovation systems. We do this by expanding on the technological innovation systems and system functions literature, and by employing the method of 'event history analysis'. By mapping events, the interactions between system functions and their development over time can be analysed. Based on this it becomes possible to identify forms of positive feedback, i.e. cumulative causation. As an illustration of the approach, we assess the biofuels innovation system in The Netherlands as it evolved from 1990 to 2005.

Keywords: Technological Innovation System; Emerging Sustainable Technology; Event History Analysis; Biofuels.

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1. Introduction

The innovation systems literature stresses the importance of path dependency, positive feedback and cumulative causation for understanding technological change and long-term economic growth (Carlsson & Stankiewicz, 1991; Lundvall, 1992; Andersen et al., 2002; Carlsson et al., 2002). Yet, our insight in what more generally could be called system dynamics, is still limited (Jacobsson & Bergek, 2004; Hekkert et al., 2007). The majority of innovation system studies done 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 infeasible, 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 which are only just emerging (Jacobsson & Bergek 2004; Lundvall, 2007). And yet in this area this is crucial, since it is these innovation systems which can still be shaped and influenced (cf. Collingridge, 1980).

The conscious shaping of an innovation system becomes especially relevant when considering that technological change is to play a crucial role in contributing to a sustainable society (Sandén & Azar, 2005). However, even with the fluidity of emerging innovation systems, the task of supporting sustainable technological trajectories remains difficult. This is illustrated by exceptionally low market shares despite efforts made by many European governments to support the development of renewable technologies (IEA, 2004). 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. In short, the innovation systems around renewable energy technologies are, as yet, only functioning weakly.

Even if trust is given to a particular emerging technology, then it is still unclear how it should be supported (Coates et al., 2001). Therefore, the aim of this article is to contribute to insights in the innovation system dynamics that induce or block the successful development and diffusion of emerging technological trajectories in the context of sustainable innovation. We will do this by, theoretically and methodically, expanding on the Technological Innovation Systems (TIS) approach (Carlsson & Stankiewicz, 1991).[1] The TIS is a social network, constituted by actors and institutions, that is constructed around a specific technology.[2] 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 & Bergek, 2004). During this formative stage, market diffusion is typically absent or insignificant, but actors are drawn in and technologies and institutions are designed and adjusted. In short, structures are shaped that, positively or negatively, influence the emerging technological trajectory.

Mostly, these system structures are regarded as statics, rendering them unfit to deal with dynamics of emerging technological trajectories (Jacobsson & Bergek, 2004). Alternatively, following Rickne (2000), Liu and White (2001), Edquist (2004), Bergek (2002) and Jacobsson & Bergek (2004), the build-up, or break-down, of innovation system structures can be conceptualised in terms of key activities, or

[1] Carlsson and Stankiewicz (1991) 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 (1983). To avoid the confusion of concepts we choose to stick to the term that now has largely proliferated within the innovation systems literature.
[2] A more precise definition of the TIS, as we apply it, will be given in the next section.

system functions. Examples are the formation of small niche markets, the emergence of pioneering entrepreneurial activities, the development of knowledge, and the mobilisation of resources (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; Jacobsson & Bergek, 2004; Hekkert et al., 2007). This helps 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 (2005) 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 one way to increase theoretical depth is to provide a clear description of system functions (activities) (Edquist, 2005). Another important recommendation is to integrate conceptual work more with in-depth empirical studies. We need insights in the particular dynamics of individual historically embedded technological trajectories. After all, each will be situated in its own socio-technical context with its own issues that affect the dynamics (cf. Lundvall, 2007).

In this article we take up this recommendation by analysing an empirical case 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. The unfolding of system functions over time is mapped in terms of events and sequences of events. Based on these sequences, we identify forms of cumulative causation, and indicate how these influenced the formation of an emerging TIS.

Our empirical focus is on the developments around biofuels in the Dutch automotive mobility sector; we will analyse 15 years of biofuel innovation system dynamics. This is an interesting case since in order to reduce oil dependency and to meet (post-)Kyoto climate targets, the automotive mobility sector is a crucial, and yet until recently highly neglected, target for innovation policy (Blok, 2005). The focus on the Dutch situation has theoretical and practical reasons: (i) innovation system dynamics are largely country-specific (Lundvall, 2007), and (ii) our method requires 'linguistic' access to the empirical field. This leads us to the following two research questions:

How can we conceptualise and measure the dynamics of emerging technological innovation systems with the aid of event history analysis?

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

Section 2 describes our theoretical approach. In Section 3 the method of event history analysis is explained; the first research question should then be answered. As an illustration, Section 4 provides the application of theory and method in the case study on Dutch biofuels. Section 5 is a reflection on the empirical results, answering the second research question. Finally, in Section 6 we will conclude with arguing the value of our contribution to innovation systems research. Throughout the paper, policy implications will be addressed.

2. Functions of Innovation Systems

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 Freeman (1995), Lundvall et al. (2002) and Carlsson et al. (2002) – 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 potential importance of a broad selection of societal sub-systems, from R&D labs and production facilities to financial and educational institutions, providing they contribute to the national innovation process.

Such a conception is highly relevant to understand macro-economical differences between modern states. However, as Carlsson & 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 (Jacobsson & Johnson, 2000; Bergek, 2002; Hekkert et al., 2007; Negro, 2007). 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.[3] These consist of actors, institutions, and the network of relations through which they are connected (Carlsson et al. 2002).[4] 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 a TIS in this case is only just beginning to emerge, providing little basis for evaluation. Carlsson et al. (2002) suggest that multiple dimensions should be addressed when assessing the development of emerging technologies, covering the generation, diffusion, and use of knowledge. These dimensions should be measured by indicators of scientific research input, societal embedding, and market penetration. Such an analysis is very useful, and resembles in fact, partly, what we will do in this paper. Still, such an approach does not provide insight in cumulative causation. For that we also need insight in 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 (Johnson, 1998; Bergek, 2002; Jacobsson & Bergek, 2004; Edquist, 2005; Hekkert et al., 2007; Negro, 2007). These system functions are crucial processes, or key activities, that influence each other and foster the shaping and the

[3] This is loosely based on the following definition by Carlsson & Stankiewicz (1991): '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.

[4] Naturally, the structure of the Innovation System 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 & Jonasson (2005) for an application of this idea.

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 1 for definitions.[5]

<<INSERT Table 1 around here>>

Various 'lists' of system functions have been constructed; see for instance Johnson (1998), Rickne (2000), Liu & White (2001), Bergek (2002), Carlsson & Jacobsson (2004), Borras (2004), and Edquist (2005). Authors like Bergek et al. (2005) and Hekkert et al. (2007) give useful overviews. 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 (2005) 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. For a large part such empirical validation has been provided, for instance in studies by Negro et al. (2006a), Negro et al. (2006b) and Alkemade et al. (2006). 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

[5] Note that system functions are related to the structural elements of the TIS, but not on a one-to-one basis; various structural elements may (positively or negatively) influence the same system function; also a single structural element may influence multiple system functions.

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 collapse due to the absence of a single system function. For example, Kamp (2002) has shown 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 exchange 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 (Jacobssons & Bergek 2004; Hekkert et al., 2007). Even in immature TISs, with little activity taking place, it will be possible to identify how system functions drive each other. 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.

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 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.

3. Event History Analysis

The analysis of a TIS in a formative stage requires an empirical methodology that captures the micro-dynamics 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. 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 'event history analysis' as it has been developed in the context of organisation studies; see Poole et al. (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.[6] 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. Besides events, also context information is retrieved from the documents. This provides the background for understanding the events and guides positioning them in a narrative.

[6] The clustering is based on basic similarities between the events; for instance all feasibility studies are considered one event type 'feasibility studies' and all projects that are started are clustered in the event type 'projects started'.

The next step is to determine if and how the event types can be allocated to system functions. For instance, feasibility studies are regarded to contribute to system function 2 (knowledge development) and the projects started contribute to system function 1 (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 farfetched 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 either 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, biodiesel, dme (dimethylether), fischer-tropsch, htu (hydrothermal upgrading), pure plant oil, ppo (pure plant oil). See Table 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 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.

<<INSERT Table 2 around here>>

<<INSERT Table 3 around here >>

Based on the ideas of Poole et al. (2000) and Abell (1987), 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 based on the construction of a narrative, and aims towards finding '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 in major turning points of the TIS development such as for instance a sudden decline in the intensity of the guidance function. If the available data allows for it, more detailed insight in the way system functions are specifically fulfilled can be obtained. 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 a 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 outcomes of a 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 3, we obtain insight in how system functions interact.

If system functions reinforce each other in a meaningful way, 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 knowledge development [F2], which delivers promising results, raising expectations [F4], and encouraging entrepreneurs to start businesses [F1] that result in 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, the possibility of degeneration - or a vicious cycle - arises.

In practice, cumulative causation may also be carried by a-cyclic event sequences, as long as the sequence clearly contributes to the build-up of the TIS. 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 short-hand 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 help explain the occurrence of particular trend patterns.

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.[7]

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 in episodes. Instances of cumulative causation will be identified for each episode, if present. The BIS background movements are covered as an introduction to each separate episode.

[7] 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.

4. The Dutch Biofuels Innovation System

Before starting the narrative, it is important to introduce a remarkable (technological) feature of this case study, namely 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.

It is currently expected that – in the long term – 2G biofuels will offer a possibility for larger CO_2-emission reductions at lower costs than 1G fuels.[8] 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.

[8] For a condensed technology overview of the different types of biofuels, see Hamelinck (2003); Schubert (2006).

The only exception to this is Fischer-Tropsch biodiesel, which can be applied in regular diesel engines.

4.1 Emerging Technology (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 (international) political arenas. Rather, 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 putting forward 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; Trouw, 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 busses. A number of actors is involved, among which the alcohol producer Nedalco (AD, 1992a). Another trial [F2] is started in the city of Rotterdam, where busses are fuelled with biodiesel. Funding is provided by the companies themselves and through European subsidies [F6]. Figures 1 and 2 illustrate that these, and some other, entrepreneurial experiments

[F1], and trials [F2], are the first signs of a Dutch BIS taking shape. The trials [F2] turn out to be technically successful [F4] despite the fact that the engines of the busses in Groningen incidentally take flame (Gelderlander, 1995). A less positive outcome of the experiments [F4] is the low economic feasibility: under the present circumstances, biofuels cannot compete with fossil fuels. At that time – and throughout the period studied – biofuels fall under the same tax legislation as fossil fuels.

Measures of national support are absent. This relates to the emergence of a controversy around the use of biofuels. Illustrative is that, in 1992, the 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 emphasize the strategic and environmental value of biofuels, whereas scientists and environmentalists stress the meagre performance. The Dutch government remains silent due to its internal division on 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-economical issues (SER) advises to support experiments [F7] (ANP, 1993b; Trouw, 1993). Only a year later, in 1994, the Ministry of Agriculture decides to announce a fiscal support of biofuels [F4], whereas the Ministry of Environment expresses doubt [F4] (AD, 1992c).

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 BIS. 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 3 offsetting the weak positive impulses.

<<INSERT Figures 1 to 3 around here>>

4.2 A New Hope (1995-1997)

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

In The Netherlands, 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 cyclic motor now emerges as the province decides to adopt biodiesel for its fleet of service boats. The adoption experiment results in knowledge development [F2] and, most importantly, it serves as an example to others in the field [F4]. Several other boating projects start [F1] (see Figure 1) and, once again, tax exemptions are demanded [F7], and issued [F5]. Subsequently, the 1G technologies gain more attention [F4], especially due to the positive outcome of the trials [F2].

This sequence of events indicates a process of cumulative causation. The pivot is a recurring lobby for resources by regional entrepreneurs; an important success factor is the presence of local regulations, constituting a small niche-market. Figure 3 and 4 show the shift of the guidance pattern and advocacy coalitions patterns – from 1995-1996 – (partially) as a result of these developments. Figure 5 shows how knowledge diffusion - in the form of workshops and meetings on biomass energy - now becomes part of TIS functioning.

A critical downside to the effect of this small lobby-niche motor is that, meanwhile, various impact assessments [F2] yield contradictory or negative results for 1G fuels [F4]. Studies show that 1G options cannot contribute to sustainability. Figure 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 [F5], instead of on the basis of a policy strategy (VROM, 2006). There is at this moment no commitment to sustain a structural form of support [F4] (BD, 1995). An issue that keeps coming up in this respect is the budgetary gap that would have to be filled if a fuel tax exemption was issued [F5] (VROM, 2006).

As a response to this, in 1995, a second motor is initiated – parallel to the first – as Royal 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, 1996). 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 to raise attention to the possible advantages of bioethanol (see the trend in Figure 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 [F7] 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] (Stem, 1998). However, the apparent success is undone by the fact that the tax exemption turns out insufficient to cover the investments (Nedalco, 2005).[9] As a result, the project is discontinued [F1] and the plans remain a promise.

<<INSERT Figures 4 to 5 around here>>

Nevertheless, Nedalco's project is successful in the sense that it takes a stance against the government's resistance to (1G) biofuels. The entrepreneurial project serves as a pivot in the unfolding of what could be considered a second motor. The event sequence is characterised by an initial impulse of multiple system functions simultaneously, including entrepreneurial activities, knowledge development and knowledge diffusion. But the motor especially depends on guidance of the search (public opinion, press releases, Novem) and support from advocacy coalitions (especially their own lobbies). An interesting fact is that Nedalco's lobby work is not supported by any market dynamics. A lasting effect that can partly be ascribed to this

[9] Especially Nedalco's partners are unsatisfied with the limited volume of bioethanol qualified for tax exemption (VROM, 2006).

'lobby motor' is the recognition that 1G biofuels are a viable option. Figure 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 tax scheme remains an important barrier, still not differentiating between fossil fuels and biofuels. Figure 6 shows that it is not until 1995-1997 – with Nedalco and the boating experiments – that the first policy events take place that can be recognized as instances of market formation.

This episode is characterized by the distinct increase in attention and the first real steps being taken by national government authorities. Still, 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 getting media coverage [F4]. Academic researchers and environmentalists have mainly been calling attention to the negative properties of 1G fuels (DE, 1996b; 1996c; 1996d), thereby discrediting the biofuels option as a whole [F4]. However, the criticism now becomes more constructive in a way, as an alternative is proposed in the form of 2G biofuels [F4]. Previously, the 2G technology 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] (E&M, 1997). This R&D project is financed by both Shell and a national subsidy programme [F6] (Biofuel, 2005).

The rise of R&D activities and the first entrepreneurial experiments in the field of 2G biofuels are typical for this episode (DE, 1996d; E&M, 1996b); this is clearly visible in Figure 1 and 2.

<<INSERT Figure 6 around here>>

4.3 Technology Contests (1998-2000)

In 1998, the climate issue becomes an important background movement. A milestone is the signing of the Kyoto treaty by European member states 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, 1998; E&M, 1998a; 1998b) and, furthermore, the automotive mobility sector is increasingly considered an important target for energy policy (E&M, 1998a; 1998c).[10] 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). The GAVE programme is, by far, the most important Dutch government initiative of the entire period studied, although its focus will mainly be on R&D activities.

So far, the emerging BIS dynamics have received little public 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 three trend patterns marking this episode.

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

The first trend pattern is related to the guidance of the search. Scarcity of biomass has been increasing as a result of growing demands for electricity production [F6] (Stromen, 1999), causing a stronger 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, 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 this argument, GAVE turns to the responsible government ministries and manages to have the issue put on the national policy agenda [F7] (GAVE, 2005).

A second trend initiated by GAVE is the R&D development for 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 exclusively support projects with which a CO_2-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 technologically advanced options (GAVE, 2005). Figure 2 shows a shift in the trend pattern. The 2G biofuels remain the predominant topic of research from 1999 to 2003.

The third trend is GAVE's contribution to knowledge diffusion. As Figure 5 shows, there are no biofuel specific meetings [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 biomass.[11] Specific biofuel (mainly 2G fuels) meetings start occurring from 1999 onwards.

Figure 3 shows the positive impact of GAVE on guidance of the search, as from 1998 to 2000, the level of guidance towards 2G biofuels increases and becomes predominant to the guidance towards 1G biofuels.

The programme serves as a catalyst, bundling and connecting activities that, until then, had been developed in relative isolation. Pivot of the unfolding subsidy-R&D motor are promises made by entrepreneurs plus visibility, networks, and funding delivered by GAVE. Note that the event sequence involves knowledge formation, knowledge diffusion, resource mobilisation and support from advocacy coalitions; all these system functions are tightly interrelated. As a result, GAVE has strong influence on the BIS dynamics to come.

The subsidy-R&D motor results in a divergence of events, even involving activities that are not directly connected to GAVE. New undertakings of Nedalco and the Biofuel Company make the subsidy-R&D motor's consequences apparent. Furthermore, by 1999, political influence of (incumbent) industries involved in 2G biofuels (see Figure 4) is rising:

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

[11] 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.

[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] (NRC, 1999; Novem, 2000; E&M, 2000).

Moreover, Nedalco has shifted its attention in response to the rise of 2G biofuels. With the original plan discontinued (as mentioned above) the use of 2G biofuels is now researched [F2]. Once again, just like in 1998, a highly innovative R&D project on the production of cellulose ethanol is initiated. Other organisations involved are Wageningen University, TNO, and Shell [F3]. The project is partly funded by government subsidies [F6] (Nedalco, 2005).

The consistent promises of 2G technologies trigger fruitful BIS dynamics, yet, the negative aspects of 1G biofuels are now further stressed [F4]. Figure 2 and 1 show a stagnation in knowledge development [F2] and entrepreneurial experiments [F1] around 1G in the late 1990s. The complete absence of a complementary policy environment for 1G fuels results in a dynamics of exclusion. Whether this will be fruitful on 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 environment', there are no further market dynamics.

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 security of oil supply is gaining importance, especially since the 9-11 event. In The Netherlands, these background movements are reflected in a variety of policy measures aimed at reducing fuel consumption in the mobility sector (VROM, 2001). Despite the scarcity of ministerial support, the work of GAVE continues (Stromen, 2001b). From 2001 to 2002, GAVE installs a subsidy programme [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 (see Figure 6). 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 options.

Two entrepreneurial experiments [F1] focusing on combining biomass gasification with Fischer-Tropsch synthesis, are most 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 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, 2002a). The projects are successful [F4], particularly with respect to solving some technological bottlenecks, such as gas cleaning [F2] (Boerrigter et al., 2002).

A critical note is the fact that many – if not all – of the actors involved, were already working with biofuels before the programme began (GAVE, 2005). In this respect, GAVE has been a mediator, not a prime mover. Yet, developments were certainly accelerated by GAVE.

The final purpose of the subsidy programme was to realize 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] [F6] (GAVE, 2002b; GAVE, 2005). The subsidy programme stops [F6]; once again, the absence of fiscal instruments forms a critical barrier to market implementation [F5]. The investment subsidies are not sufficient to establish a commitment to accelerate further development of the BIS (GAVE, 2005).

The subsidy-R&D motor has been running for two years. From a technology perspective, the approach of GAVE has resulted in some important cases of success. Still, a crucial system function – namely market formation – is left unaddressed; the exclusive orientation towards 2G will, as we shall see, result in the neglect of potentially powerful demand-side dynamics.

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

During the whole episode, the support of 1G biofuels by advocacy coalitions becomes more powerful (see 2001 and 2002 in Figure 4). With respect to guidance, it seems that 1G and 2G biofuel technologies increasingly coexist, without raising further controversy (see 2001 and 2002 in Figure 3); this trend will be shattered in the next, and final, episode.

4.5 European Intervention (2003-2005)

So far, the GAVE programme – with its subsidy-R&D motor – has played a dominant role. However, things change in 2003, when Europe decides on a biofuel directive demanding from its members to substitute a percentage of the supplied transportation fuels by biofuels (EU, 2003). This background movement has drastic consequences, as Europe is largely directed at 1G biofuels.

With GAVE's subsidy programme terminated, and with the new national task of implementing the European directive on a national policy level, a reorientation of the national government is imminent (Stromen, 2003). As a result, from 2003 onwards, 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 (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 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, their venture in R&D on 2G ethanol has been extraordinary fruitful (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 Dutch future biofuels policy.[12] The effect of the first lobby motor still echoes through: the company is widely mentioned as a pioneer in Dutch biofuels development, even though it has never come close to building a biofuel factory.

Despite the absence of a clear supportive national programme [F4], a variety of 1G initiatives is started from 2002 onwards [F1] (see Figure 1). This initiates an interaction pattern within the BIS, in which multiple system functions are fulfilled – bottom-up – by a collaboration of various actors. 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[13] [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 which farmers, farmers' associations, and local government authorities [F3] who are made shareholders [F6] (see Figure 6). 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; 2002b); see also 4. The government eventually agrees with the company's terms [F5].

[12] Only recently did the national government respond to Nedalco's request; a factory is now planned in 2008. Since this event did not occur within the time-span of our analysis, it is not included in the narrative.
[13] PPO – or Pure Plant Oil – 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.

SOS makes sure that multiple system functions are realized simultaneously (SOS, 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 province. This success triggers a diverging wave of events: from 2002 onwards, entrepreneurial projects [F1] are initiated throughout the country, most specifically in rural areas (see Figure 1). The SOS project is often mentioned as an example [F4] (DvhN, 2004; 2005a; LC, 2004; PZC, 2004) and in 2004, numerous municipalities start adoption experiments with their car fleets [F1] [F5] (Stromen, 2004; RD, 2004).

Once again, it is the regional authorities and entrepreneurs – this time supported by a European directive – who drive the BIS forward, (partly by supporting their biofuels supply with a demand-side strategy). The rural developments are complemented by the initiation of the Energy Valley cluster [F3] (Energy Valley, 2006). This cluster strives for the alignment of public investments with local economic interests [F4] [F7].

This episode is characterized by a simultaneous boost of all system functions (Figures 1-6 all illustrate this trend). Although it is impossible to oversee all events, it is clear that a motor is emerging. The perspective of a market for biofuels – offered through the European directive – plays a crucial role. The guidance of the search initiates the event sequence, but, more importantly, the entrepreneurial activities trigger events that contribute to a variety of other system functions. The entrepreneurs and their expectations play a pivotal role; however since it is the market formation that is unique for this period, we call this form of cumulative causation a promising market motor.

A remarkable trend pattern is a counter movement formed by the oil industry, environmentalists, and academia (see the negative peaks in Figure 3 and 4) (ANP, 2003; DE, 2003; DvhN, 2005b). Once again, the controversy around 1G and 2G seems to set off. However, there is more positive guidance for 1G than ever before. Moreover, there is now increasing support, both in terms of guidance and in terms of advocacy 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 BIS is turning into an environment in which two technology groups can actually co-exist.

It is not until the summer of 2004 that developments start to arise on the national 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 (VROM, 2004). The 2G fuels are still considered preferable, but 1G fuels are now explicitly considered a stepping stone option. Whether this first instance of systematic and consistent support for the implementation of biofuels *in general* will turn out to be a pivotal event triggering a take-off, remains to be seen. At the moment of analysis, no new policy measures had been issued and the tax scheme still offered no generic policy incentive.

5. Reflections on Cumulative Causation

With our analysis, the development of the seven system functions of the BIS has been conceptualised in dynamic terms. Occurrences of cumulative causation have been pointed out in the form of four 'motors', and particular drivers and barriers related to these motors have been revealed. Coming back to our research question, how do these forms of cumulative causation determine successes and failures in the formation of the biofuels innovation system? Implications are given for policy makers and entrepreneurs.

5.1 Lack of Continuity

As we have seen, cumulative causation mostly emerged where entrepreneurs started to deliberately shape the BIS. Notable examples are the boating experiments, initiating a lobby-niche motor, and the recent successes around 1G biofuels, triggering a promising market motor. Furthermore, GAVE and Nedalco have initiated influential event sequences, all contributing to virtuous dynamics: a lobby motor and a subsidy-R&D 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 BIS development. The absence of follow-ups to entrepreneurial activities played a key role, clearly illustrated by the isolation of the early adoption experiments with public transport, the cancellation of Nedalco's expansion plans, and the failure of GAVE to realise a demonstration project. Recurring barriers are 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 a more dedicated policy design. Also entrepreneurs could have made a stronger point themselves for the support of more 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 – 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.

5.2 The Tragedy of Linear Thinking

The strength of a systematic and consistent policy design is shown by the only notable success of the Dutch biofuels policy: its impulse to R&D developments around 2G fuels via the GAVE program. The resulting technical successes are internationally appreciated. However, as soon as the national government decided that biofuels should be supported, its strategy was to exclusively initiate knowledge development among incumbent industry networks. The orientation was on lab-scale knowledge development, whereas market formation activities were absent. Furthermore, developments were not linked to already emerging motors initiated by 1G entrepreneurs. The failure of GAVE's demonstration – planned as a follow-up on the R&D phase – can be ascribed to the absence of such complementing system functions, mostly guidance of the search and market formation. As a result, the 2G projects are a technical success, but turn out to be economically infeasible.

The general lesson to draw from this is that the linear model of innovation – known to lead to system failure (Smits & Den Hertog, 2007) – is still operational today. If the sole purpose of government authorities is to boost R&D, the downstream part of the system is neglected and feedbacks between the production and the demand side of the TIS cannot come in effect. With such conditions, market, advocacy and (user) guidance based motors cannot fully emerge.

5.3 A Controversy

The absence of a broader scheme of national support can be related to the Dutch BIS's discord on whether 1G biofuels have the potential to significantly contribute to a sustainable mobility sector. 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 BIS, has become a driver of conflict that goes on until today. This conflict is mirrored by a scattered and partly negative realisation of various system functions, mainly in guidance of the search and support from advocacy coalitions. This is primarily 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 joined cause, rendering a conflict almost impossible to avoid.

Perhaps excluding alternatives from support is sometimes justified. Still in the case of emerging technologies, 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 (cf. Van de Ven, 1993) can entrepreneurs (and local governments) increase their chances of establishing a foothold within the incumbent transport energy domain. The challenge for policy makers is then to refrain from selecting technologies all together, and to - instead - build and facilitate a selection environment, consisting of actors and institutions that aim for inclusion.

5.4 Levels of Government Authority

The development (and policy) of biofuels has largely been the result of European pressure. During the entire period, 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, (niche) 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 four motors identified, national policy only played an initiating role in one of them (the subsidy-R&D motor); the national government generally lagged behind or even hampered regional developments.

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 an 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 lobby-niche motor and the promising 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 Summary

In short, the formation of a TIS requires that multiple system functions are being increasingly fulfilled by a broad group of actors, governments and entrepreneurs alike. Within the Dutch BIS 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, and consequently the emerging motors as well. Only recently the European biofuels directive has brought the promise of a market for biofuels. This seems to have triggered, for the first time, virtuous dynamics within the BIS, both among entrepreneurs and policy makers. The choice between two conflicting opposites now seems to have been transformed into an embrace of complements, with 1G fuels providing a possible market incentive for endeavours related to 2G biofuels. This way, a vision of a 'stepping stone technology' may very well lead to solutions that will take into account technological features *as well as* the broader functioning of the TIS.

6. Concluding Remarks

We started this paper by expressing the need for increased insight in the formative stage of innovation system development, particularly in order to be able to support sustainability 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 detailed insights in the influence of cumulative causation, i.e. of various motors that played a role during the build-up of a TIS.

Our case study revealed four motors that supported biofuels development in The Netherlands: a subsidy-R&D motor, a lobby motor, a lobby-niche motor, and a promising market motor. The subsidy-R&D motor involved research and development guided by a government programme. The lobby motors were initiated by entrepreneurs pushing government to support market formation. The lobby-niche motor was the stronger one since here an already present niche-market complemented its dynamics. The (so-far) strongest motor, the promising market motor, was mainly driven by solid positive expectations, directed at the formation of a mass market, directed by European guidance.

What does this all add to the existing innovation systems literature, in general? First of all, our approach allows for a fruitful combination of quantitative and qualitative analysis, that is especially 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 longer period of time and covering a broad variety of activities, could not have been found 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 of different innovation systems.

Second, our approach offers advantages with respect to integrating empirical and conceptual work. With the event history analysis case studies can be conducted in a highly systematic way, where theoretical concepts - the list of system functions - serve as a clear heuristic guide. 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 dynamics of different TISs can be compared, leading to a more general insight in what system functions matter, and in the types of motors that (may) occur. This way, eventually, this empirically grounded approach has the potential to largely contribute to our theoretical understanding of innovation system dynamics.

Thirdly, our approach not only identifies forms of cumulative causation. With the detailed narrative analysis it also becomes clear why particular motors emerged, or why they did not. In the biofuels case we identified some persistent issues that pervaded all that happened: (i) a severe lack of continuity in terms of guidance, (ii) if there was any guidance, it was in a linear fashion, and (iii) a reigning controversy which manifested itself in frequently shifting positive and negative efforts for various technologies. These issues are all characterized by there dynamic nature: (i) continuity can only be found in longitudinal studies, (ii) a linear model is best captured by following through and identifying particular stages, and (iii) a controversy - and especially its effects - can only be fully understood by following through the debate and the actions which result from it. So, a main strength of our approach is that it recognises the sequence, the order in which events occur, as an explanatory factor. We believe that this adds to the explanatory power of the innovation systems approach, especially in the formative stage.

Our approach provides a new perspective on (sustainability) technology policies. Instead of targeting mainly the supply-side (R&D programs) or the demand-side (market formation programmes) of the innovation chain, it stresses the systemic nature of technological change. The policy paradigm that follows is that instruments should contribute to the formation of new technological innovation systems, thereby increasing the success chances of new technologies. The system functions 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 presence of motors could be monitored, and policy should then be directed at accelerating these cumulative causation processes. Empirically grounded studies like ours provide information on the specific ways to do this, in our case in the context of sustainability technologies. There are also implications for entrepreneurs that are active in an emerging technological field. Their chances of survival will improve when the innovation system functions well. Therefore they should be aware of innovation system 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 an innovation system.

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Tables

Table 1: Innovation system functions.

	Definition
F1: Entrepreneurial Activities	Entrepreneurs are at the core of a TIS. They perform the innovative market-oriented experiments necessary to establish a 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. One of its system functions is to facilitate 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.

Table 2: Literature Sources.

Professional Journals	**National News**		
Agrarisch Dagblad	Algemeen Dagblad	Dagblad van het Noorden	Rotterdams Dagblad
Boerderij	ANP	Dagblad voor Zuidwest-Nederland	Utrechts Nieuwsblad
Duurzame Energie	De Telegraaf	De Dordtenaar	Veluws Dagblad
Energie- en Milieuspectrum	De Volkskrant	De Gelderlander	Zwolse Courant
GAVE Newsletter	Elsevier	Deventer Dagblad	
Logistiek Krant	NRC Handelsblad	Eindhovens Dagblad	**Financial News**
Stromen	Trouw	Gelders Dagblad	AFX - NL
		Goudsche Courant	BIZZ
Web Sites	**Regional News**	Haagsche Courant	FEM Business
Website & Publications ECN	BN/DeStem	Het Parool	Het Financieele Dagblad
Website NEO	Brabants Dagblad	Leeuwarder Courant	
Websites Senter, Novem, SenterNovem	Dagblad Flevoland	Provinciale Zeeuwse Courant	
Website VROM	Dagblad Tubantia/Twentsche Courant	Rijn en Gouwe	

Table 3: Measurement scheme for mapping empirical events to system functions. 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 BIS contribution (sign).

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	Networks / Coalitions	Cooperation between actors.	N/A	N/A
	Meetings	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
	Expectations Positive	Expression of the technology's future expectations.	224	+
	Expectations Negative	Vice versa.	46	–
	Award	–	5	+
	Outcome Study Positive	Results of research and trials, often mentioned when reports are published.	81	+
	Outcome Study Negative	Vice versa.	32	–
	Promise / Target Positive	Promises by actors with the power to change institutions, complementing the technology.	171	+
	Promise / 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 Markets	Protected spaces where practical experiments can be conducted in a market environment.	N/A	N/A
F6: Mobilisation of Resources	Feedstock	Content related to availability of biomass resources.	N/A	N/A
	Investments / Subsidies	Including dedicated subsidy programs.	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 / Advise Pro	Pressure on actors in power to change institutions, complementing the technology.	138	+
	Lobby / Advise Contra	Pressure on actors in power to change institutions, hampering the technology.	20	–

Captions to Figures

Figure 1: Key events related to Entrepreneurial Activities (Function 1).

Figure 2: Knowledge Development (Function 2) [aggregated events / year].

Figure 3: Guidance of the Search (Function 4) [aggregated events / year].

Figure 4: Supp. Advocacy Coalitions (Function 7) [aggregated events / year].

Figure 5: Knowledge Diffusion (Function 3) [aggregated events / year].

Figure 6: Key events related to Resource Mobilisation & Market Formation (Functions 5 & 6).

Figures

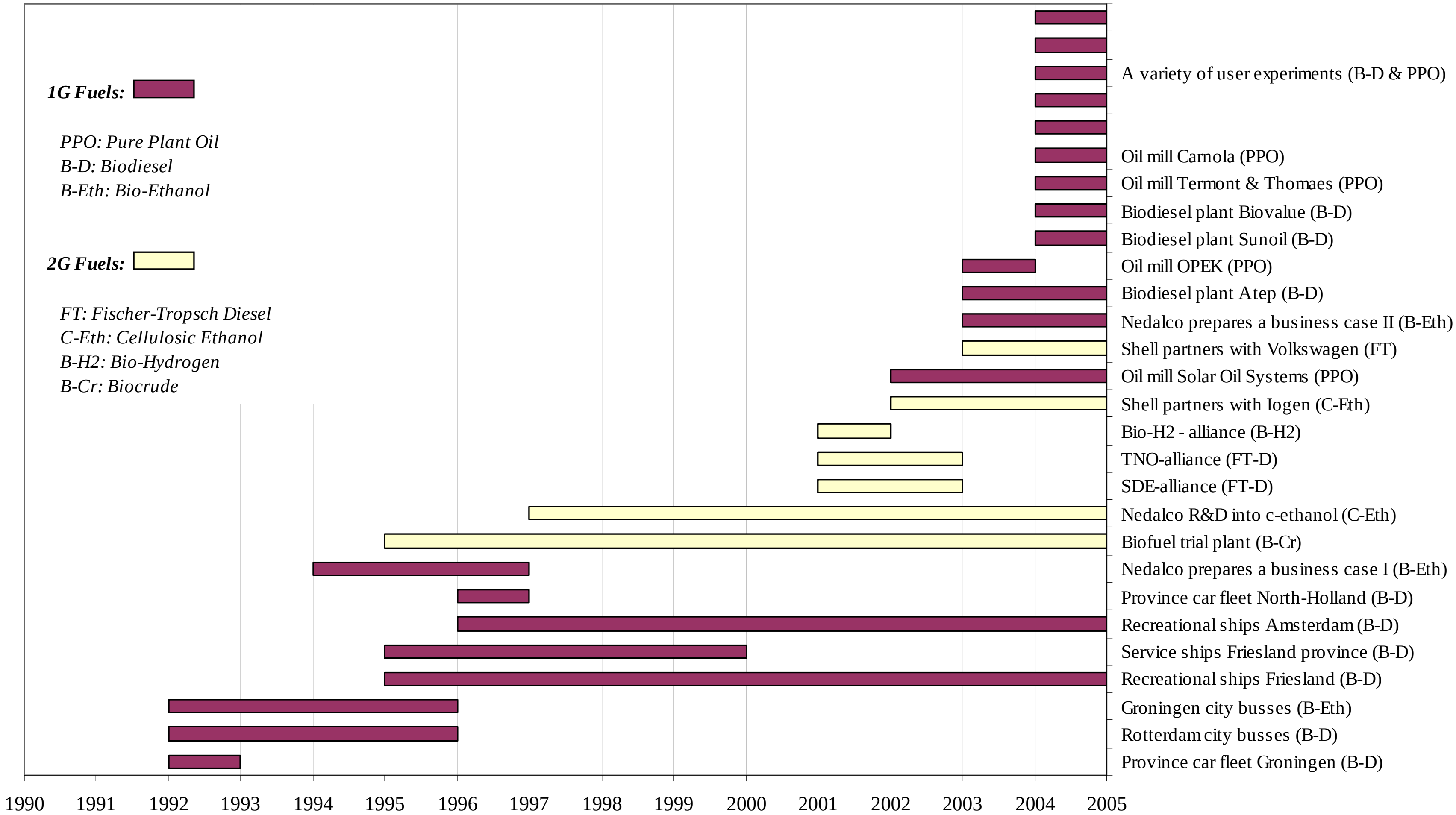

Figure 1: Key events related to Entrepreneurial Activities (Function 1).

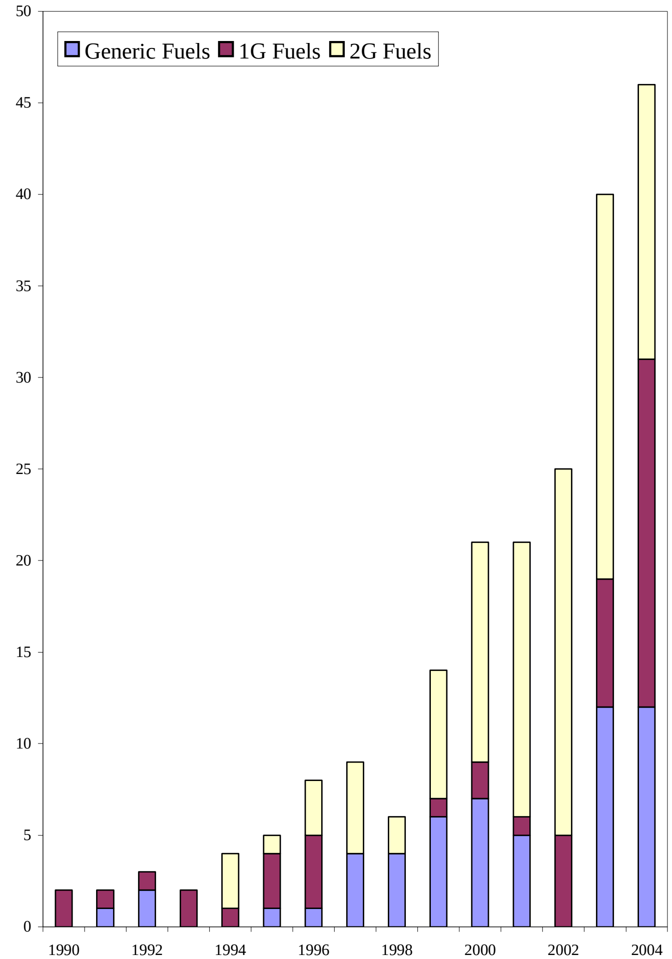

Figure 2: Knowledge Development (Function 2) [aggregated events / year].

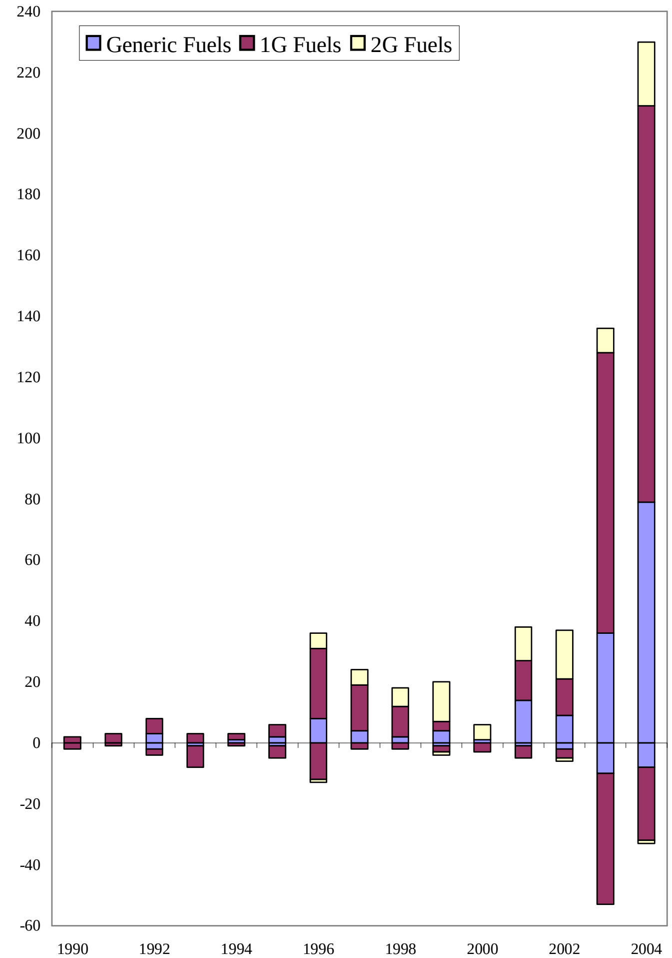

Figure 3: Guidance of the Search (Function 4) [aggregated events / year].

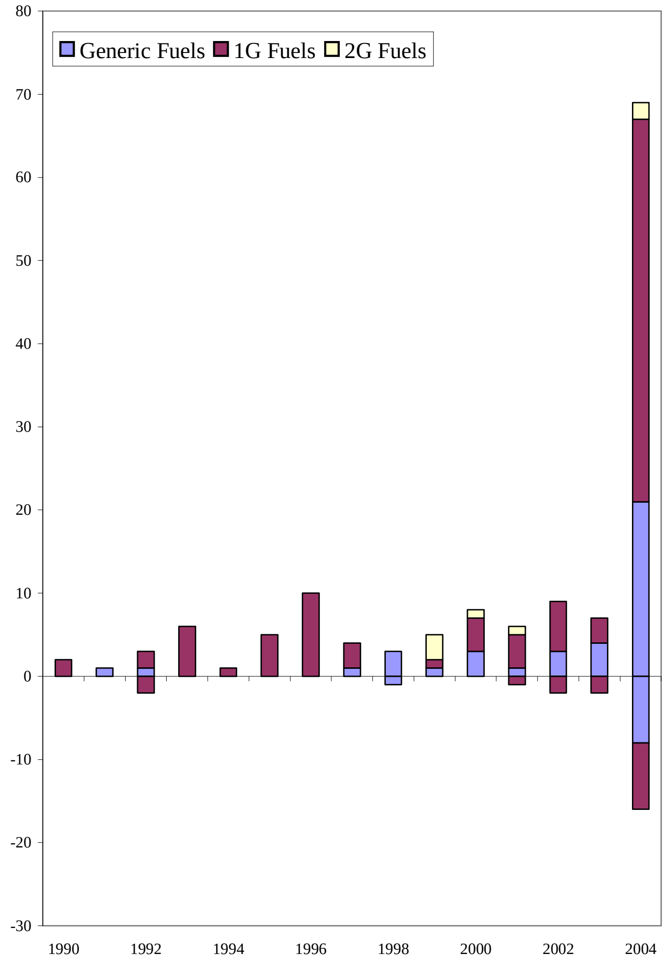

Figure 4: Supp. Advocacy Coalitions (Function 7) [aggregated events / year].

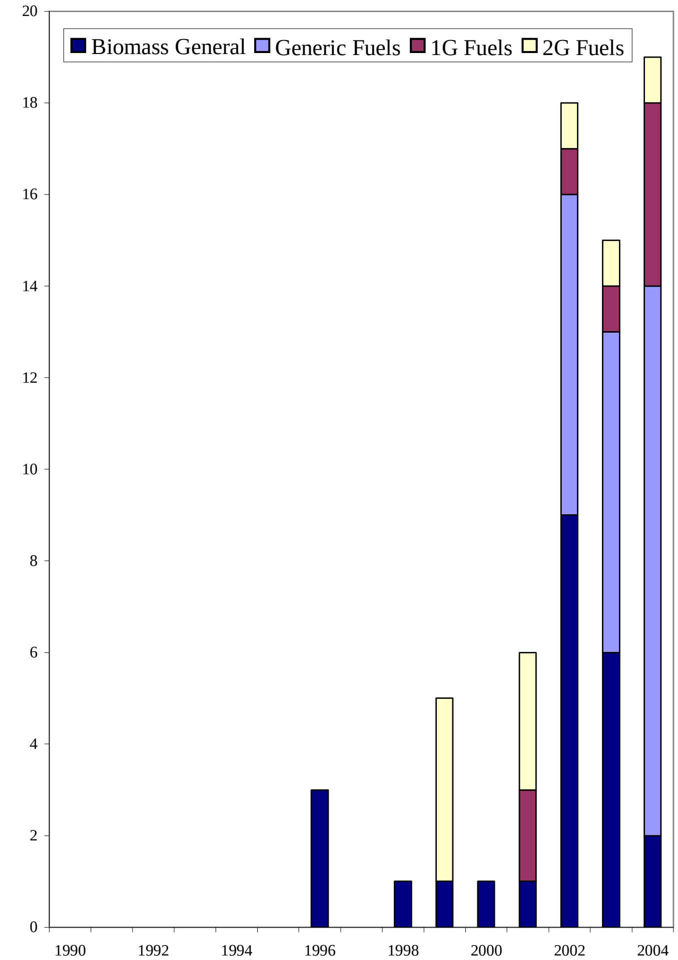

Figure 5: Knowledge Diffusion (Function 3) [aggregated events / year].

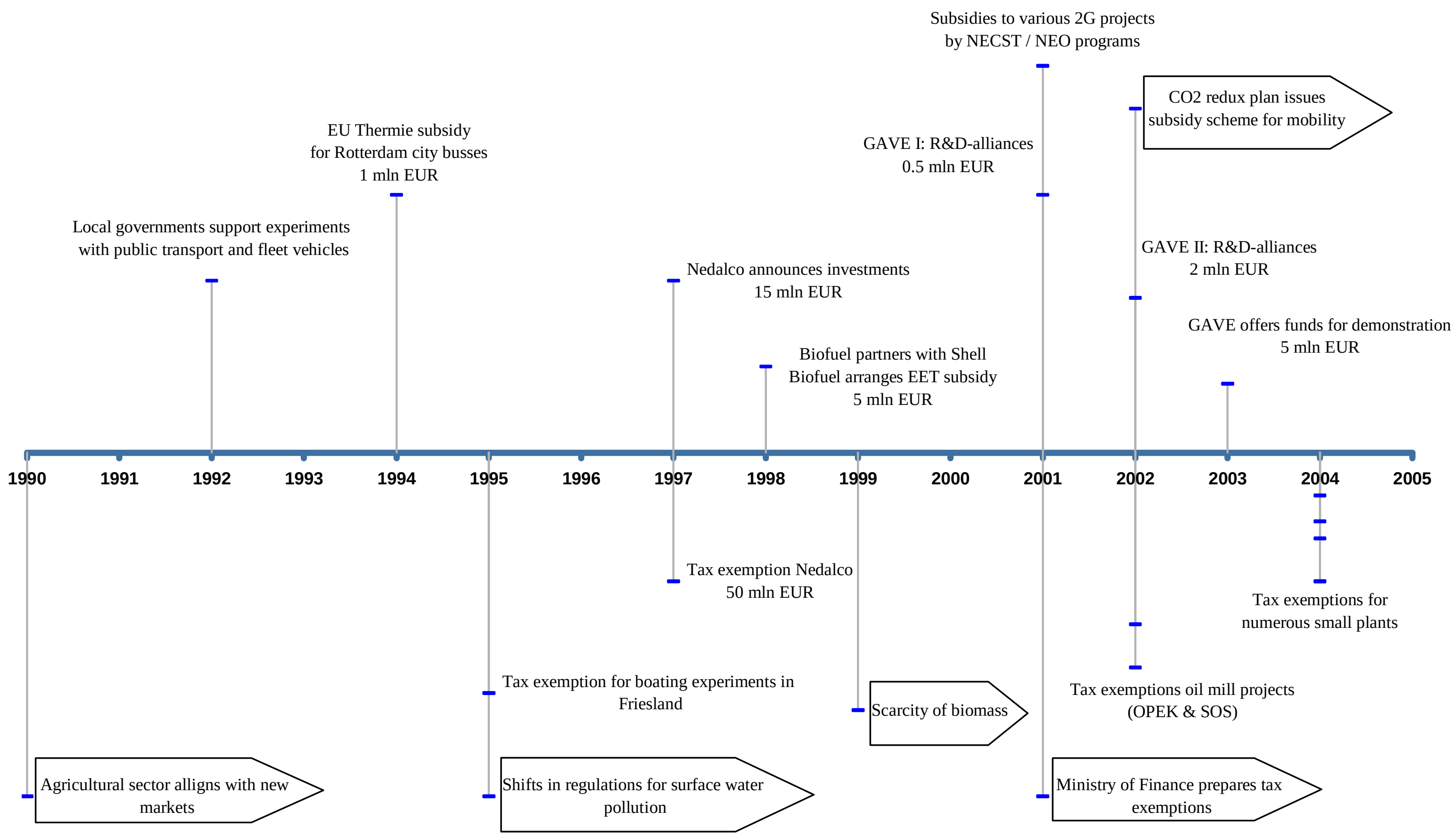

Figure 6: Key events related to Resource Mobilisation & Market Formation (Functions 5 & 6).