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Competition between first and second generation technologies: Lessons from the formation of a biofuels innovation system in the Netherlands

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ABSTRACT

The support 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 historical development of biofuels in the Netherlands as the topic of study. Special attention is paid to the simultaneous development of two technology generations within the field: a first generation (1G) and a second generation (2G) of biofuels. A critical question asked is whether deployment programmes for a 1G technology may have positive effects on the development of later generations. Two archetypical support strategies are identified: one is to keep investing in R&D concerning 2G technology, where the expected outcome is a fast move from one technology generation to the other. The other strategy is to focus on learning-by-doing in the 1G technology. In that way progress can be made in 1G technologies but the effects on 2G technologies are uncertain. We apply a Technological Innovation System perspective to analyse the strategies followed and their effects. From the results we draw lessons of relevance for practitioners who 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 for decision makers with a need to influence the course of technological change [1–3]. A traditional method for policy makers to stimulate energy innovation trajectories is to stimulate investments in research and development (R&D), thereby supporting learning processes often labelled as learning-by-searching [4,5]. This is an effective method to improve the technological performance of pre-commercial technologies and to increase their variety. However, investments in R&D alone do not explain the outcome of technological trajectories in the energy sector. Additional efforts to promote market diffusion of new energy technologies play a crucial role, especially when it comes to translating results of R&D to changes in the energy system [4–6]. Practical experiences in the market allow for learning processes to take place that are not stimulated by R&D; these are often labelled as learning-by-doing [5]. Learning-by-doing has proved to be critical in solving technological problems and establishing cost reductions for new technologies.

It is important to find the right balance between investments in R&D and investments in technology deployment by market formation measures [6]. This idea has been well established in the evolutionary economics literature, which stresses the importance of continued interactions between the activities of basic science, technology development and market formation, in technological change processes; see Kline and Rosenberg [7] for an overview. Scholars of evolutionary economics have since long rejected the so-called linear model of R&D, which considered technological change a unidirectional process, starting with basic research, followed by applied R&D, and ending with production and diffusion; see Godin [8]. The linear model does not fit the actual complexity of technological change [7]. In reality, technological change is a non-linear development which is constituted by numerous processes. These include R&D, and also production and market formation, running in parallel, and thereby reinforcing each other through feedback mechanisms.[1] If such feedbacks are neglected, by policy makers or entrepreneurs, this is likely to result in the failure of support policies [4,7,12,13].

This balancing exercise becomes even more challenging when one realises that a technological trajectory, in many cases, does not consist of a single technology being invented, developed and

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[1] Alternative models employed within the evolutionary economics field are the chain-linked model [7] or the innovation system model [5,9–11].

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diffused in the market, but of various technologies in different development stages: technology generations. Take for example the technological trajectory of photovoltaic solar cells: here two technology generations can be discerned: thick crystalline silicon cells and thin films. New cell types like organic dye solar cells or spiral technologies might invoke even more generations. These technology generations have some commonalities with respect to the service or societal function they provide, but differ strongly in technology base, and in their (expected) distance to the market. With the existence of technology generations, energy policy is not only a matter of balancing R&D vs. market formation, but also a matter of dividing resources across multiple technological options. So far little research has been done that focuses on the effect of such technology dynamics on the outcomes of innovation trajectories.

The situation may be regarded an opportunity to combine and interlink these two processes within one technological trajectory. A critical question is then whether deployment programmes for a first generation (1G) technology may have positive effects on the development of a second generation (2G) technology. Two archetypical strands of policy making may be discerned. One strategy is to keep investing in R&D on 2G technology. The expected outcome is a fast move from one technology generation to the other. The other strategy is to focus on learning-by-doing in the 1G technology. In that way progress can be made in 1G technology but the effects on the 2G technology are uncertain. The 1G technology may pave the way, in terms of markets and infrastructures, for the 2G technology, but there is also the risk of early lock-in: 1G technology driving 2G technology out of the market before it ever stands a chance.

To increase our insight in the possible implications resulting from these strategies, this paper takes the development of biofuel technologies in the mobility sector as the topic of study. The biofuels domain offers a prime example of different technology generations competing for support. The 1G biofuels have limited performance in terms of CO_2-reduction and require much land, but they are already in a (near-) commercial stage of development [14]. Examples are biodiesel from rapeseed, ethanol from corn, sugar beets and sugar reed. The 2G biofuels are expected to perform much better in terms of costs, land use and CO_2 emissions reductions. However, they are in a pre-commercial stage of development. Examples are ethanol from lignocelluloses (woody biomass) and synthetic diesel from woody biomass, based on the Fisher–Tropsch process. See Schubert [14] for an overview.

The aim of this study is to analyse and evaluate the dynamics involved in the development of biofuel technologies and to relate these dynamics to the effect of strategies followed by policy makers and entrepreneurs with respect to 1G and 2G technologies. Based on this analysis we provide a general discussion that is also relevant when dealing with other sustainable technological trajectories.

As an analytical framework we take up a conceptual model that is firmly rooted in the evolutionary economics literature: the Technological Innovation Systems (TIS) approach [9]. 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 the fact that most emerging technologies will pass through a so-called formative stage before they are subjected to a market environment [15]. During this formative stage actors are drawn in, institutions are designed and adjusted. In short, many processes unfold that, positively or negatively, will influence technology diffusion. The build-up, or breakdown, of these processes is conceptualised as the fulfilment of a set of system functions. Examples are the emergence of Entrepreneurial Activities, Knowledge Development and Resource Mobilisation [16]; 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. Based on this idea, the system functions will serve as evaluation criteria. With the aid of the TIS framework we will be able to particularly pay attention to the dynamic nature of technology development.

We will analyse 17 years of biofuel innovation system dynamics. The focus on the Dutch situation has theoretical and practical reasons: (i) technology dynamics are largely country-specific [5] and (ii) the analysis requires direct access to the empirical field. The research question to be addressed is:

What strategies were followed with respect to the support of 1G and 2G biofuel technologies by decision makers in the Dutch biofuels innovation system, and how did these choices affect the development of system functions in the last 15 years?

Based on the analysis of system functions we indicate to what extent decision makers have been effective in supporting TIS development. From the results we draw lessons of relevance for scholars, policy makers and entrepreneurs who aspire to understand and influence emerging energy technologies.

The structure of the paper is as follows. In Section 2 the research design, including theory and method, is revealed. Section 3 provides the case study on the Dutch biofuels developments. In Section 4 we evaluate and discuss our results. Section 5 concludes by summarising the most important issues.

2. Research design

Our theoretical approach is based on the work by Carlsson and Stankiewicz [9], Bergek [17], Jacobsson and Bergek [15] and Hekkert et al. [16]. The method we use is derived from Abell [18] and Poole et al. [19], and thoroughly illustrated by Hekkert et al. [16], Suurs and Hekkert [20] and Negro et al. [21]. Since there is already a lot of literature on this approach, both from a theoretical and a methodical perspective, we 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 [5,9–11]. The central idea behind the IS approach is that determinants of technological change are not (only) to be found in individual firms or in R&D networks, but also in a broader social structure in which the firm as well as R&D networks are embedded. Since 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 [22]. The TIS approach focuses on particularly that structure that surrounds a specific technology. We follow this idea in defining the Dutch Biofuels TIS (BIS) 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 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 [23]. However, a weakness of past innovation system studies is that they fail to address historical features in dynamic terms [16,20]. Recent TIS literature suggests that dynamics can be captured by pointing out positive (and negative) interactions between system functions [15–17,20]. These system functions are processes that foster the shaping and the diffusion of a technological field. The premise is that a TIS should realise multiple system functions, each covering a particular aspect of technology development. Based on a review of innovation systems literature, a shortlist of seven system functions has been formulated [16]. 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. Given the earlier mentioned insights from evolutionary economics, it is also expected that system functions need to be realised in parallel, 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 in such a way that it becomes possible to discern a positive feedback, or as Jacobsson and Bergek [15] 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.

We will breakdown the analysis of dynamics for 1G and 2G biofuels, point out the conflicts and complementarities, and relate them to strategic choices made by the actors in the BIS.

There exist other theoretical approaches that can be used for analysing and evaluating technological change and innovation. Most of them focus on isolated processes or particular aspects of innovation [24,25], but since the 1990s there have emerged various studies that develop a more holistic approach [3,25]. These studies have much in common as they share the basic elements, actors and institutions, and the purpose, supporting emerging technologies, of the analysis. They also tend to share the core ideas of evolutionary economics that we have set out in the introduction. It is beyond the scope of this article to give a review of this literature (see [3,25] for a suitable starting point to explore this literature), but there is one strand of theory that should be discussed, as it is, because of its similarity, a contester of the TIS approach.

This strand of theory is the Strategic Niche Management approach (SNM) [26–29]. SNM stresses the possible role of protected societal experiments, or niches, as a means to support emerging technologies. Like the TIS approach, SNM studies suggest the importance of stimulating particular processes (learning processes, shaping expectations, network formation) to support the progressive development of such niches [12,29].

Both approaches have their pros and cons; see Markard [3] for an overview. An important pro of the SNM literature is that it has incorporated a dynamic analysis of emerging technologies ever since it emerged in the 1990s. The SNM approach is also well positioned within an 'all encompassing' framework that covers the interplay of sectoral dynamics and landscape factors in relation to niche development (see Geels and Raven [29,30]). On the other hand, as discussed above, the TIS literature has recently managed to move away from its static focus, and, indeed, has surpassed SNM studies in the sense that attention is given to a larger variety of processes (system functions), with, as a result, a more fine-grained approach to dynamics. Moreover, the TIS approach involves a more inclusive perspective on how a TIS develops over time—i.e. gathering momentum through interaction of system functions, gradually including more actors and institutions—whereas in SNM it is unclear how a niche will become something else than just a protected experiment. It should be mentioned that SNM studies have started to address this issue by studying the emergence of connections across various niches [31].

In a sense, the choice for either of these theoretical approaches is a matter of style and taste. After all, the drawbacks of both approaches are being worked on. Additional work, conceptual and empirical, will benefit a fruitful dialogue between both literature strands that has existed for some years now (see Markard [3]). The superiority of one approach above the other has not (yet) been established and will certainly not be decided upon in this article.

Note that the dynamics of technology generations, the core topic of this article, have so far not been covered by any of these studies.

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 for innovation to occur. 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. This system function relates to such exchange activities.
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 also realised 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. This system function can be fulfilled by entrepreneurial investments or through government support programmes.
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

The analysis of a developing TIS requires a 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 measure the realisation of system functions is 'event history analysis' as it has been developed in the context of organisation studies [19].

The 'event history analysis' has been most used in a series of studies oriented towards firm level innovation trajectories [32]. With a focus on the micro-level, these studies monitored the day-to-day business activities of a firm in real-time. By using quantitative and qualitative approaches, they have distilled a number of interesting dynamic patterns, resulting in theoretical insights on the nature of innovation dynamics [19,32]. Another important contribution of these studies was the development of statistical tests which could distinguish between a variety of organisational dynamics. For a meso-level analysis, like ours, the size of the system is too large to allow for this kind of approach. For one thing, change processes typically take more time (in the order of decades rather than years), implying that an *ex post* analysis is more suitable. Also, the size and heterogeneity of a large socio-technical systems makes it more difficult to come up with sensible aggregate variables to be used for statistical testing. But, as Van de Ven [33] has shown himself, the 'event history analysis' can be adapted to fit to larger systems as well.

The empirical basis of the 'event history 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 1990–2007. The following keywords were used (translated from Dutch): bio(-)fuel; bio(-)ethanol; biodiesel; dimethylether (dme); Fischer–Tropsch; hydrothermal upgrading (htu); pure plant oil (ppo). In total, about 1100 events were retrieved and collected in a database.

With the overview provided in the database, the events can be clustered into types that correspond to the system functions. This clustering exercise is iterative by nature and will yield somewhat different outcomes for each empirical case. For our study the outcome is presented in Table 2. In this table, each event is mapped on a particular system function. This way, the events serve as empirical counterparts of system functions.

The next step is to construct a narrative in which the events are interpreted and connected in a meaningful way. This can be done by forming storylines consisting of event sequences. The construction of these storylines is possible since the relations between events can be traced back in time by using the database. On the system level, each event can be connected to a system function, according to Table 2. With this in mind, it becomes possible to point out what system functions are involved in the unfolding of a particular storyline. It even becomes possible to indicate whether particular system functions reinforce (or antagonise) each other through time. A very simple example of an event sequence could be that a government subsidy [F6], results in an R&D project [F2], which delivers promising results, raising positive expectations [F4], thereby encouraging the government to provide even more subsidies [F6], which are used to conduct more R&D [F2], and so on. The narrative will consist of multiple storylines, each made up of sequences of interrelated events. If system functions reinforce each other positively, this is called cumulative causation. Such a mechanism will result in the rapid build-up of a TIS. If system functions reinforce each other negatively—for example through negative expectations that affect the willingness of investors to step in—the possibility of a TIS breakdown arises.

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, advice

In this case, we also indicated in our database whether events belonged to one of three categories: 1G biofuels, 2G biofuels, or generic.[2] By looking for different contributions to system function fulfilment of events related to 1G and 2G technologies we will be able to say something about the effect of technology generations, or strategies followed, on the dynamics of the BIS.

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 minimise personal bias, the narrative was verified, i.e. triangulated with other data sources, and, where necessary, reconstructed, by including feedback from interviews with experts. 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.

Note that the event history analysis as conducted within this study, constitutes a more rigorous and more systematic approach to case study analysis than usually the case. In our view this is an important contribution to qualitative research in the field of innovation, and science and technology studies.

3. The dynamics of the Dutch biofuels innovation system

In this section, we reconstruct the development of the BIS and refer to the various system functions as F1, F2, F3, etc., following Table 1 and 2. The narrative is chronologically organised, covering six episodes. In each episode, the narrative starts out with an outline of important external developments of the time. A short account on the general features of the technologies involved is given in Box 1.

[2] The 1G biofuels being biodiesel, pure plant oil and ethanol from agricultural crops and 2G biofuels being dme, Fischer–Tropsch diesel, htu products and cellulosic ethanol. The generic category contains those events which did not imply a choice between those specific technological options.

Box 1–Technical features of 1G and 2G biofuel technologies

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 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 [14] 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 CO_2-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. 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 [34]. 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 [35] 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 [36,37].

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 buses. A number of actors is involved, among which the alcohol producer Nedalco [38]. Another entrepreneurial project [F1] is started in the city of Rotterdam, this involves a trial [F2] where buses 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]. A less-positive outcome [F4] is the low economic feasibility: under the present circumstances, biofuels cannot compete with fossil fuels [39].

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] [40,41]. Various assessment studies [F2] now set the tone for a debate [F4] that goes on until today. Regional actors emphasise the strategic and environmental value, whereas scientists and environmentalists stress the meagre environmental performance of biofuels. The national government stands divided on the issue and refrains from action [F4] [42–45].

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 has not been invented yet.

3.2. *A first niche market (1995–1997)*

From 1995 onwards the climate issue is gaining political momentum and the concept of biomass is becoming important in the energy sector [46,47].

Against this background, a first series of projects starts which will contribute to a sequence of further activities. This begins 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 quality [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 2 years—is provided [F5] [48]. A positive feedback now emerges as the province decides to adopt biodiesel for its fleet of service boats. The adoption experiment results in (practical) 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) biofuel 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 water quality regulations.

A critical downside is that, meanwhile, various impact assessments [F2] yield contradictory or negative results for 1G biofuels [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, and not on the basis of a general vision [49].

The story of struggling entrepreneurs also fits the role of Nedalco, an alcohol producer. Nedalco plans a business expansion [F1], starting with the trial production of bioethanol [F2] [50]. 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 [51]. Nedalco succeeds to raise general attention to bioethanol, especially also in the media [F4] [51,52]. In the summer of 1997, Nedalco succeeds in persuading [F7] the national authorities to guarantee a 10 year tax exemption [F5] for the annual production of 30 million litres of bioethanol. However, the amount turns out insufficient to cover the investments [51,53]. As a result, the project is discontinued [F1] and the plans remain a promise. Nevertheless, Nedalco's project is successful in the sense that it has started to break 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 lobbies). Note that 2G biofuels are still not mentioned in this period.

3.3. The invention of technology 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 transport domain is increasingly considered an important target for energy policy [54,55]. A 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 [56]. The programme 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] [57], causing a fierce discourse on the use of biomass streams for transport vis-à-vis electricity purposes [F4] [49]. However, an influential study [F2], authorised by GAVE [F4], designates that biofuel production might certainly be favourable, provided that production scales are sufficiently high [F4] [58,59]. 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 national policy agenda [F4, F7] [56].

The second breakthrough initiated by GAVE, is in 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 [F2] [60]. The advice is to exclusively support projects which promise a CO_2 reduction of at least 80% [F4] [56]. Subsequently, all 1G options are (de facto) excluded from further assessments. It is within this context that the category of 2G biofuels is actually invented to distinguish the contested agriculture-based biofuels from emerging biofuels options that are expected to offer a better CO_2 balance in the future. Other European countries, most notably France and Germany, are by this time actively supporting the market diffusion of 1G biofuels.

Thirdly, the programme serves as a catalyst, bundling and connecting (2G) activities that, so far, have been developing 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. 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 all 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 rise of 2G biofuels [F1, F4]. 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] [51].

To sum it up, the consistent promises of 2G technologies, trigger fruitful BIS dynamics, largely supported by the Guidance of the Search provided by the government's GAVE programme. The BIS focuses strongly on 2G Resource Mobilisation and Knowledge Development. The 1G biofuels are not supported and in fact, there are hardly any new 1G activities to speak of in this period.

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 [61]. From 2001 to 2002, GAVE installs a subsidy scheme [F6] aimed at guiding entrepreneurs towards the realisation of demonstration-scale fuel chains [F4] [62]. The scheme 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% CO_2-reduction criterion still holds.

All projects that are supported by GAVE are directed at 2G options [F1]. Two 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 and a car company [63]. The projects are successful [F4], particularly with respect to solving technological bottlenecks related to cleaning the synthesis gas that is required for the Fischer–Tropsch process [F2] [64].

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 viable 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. According to the candidates, such an investment is not feasible without a flanking market stimulation programme, e.g. tax exemption measures [F5] [56,65]. The subsidy programme stops [F6].

From a purely technological perspective, the approach of GAVE has resulted in important successes. But the absence of Market Formation activities forms a critical barrier to the development of 2G demonstration projects [56].

3.5. A paradigm shift (2003–2005)

In 2003 Europe decides on a biofuel directive, thereby demanding from its members to substitute a percentage of all transportation fuels, by biofuels [66]. With GAVE's subsidy programme terminated, and with the new task of implementing the directive, a reorientation of national policy is imminent [67]. Therefore, 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 [56,68].

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] [51]. 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 meanwhile their venture in R&D on 2G ethanol has been extraordinarily fruitful [F4] [51,56]. Still, the national government does not readily respond [F4] and the project is halted [F1].

There is still no national support programme for 1G biofuels, but in anticipation on EU policy [F4], a variety of 1G initiatives are 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 farmers 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-specific basis [F5] [69]. In 2004 numerous municipalities start to adopt biodiesel for their car fleets [F1] and by 2005, the first 1G biodiesel plant is built [69–71]. These successful outcomes [F4] trigger positive dynamics in the sense that now numerous projects [F1] start all over the country, especially in rural areas [72–76].

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 anticipation on Market Formation policies, to be issued through the EU directive, plays an important 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 catalyst, to a facilitator of Knowledge Diffusion and Market Formation. In the process, the concept of a stepping stone technology—from 1G to 2G—has gained popularity. The 1G fuels are now explicitly regarded as a bridging option [56,68]. This can be regarded an important paradigm shift, having a large influence on the further unfolding of BIS dynamics.

3.6. A market in distress (2006–2007)

With oil prices rising, biofuels are becoming an ever more important subject of energy policies, not only in the EU but worldwide [14]. A drawback is that, with market diffusion of (1G) biofuels taking off globally, the resistance against biofuels is growing at the same time. The controversy is becoming stronger as studies show that the increased land use for energy crops—for 1G and 2G alike—result in rising food prices and in the cutting of vulnerable nature areas like rainforests [77].

In the Netherlands the EU directive is translated in national policies [F4]. For 2006, a generic tax exemption is issued (as a temporary measure), which is replaced, in 2007, by a scheme of obligatory blending [F5]. The scheme obliges oil companies to sell biofuels in an increasing share of their fossil-derived fuel sales; from 2% (on an energy basis) in 2007 to 5.75% in 2010 [78]. In addition, to promote R&D on 2G biofuels a 60 million Euros subsidy programme, specifically directed at 2G biofuels production pilots (IBB), is installed for 2006–2014; with 12 million Euros allocated for 2007 [F6] [79]. For the first time Market Formation and Knowledge Development are supported in parallel.[3]

As the result of these supportive policies, the number of business start-ups increases [F1]. Biofuel plants (1G) and logistic facilities are being built in the Rotterdam harbour [77]. A positive effect of the biofuels market that has been created, is that entrepreneurs no longer have to lobby for subsidies [F7]. Instead, successful businesses breed ever more start-ups without the need for specific government interventions [F4] [77].

An exception is formed by entrepreneurs aiming for the further development of 2G technologies. The 2G biofuels are, as yet, not developed far enough to be commercially available [14]. The support for R&D, and the anticipated market, induces a number of companies—e.g. Shell and Nedalco—to invest resources [F6] in 2G technologies R&D [F1, F2]. There are even plans made, most notably by Nedalco, for the construction of 2G pilot plants. These initiatives are, however, largely dependent on government funding, and the allocated resources are rather marginal [F6]. Indeed, they are comparable to what was available within GAVE and this turned out insufficient at the time. But now that there is a market, Nedalco continues its course of activities in much the same way as it begun, by lobbying towards the government for a large subsidy [F7]. According to the latest information, the company was granted a subsidy for the building of a 2G pilot plant, but is currently still undecided on whether to realise its plans [77].

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

Despite the strong position in terms of Knowledge Development, entrepreneurs are generally hesitant to initiate Entrepreneurial Activities. The problem in general, for potential 2G biofuel producers, is the uncertainty on the biofuels market [F5]. After all, it remains to be seen whether 2G biofuels can eventually compete with the 1G biofuels [F4]. This uncertainty is the more striking in the face of cheap imports from Brazil and Eastern Europe. In fact, even 1G biofuel producers have a hard time competing with the biofuel imports [F4, F5]. Reason for some entrepreneurs to call for market protection policies in biofuels trade, especially since some of the biofuels imported are deemed unsustainable [F7] [77].

The latter point relates to a more stringent issue: a renewed rise of the biofuels controversy. With the increasing market diffusion, scientists and environmental organisations have continued to stress that biofuels are not a solution but a problem [F4, F7] [80,81]. Their distress calls are heard by politicians and the Dutch government picks up on this by reaching back on the original distinction between 1G and 2G biofuels, although it is a more fine-grained distinction this time around. A system of sustainability criteria is developed that should allow policy maker to incorporate the CO_2-reduction potential and land-use of particular biofuel chains [82]. The most recent development is that a debate has started, on the EU level, about the question whether the biofuels directive should be adjusted to take into account such sustainability criteria. Dutch policy makers have a large say in this discussion since they have already started to develop sustainability criteria, as a response to the early rise of a biofuels controversy in the Netherlands [77].

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

4. Analysis and evaluation

Having analysed the historical development of the BIS in detail, our main questions can now be addressed explicitly. We will start out by giving an account of the strategies that have been followed by entrepreneurs and policy makers. Subsequently we will evaluate the implications of these strategies for the dynamics of the BIS in terms of system functions.

4.1. A typology of strategies

From the progression of events it becomes clear that different actors have followed different strategies with respect to supporting 1G and/or 2G biofuel technologies. Also, these strategies have changed over time. What is interesting from a theoretical point of view is that both archetypical strands mentioned in Section 1—the R&D-oriented approach and the market diffusion-oriented approach—seem to be contained in the BIS, but there are others as well. We will now identify four typical strategies and relate them to some important examples.

First of all there is the wait-and-see strategy. This approach was dominant at the beginning of the Dutch biofuel developments (1990–1994) and was mainly followed by the Dutch national government. Government authorities were divided and did not take a stance in the emerging debate around the feasibility of 1G biofuels. The dominant idea was that allocating biomass for utilisation in the transport domain was inefficient compared to utilisation in the electricity domain but this was not translated in to policy. Some entrepreneurs managed to get a specific tax exemption, by actively lobbying for it, but these were exceptions and not part of a policy strategy. Obviously, many actors—also entrepreneurs—choose to be passive in situations characterised by uncertainty. Nevertheless we stress the role played here by the national government because many entrepreneurs expected a more structural form of guidance.

Secondly, there is the typical R&D strategy as proposed in Section 1. This more or less traditional approach is dominant in the period of the GAVE programme (1998–2002). After GAVE was started the government and its energy agency, Novem, started giving clear signals that biofuels should be developed, and, moreover, that 2G biofuels were to be preferred over 1G biofuels, effectively excluding 1G experiments from government support. Policy was aimed towards stimulating R&D. This 'technology push' approach was also followed by research institutes and firms participating in the GAVE programme. Note that most of these firms were incumbents: medium-to-large organisations and part of the energy sector.

A third strategy that can be identified is the other extreme discussed in Section 1, namely a total focus on Knowledge Development, in the form of learning-by-doing, and Market Formation. This diffusion strategy was especially favoured amongst actors that promoted 1G biofuels in the period 1995–1998, for instance the boating companies and Nedalco. But also from 2002 to 2005 amongst farmers and small entrepreneurs. Note that all of these were relatively small actors, for the large part, new to the 'fuel business'. Also, local governments adhered to this market-oriented approach, for instance by starting small procurement programmes.

The fourth strategy, the bridging strategy, involves combining the latter two approaches. By simultaneously supporting 1G and 2G biofuels, R&D and learning-by-doing processes may possibly be linked up. An example is the Nedalco project. This company—a new entrant—already produced consumption ethanol (essentially 1G technology) and actively advocated the diffusion of this technology in the transportation domain. But at the same time it invested in R&D on 2G biofuels. Another example is the national government's attitude around 2003–2007. Under influence of the European directive—promoting market diffusion—1G technologies were supported when it turned out that 2G technologies would fail to be commercialised in time. From our perspective the bridging strategy is most interesting since it relates to the question with which we started this paper, namely whether such developments can indeed complement each other in a positive sense. Do they have a positive influence on the dynamics of the BIS? To answer this question we will now relate these strategies to the fulfilment of the seven system functions and their dynamics.

4.2. *System function fulfilment for 1G and 2G biofuels*

If we want to provide an evaluative insight in the build-up of the BIS, then the 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 can be no build-up in the TIS. We have demonstrated this in Section 3 by pointing out how sequences of events may result in positive feedback or cumulative causation. So, given our narrative, what are the strong points and what are the weak points of the Dutch biofuels trajectory with respect to dynamics, and how does this relate to the strategies listed above?

When the BIS started developing around 1990–1994, the system functions were only weakly fulfilled and their interrelatedness was poor. Some small entrepreneurs and local governments followed a diffusion strategy but it was the national government's wait-and-see strategy that was dominant. The biofuels option was debated amongst policy makers and energy specialists without paying attention to what was actually happening in the country in terms of Entrepreneurial Activities and Support from Advocacy Coalitions. The result of this polarisation was that in this stage of emergence, characterised by high uncertainties anyway, entrepreneurs were subjected to a very ambiguous Guidance of the Search process. In multiple cases technically successful projects stopped because of poor economic conditions, conditions that could have been improved with the aid of government support. One could argue, although this is speculative, that in terms of diffusion and the associated learning-by-doing process, this was a missed opportunity.

Later on, around 1995–1998, BIS dynamics became more progressive, as entrepreneurs managed to utilise 1G biofuels, for instance in boats. This market diffusion strategy has been quite successful, for many of these entrepreneurs are still active today. The Entrepreneurial Activities could continue because of the presence of surface water quality regulation. Also the national government provided tax exemptions which additionally supported this niche market. The trials that resulted from these actions contributed to Knowledge Formation (learning-by-doing), and the positive outcomes (technically and economically) encouraged the start-up of other Entrepreneurial Projects as well. Still these developments were strongly dependent on successful lobbying activities, Support from Advocacy Coalitions, by the companies and local governments involved. For each tax exemption entrepreneurs had to lobby again, thereby highly increasing the transaction costs of their business. Moreover, this kind of ad hoc policy does not provide clear signals to other, more risk aversive, actors in the field. In fact, with the initiation of GAVE, the Guidance of the Search even became negative. Still, despite the exclusion of 1G biofuels from programmatic support these technologies could slowly develop in a niche context. The 2G biofuels did not come close to the market in the period studied. Therefore the diffusion strategy was not really an option for the actors promoting these technologies. One exception is the Nedalco company, on which more below.

The R&D strategy became dominant in the BIS around 1998–2002 when the GAVE programme started directing support for 2G biofuels. This was more or less a top-down subsidy scheme which resulted in the set-up of alliances and a number of R&D projects with promising outcomes. This way GAVE contributed to Resource Mobilisation, Knowledge Formation and Knowledge Diffusion. The knowledge developed around 2G biofuels mostly involved laboratory experiments and feasibility studies, i.e. learning-by-searching. Unfortunately, a crucial limiting factor of the government's R&D strategy was Market Formation. Due to the lack of any promise of a future market, the companies involved could not continue the technological trajectory to which they were committed. In this sense we could say that the R&D strategy has so far failed.

Note that for 1G biofuels, Knowledge Formation was mainly incremental. From that perspective it made sense to focus R&D expenditures on 2G biofuels. Nevertheless it is striking how radical the segregation between technology groups was. Bridging strategies were rather difficult to find. For 2G biofuels, events were mainly driven by the national government, research institutes and large companies, whereas for 1G, it was many small companies, farmers and regional governments that took the lead. Apparently, the low-tech characteristics of the technologies allowed for easy entry. Around 2G technologies barriers to entry were higher, due to their complexity and capital intensiveness and the associated risks of technological failure. An important exception to this was the network around Nedalco's project, which entailed both 1G and 2G actors. Nedalco combined R&D in 2G biofuels with (planned) market diffusion of 1G biofuels. So far the outcomes were indefinite as they still had not started any biofuels production activities. It is unknown whether Nedalco's R&D effort has had any positive effect on their regular business activities, but surely on the level of BIS dynamics they have established a reputation for being innovative and this helped them advocating the feasibility of 1G biofuels. This means that Nedalco successfully contributed to the fulfilment of Entrepreneurial Activities, Support from Advocacy Coalitions, Guidance of the Search, Knowledge Development, Knowledge Diffusion and Resource Mobilisation. In the sense of contributing to the BIS and the build-up of a variety of system functions, their bridging strategy has been rather effective.

Most recently, the bridging strategy became the more dominant approach within the BIS as a whole, especially when around 2004 the GAVE programme responded to the failure of its R&D strategy and had to follow up on the diffusion-oriented EU directive. A lot has happened since then, in terms of Market Formation, but also with respect to the Entrepreneurial Activities and Guidance of the Search. Still, most of these activities have revolved around 1G biofuels, whereas the development of 2G biofuels lags behind. And with the biofuels controversy raging on, it seems that business perspectives for risky projects have turned bleak. It should be noted here that the debate over the sustainability of biofuels, involving many Advocacy Coalitions, has raised important issues related to ethical problems of global scale. One might argue that because of these problems, the 1G biofuels should not be supported at all since they jeopardise the technological trajectory as a whole. On the other hand, the debate could also be regarded as an important outcome of learning-by-doing processes, initiated by 1G technologies. If BIS actors want to overcome resistance, it may be a fruitful strategy to do away with the rigid distinction between 1G and 2G biofuels and to implement a more fine-grained differentiation between various biofuel options. This is now, in fact, starting to happen as sustainability criteria are in the process of being developed.

Our main question was whether support for the diffusion of 1G biofuels could indirectly stimulate R&D of 2G biofuels. This remains a difficult question to answer because we did not find a lot of examples of this strategy in our case, and the examples that we did find, only provided tentative outcomes. It is just too early to evaluate these recent changes in terms of outcomes. Still, our results suggest that it is worth a try to induce couplings between activities related to different technologies. After all, the R&D strategy did not work for 2G biofuels because of the absence of a market environment. The diffusion strategy has resulted in some Market Formation but did not result in promising improvements for 1G biofuels. By complementing the support for R&D in 2G technologies with a diffusion-oriented policy for 1G biofuels, this problem could be overcome. After all, the broader structure of the BIS, markets, knowledge infrastructure, user expectations, may benefit greatly from such a process.

4.3. Discussion

This study should be regarded as an application of evolutionary economic ideas in the specific technological field of Dutch biofuels development but it provides a more general contribution as well. Although many other studies have been published that apply an innovation system perspective, these have not focused on the specific topic of competing technology generations. In fact, innovation system studies usually take technological features into account only as a background factor (see Sanden et al. [83] for an elaborate argument along these lines). In this sense this study is a step towards a better integration of our understanding of the interactions between technological and social systems.

Another key contribution of this study, especially compared to other innovation system analyses, is the explicit focus on decision-making strategies. There are not many studies that combine knowledge of strategies of individual policy makers and entrepreneurs with a full fletched dynamic systems analysis (see Meijer [84] for a positive exception). By pointing out how strategies of decision makers are likely to affect energy system dynamics, this paper contributes in an important way to insights of value to scholars as well as practitioners.

5. Concluding remarks

We have analysed and evaluated the dynamics of 1G and 2G biofuel technologies and have related these to four possible strategies of dealing with different technology generations. The strategies identified are a wait-and-see strategy, a R&D strategy, a diffusion strategy and a bridging strategy aimed at combining R&D and market diffusion. To map the dynamics of the Dutch biofuels developments we adopted the Technological Innovation Systems (TIS) framework and analysed the build-up of system functions over time as related to these four strategies. What follows now is a general reflection on the results from this analysis.

The dominant support strategy changed during the development of the BIS. The 1G biofuels developments started out with marginal practical trials by small entrepreneurs and local authorities that could count on very little support. Government policies were absent, despite some ad hoc tax exemptions for specific projects (wait-and-see strategy). Nevertheless some entrepreneurs succeeded in developing a protected niche for 1G biofuels and started practical trials in market-oriented businesses (diffusion strategy). For 2G biofuels a positive Guidance of the Search was established rather late in the form of the GAVE R&D programme (R&D strategy). From that moment on 1G biofuels started to become excluded, as GAVE did not support these technologies. Recently, with the European biofuels directive, 1G biofuels gained credit again and the Dutch government started regarding 1G biofuels as a stepping stone towards 2G biofuels (bridging strategy).

We have discussed the strengths and weaknesses of BIS development as related to these four strategies. It turned out difficult to reach a definitive conclusion. One important issue is that the BIS was successful in facilitating Knowledge Development and Knowledge Diffusion around 2G biofuels. It also succeeded, though very late, in contributing to Market Formation, but the activities were exclusively related to 1G biofuels. Despite government support, 2G biofuels never got close to a demonstration. This could be regarded as a radical failure of the R&D strategy, which is understandable as the enormous risks involved with developing a supply infrastructure of 2G biofuels can only be overcome when uncertainties in the demand side are minimal. A market needs to be already organised for this type of investments to be made. This is exactly what 1G technology could have done: pave the way for 2G technology by creating the necessary legislative infrastructure and a first market. But so far, Market Formation activities were only loosely coupled to 2G development.

Next to this stepping stone mechanism, it also has other advantages to start with deployment of 1G technology. This is somewhat speculative but learning-by-doing effects may increase significant performance increases in 1G technologies that make them better fit for future sustainable energy systems. Given the long time span of technology development this is not such a strange thought. Along similar lines we should consider that the promise of 2G technologies still needs to be lived up to. In other words, the 2G biofuels may never deliver what is expected from them. Always waiting for a better alternative is in the long run most beneficial for incumbent fossil fuel-based technologies. The introduction of new technologies always involves technologies that are in the beginning of the learning curve and, therefore, have great difficulty to compete with incumbent technologies that have gone through decades of technological improvements. For every new technology that is introduced, one can think of a better alternative that is still on the drawing table. Stimulating real changes to the energy system implies that new technologies are actually diffused and implemented instead of just being developed in R&D labs. The risk of comparing 1G and 2G technologies is that the performance is benchmarked to each other and not to the incumbent system.

Finally, there is a big risk in a deployment strategy of 1G technology. This is the case when the 1G technology is so controversial in terms of moral issues that it may create negative attention for the technological trajectory as a whole. This may destroy market chances of 2G technology instead of increasing them. A way of avoiding this pitfall would be to prevent the support of any biofuel option that does not meet some basic level of sustainability. Currently, policy makers and entrepreneurs are working on this by developing and implementing sustainability criteria. If successful, this may also mean that the rather crude distinction between 1G and 2G biofuels will be substituted for a scheme that allows for a more subtle differentiation between the rich variety of technological options that is currently still emerging.

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