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Fuel cell adventures. Dynamics of a technological community in a quasi-market of technological options

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Abstract

In this paper some insights from a social science perspective in the dynamics of the fuel cell community will be provided. An important concept used in the analysis is that of a 'quasi'-market of technological options. The strategic choices of actors for certain technological options can be regarded as analogous to choices of consumers made on a market. A scientometric research approach has been used to investigate the aggregate effects of this and other variations of strategic behaviour. These concepts and analyses are shown to be helpful in answering questions such as why fuel cells are so popular today whereas they have not always been, and why preferences for different types of fuel cells shift over time. At the end of the paper the relevance of these kind of analyses for technology forecasting and management practices is briefly discussed. © 1998 Elsevier Science S.A.

Keywords: Fuel cells; Technology dynamics analysis; Scientometric research

1. Background

Over the last two decades the study of the dynamics of technical change has been taken up with more emphasis than before by scholars from a wide array of academic disciplines, in particular (evolutionary) economics (for an overview see Ref. [1]), sociology of science and technology (for an overview see Ref. [2]) and history of science and technology (for examples see Refs. [3,4]). Although originally hardly in touch with each other, these scholars today can be said to form a new academic field sometimes summarised under the umbrella term 'technology dynamics' [5]. In 1994 a Ph.D.-research project started at the business unit Policy Studies of the Netherlands Energy Research Foundation ECN to investigate whether insights generated by the technology dynamics field could be useful for forecasting and management practices. In the first phases of this project it became clear that the theoretical concepts available within technology dynamics at the time had not been developed for these kinds of purposes, although they could serve as a basis to start from. Additional concepts that could be more useful with regard to forecasting had to be developed, based on new empirical evidence. It was decided to take the historical and current developments of fuel cells as a 'case study'. This paper will report on some of the main results from this project.

2. Introduction

In an earlier paper presented at a fuel cell conference, some main findings of technology dynamics have been summarised and illustrated with examples from the history of fuel cells [6]. These findings represented some of the ideas the technology dynamics scholars from the different academic backgrounds seem to agree upon. However, there remain some very basic differences between different 'schools' within technology dynamics. Sociologists, for instance, tend to be more interested in understanding the practices of scientists and technologists whereas the economists want to explain technological developments by referring to aggregate trends (for instance 'computerisation'). The basic disagreement lies in the fact that sociologists see 'trends' as something that has to be explained, while economists tend to use trends as explanations of technical developments. Sociologists, however, do not focus on

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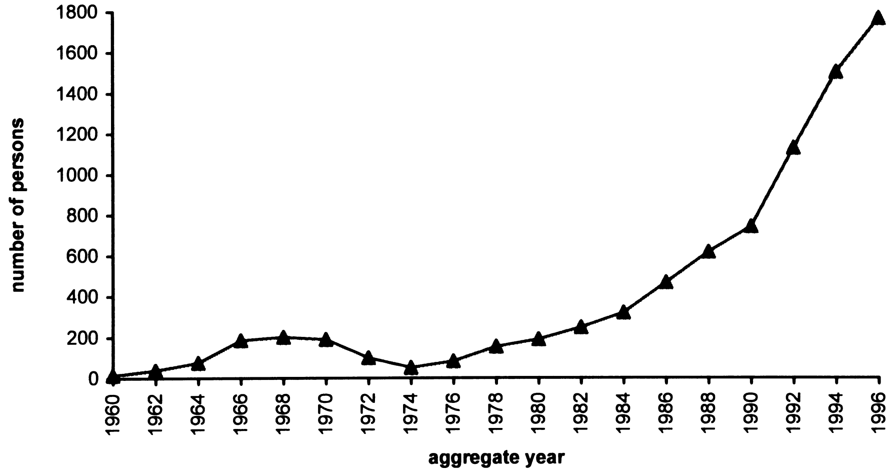

Fig. 1. Development of the population of the fuel cell community, for each year defined as the number of persons who published a paper in that or a later year or whose last paper had been published at most 2 years before.

explanations of trends, but instead they tend to analyse the way in which scientific and technology actors construct and use the idea of trends as a tool to convince others in their day-to-day practices ('because the trend is such and such, we should do so and so').

3. Theoretical and methodological issues

During the first years of the research project a set of concepts was developed to overcome the 'gap' that seemed to exist between the economist and sociologist approaches. By using social science methods such as interviews, text analysis and participatory research, all within the fuel cell community, it was postulated that the outcomes of the process of technological developments can be explained as an effect of decision-making processes by actors within the technological community. These choices are guided by 'strategic behaviour' of the actors involved. With 'strategic' we mean that actors, in their behaviour and choices, take into account what is going on elsewhere in the field, i.e. the actor's perception of what other actors say and do. In the next sections, some additional concepts are introduced that will be helpful in understanding the dynamics in technology communities and of the fuel cell community in particular.

Research by interviews, text analysis and participatory research has been combined with 'scientometric' analyses. For this purpose data on fuel cell articles from several existing databases were used. A well-known example is the Science Citation Index database as provided by the Institute for Scientific Information (ISI). Besides using these data, we established a more detailed database which is intended to include all papers and posters presented at 52 major international fuel cell conferences that have been held between the first American Chemical Society Symposium on Fuel Cells in 1959, published in Ref. [7], and the last Fuel Cell Seminar held in Orlando in 1996 [8].[1] Currently the database contains numerical information on 2974 fuel cell papers and posters. These publications have been produced by 3872 (co-)authors, which were employed by 730 institutions (such as firms, universities, technological research institutes, commercial users, government agencies, consultants and so on) and 1010 departments of these institutions, which represented 40 different nationalities. All this information has been linked together using MS Access 2.0 software.

In this paper some insights from a social science perspective in the dynamics of the fuel cell community will be provided to the reader. These insights will be shown to be helpful in providing answers to questions like: Why are fuel cells so popular today, and why haven't they always been? Why are certain types of fuel cells so popular among the fuel cell community members and why do such preferences change over time? We will mainly use results from our database analyses. The discussion of these results relies on concepts developed in an earlier phase of the project in which the other research tools were more dominant.

4. Results

In Fig. 1, the number of people publishing papers about fuel cells are used as an indication of the popularity of fuel cells through time. For a given year, all persons that would publish in a later year or had published no longer than 2 years ago are included as fuel cell community members. This graph clearly shows that the 'fuel cell community' has grown strongly, in particular after 1976. However,

[1] Unfortunately copies of proceedings from the Second International Conference on Fuel Cells held in Brussels 1967 and the National Fuel Cell Seminar held in the USA in 1978 are still missing. The information from the National Fuel Cell Seminar held in San Diego, 1980, has not yet been implemented. This means that currently the analyses are based on data from 49 fuel cell conferences.

there have also been times of decrease. How can this pattern be explained? We will treat this question in several steps.

4.1. The quasi-market of technological options

The dynamics of technological developments can be regarded as analogous to certain market processes, although some differences remain. Technology developers have to make a choice from a wide range of research options, and they will tend to choose what they regard as the most *valuable* option. In this value-assessment process, a developer will be influenced by what other developers (the community) say and do. In this way values for the different options are constructed. Just like the price mechanism on a market for commodities results in prices that differ not too much from each other, these values will not differ too much from each other either. Therefore, we are tempted to speak about a 'market of technological options'.[2]

It is obvious, however, that the analogy between the market for technological options and the market for commodities has its limitations. The main difference lies in the value construction mechanism. On the market for technological options, a value is not constructed by the price mechanism, but by shared 'accounts', i.e. accounts that are perceived by most members of the fuel cell community as containing worthy statements about the status and features of a technological option.[3] Secondly, technological options are not traded between a producer and a consumer. Actors can play different roles; as consumers they use value-awarding accounts in their research decisions; in publishing their results and sharing their expectations they become producers of such accounts. Another feature that makes a difference is that actors such as sponsoring and governmental agencies, and consultants also play a role in this 'market'. Because of these differences, we prefer to speak of the 'quasi-market of technological options'.

An actor's decision which technological option is valuable enough to invest time and money in, is the result of many interactions with other actors. These interactions occur in many ways, ranging from reading articles and handbooks to informal discussions while drinking beer at the bar. Events that are very important for this value construction process are symposia and conferences, where people spend a lot of time exchanging information and opinions. One of the aims underlying the scientific discussions is to secure or expand the value awarded to the options chosen earlier, or to evaluate possible new research topics. For this reason, the number of papers in the fuel cell conference database can be regarded as a 'measure' of the change of the 'quasi-market value' of fuel cells over time.

4.2. The stock-market phenomenon

One of the phenomena encountered in the quasi-market is 'stock-market behaviour'. For many actors a technology becomes more interesting to invest in if other actors, and especially those regarded as important actors, are investing in it as well ('If Siemens, Westinghouse and Daimler-Benz seem to believe in it, it must be worth something').[4] This phenomenon can be compared with the functioning of options on a stock market; when demand rises for an option on a stock market, its value rises.

An important characteristic of this phenomenon is that it is self-reinforcing. This implies that it can induce not only a rise but also a fall in interest for a technological option. The decision of a large or reputed actor to abort the research can have a strong negative impact on the value of a technological option. This also means that there must be other factors counterbalancing the positive feedback loop, because otherwise interest for an option would either grow exponentially or be reduced to zero. Both effects can of course be observed in specific cases, but only for limited periods of time in the case of growth, and not for all options in the case of decrease.

The stock-market phenomenon is counterbalanced by two important elements. First, the existence of an upper limit. Not everybody is a scientist/technologist, and not every developer is interested in energy technology. And even for those developers who are interested in energy technology, there are a lot of other interesting options as well. This limitation means that an upper limit exists, which together with the self-reinforcing stock market phenomenon will result in an S-shaped growth curve over time. Secondly, there may be a group of 'high-risk/high-reward actors' following another line of reasoning. For those actors the fact that others do not value an option highly is the very reason why they choose to invest in it. The option might never become a 'winner', but in the case that it does, they will be the absolute leader in the field. These actors can keep the attention for a technology 'simmering' during periods of low interest.

The stock market phenomenon combined with the two limiting factors is expected to result in a wave-shaped development of the 'value' of an option in time. If we look at Fig. 1, the first half of the period under consideration

[2] The 'market' and 'value' analogy has been used by several other social scientists as well. Latour [9] explains the behaviour of scientists by saying that they strive for 'credibility capital' (which can have several forms, ranging from citations, to recognition, to high salaries) and that in this sense a 'market' for scientists exists. Debackere et al. [10] describe a technological community as a 'market of ideas', which can be analysed by scientometric methods.

[3] An example can make this point a bit more clear. Today most, but not all, members of the fuel cell community agree on the statement that alkaline fuel cells are not fit for commercial electricity production because of its CO_2-intolerance. Since this statement is accepted as true by most researchers, it has, together with other statements in accounts on the alkaline fuel cell that are shared by most fuel cell community members, a considerable influence on the 'value' that is attributed to this specific fuel cell type.

[4] This kind of 'mimetic' behaviour is a more general phenomenon. It serves for instance as the basic starting point for cultural philosophers such as René Girard [11].

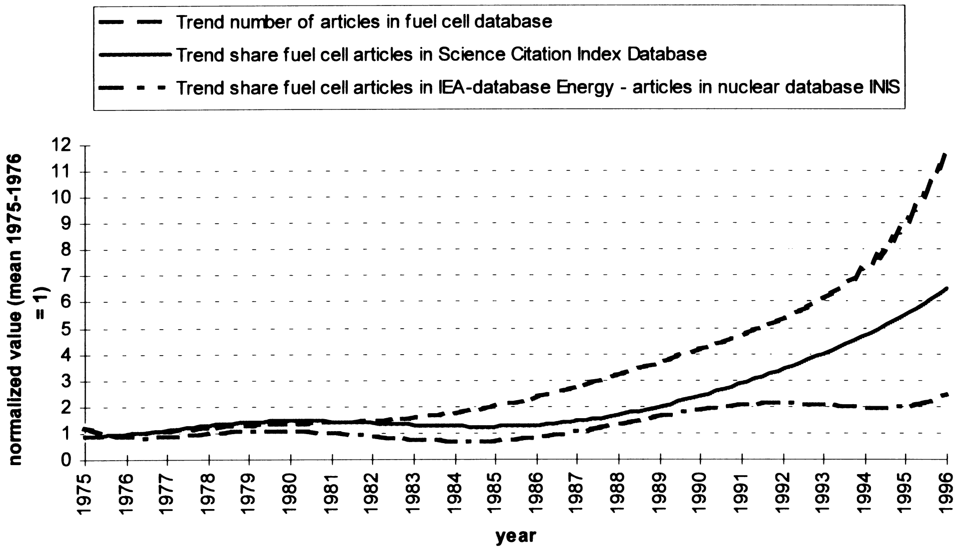

Fig. 2. Trends of number/share of fuel cell articles in several databases.

seems to comply with this expectation. However, since 1976 the curve only rises.[5] This brings up the question why the growth in the last two decades seems to be so smooth. In the next section we will show that in fact there have been more ups and downs in the 'value' awarded to fuel cells in the last two decades, but that they were offset by other developments.

4.3. The multi-layer character of the quasi-market of technological options

The fact that the waves in Fig. 1 are neither constant in amplitude nor in wave length, can be due to the multi-layer character of technology dynamics.[6] For instance, in times that the interest in fuel cells was decreasing compared to other energy technologies, overall trust in technology might have been growing, thus compensating for the decrease. More specifically, changes in the value awarded to fuel cells as measured by the number of publications on fuel cells can be explained by:

- changes in the value awarded by society to science and technology in general, measured by the aggregate production of scientific and technological publications;
- changes in the value awarded to 'energy technology' as measured by the production of papers on any energy technology issue;
- changes because the specific attention for fuel cells has altered.

[5] At first sight the curve in Fig. 1 might seem similar to the standard 'adoption curves' of new products in a market. In that case, however, decline only sets in if a new product replaces an old and obsolete one. This is not the case in Fig. 1. During the whole period the 'product' (= the technological option) remained the same, i.e. 'fuel cells'.

[6] See for extensive discussions on the multi-layered character of technology developments Van Lente [12] and Rip and Kemp [13].

To investigate these possibilities, data have been used from the Science Citation Index database as provided by the Institute for Scientific Information (ISI), the database 'Energy' of the Energy Technology Data Exchange (ETDE) international network and the nuclear energy technology database INIS (International Nuclear Information System). The number of articles responding to the keyword 'fuel cell' in the ISI database has been divided by the total number of articles in that database for every year. In order to be able to account for the idea that fuel cells are seen as a non-nuclear energy technology, the number of fuel cell articles in the Energy database has also been divided by the total number of articles in this database minus the articles in Energy which are also part of the INIS database. Next, the outcomes have been normalised to the mean value of 1975 and 1976, because of the bi-annual character of most fuel cell conferences. Fig. 2 gives the results, approximated by a 6th-order polynome in order to get 'smoother' trends. The upper line is a 'normalised growth curve' (the growth normalised to the mean value of 1976) of the fuel cell articles in our own fuel cell database.

Several interesting observations can be made analysing this graph. Fig. 2 shows that the number of fuel cell publications has grown more than 11-fold between 1976 and 1996 (upper curve) while its share in the Science Citation Index database has grown 6-fold (middle curve, relative to other science and technology options) and in the IEA Energy-INIS database 2.3-fold (lower curve, relative to other non-nuclear energy topics). Interest for fuel cells relative to general growth in science and technology has grown a lot faster than interest for fuel cells relative to energy issues in general and non-nuclear energy issues. This means that (non-nuclear) energy issues have received relatively more attention since 1975 than other science and technology issues.

For the value of the fuel cell option as compared to other technological options, this implies that until the mid-eighties, the increase was mainly due to the fact that fuel cells are an (energy) technology. After that, the value of fuel cells as a technological option by itself started to rise. This rise can be explained by the stock market phenomenon.

One step further is to decompose the relative contribution of each ‘layer of technology’ to the rise in the value of fuel cells over time. By using the values of the curves in Fig. 2 we have been able to decompose the growth in the number of fuel cell publications (the upper line in Fig. 2) into the three different ‘layers’ mentioned above. For the relation between these figures and taking the ISI-database fuel cell articles instead of our own database’s, we can establish the following equation (which is an identity relation):

$$\Delta_{i,j}(ISI_{\mathrm{fc}}) \equiv \frac{\Delta_{i,j}(ISI_{\mathrm{fc}})}{\Delta_{i,j}(ISI_{\mathrm{fc}})} * \frac{\Delta_{i,j}(ISI_{\mathrm{fc}})}{\Delta_{i,j}(Energy-INIS)_{\mathrm{fc}}} * \Delta_{i,j}(Energy-INIS)_{\mathrm{fc}} \quad (1)$$

with $i < j$ where

$\Delta_{i,j}(ISI_{\mathrm{fc}})$ = the normalised change in number of articles on fuel cells in the ISI database between year (or normalisation period) i and year j;

$\Delta_{i,j}(ISI)_{\mathrm{fc}}$ = the normalised change in the share of fuel cell articles in the ISI database between year (or normalisation period) i and year j;

$\Delta_{i,j}(Energy - INIS)_{\mathrm{fc}}$ = the normalised change in the share of fuel cell articles in the Energy–INIS database between year (or normalisation period) i and year j.

As mentioned before, in this case the mean value of the years 1975–1976 has been taken for the normalisation period i. The first term on the right-hand side of the equation gives an indication of the contribution of the change in value awarded to ‘science and technology in general’ to the rise in the quasi-market value of fuel cells. The second term represents the contribution of the change in value awarded to non-nuclear energy to the rise in value of fuel cells. The third term represents the effect of the stock market phenomenon with regard to the topic of fuel cells itself. This formula provides a possibility to distinguish between the contribution of the different layers of technological development to the value awarded to fuel cells over time. Fig. 3 gives the resulting curves.

In Fig. 3 we see that for each layer of technological development relative to the overall construction of the value of the fuel cell option, the interest takes the shape of a curve with wave-like features. This means that if we take the multi-layered character of technological development into account, the stock-market phenomenon we described, indeed results in a wave-like attention curve for fuel cells. But what is more, the figure shows that this analogy with a stock market is also valid for other layers of technological development. In other words, the societal trust in the problem solving power of science and technology in general also varies over time in a wave-like manner. This is also the case for society’s trust in energy technology to solve the energy problem and related environmental problems.[7]

Analysing the effect of the ‘stock-market waves’ of each of the technology layers for fuel cells it can be seen that all three lines have risen in value in the considered period. However, for fuel cells itself this has not occurred until 1987. Until that period fuel cells were relatively less popular than other non-nuclear energy technologies. But since non-nuclear energy technology topics as well as science and technology topics in general received more attention, the ‘net’ effect for fuel cells was still positive. In other words, the waves of the different layers of technological development often have been out of phase with one another since 1975. For example, the relative long ‘down-period’ of specific attention for fuel cells in the 1980s has been offset by an upward trend in the two other layers of technological development. The fastest growth can be found in the last three years, when first a small dip in the specific interest for fuel cells was counterbalanced by a growth in interest for non-nuclear technology (1993–1995) while in 1996 it was the other way around. Interest for science and technology in general has recovered from the small dip in the late 1980s. And currently, for the first time since 1976, all the ‘stock-market waves’ of the three layers of technology development are reaching a new peak and are ‘in phase’ with each other. This explains why today the popularity of fuel cells is larger and growing faster than ever before.

4.4. Preferences for certain types of fuel cells

Up till now, the development of the ‘value’ of fuel cells has only been studied at an aggregate level. No distinctions were made between the different types of fuel cells. In this section we will take a closer look at what happened to the values of the fuel cell types over time, and why. We will make use of the quasi-market metaphor again, supported by some additional concepts.

First, it is important to note that the value awarded by actors to technological options partly depends on the way the technologies are classified or characterised. Classifications and characterisations are results of earlier socio-economic-technical processes. For fuel cells, between 1976 and 1996 the electrolyte-based typology has been the dominant one.[8]

[7] One might wonder whether there are ‘external’ causes for these ‘shifts in trust’, comparable to the influence of political speeches or the release of economic figures on the index of a stock market. Although it is rather speculative, the small dip in the late 1980s in production of scientific and technological papers might be related to a worldwide dip in trust in science and technology caused by the major technological disasters of the Chernobyl accident and the explosion of Challenger Space Shuttle. The rise in the Energy Technology curve in the early nineties could, in the same speculative way, be related to the growth in importance of the global climate problem as induced by the Brundtland report (1987) and the Rio Conference (1992).

[8] Before 1970 this was not generally the case. Several typologies existed, and authors of handbooks had difficulties finding one everybody would agree upon. See for instance the Handbook of Fuel Cells and Fuel Cell Batteries [14].

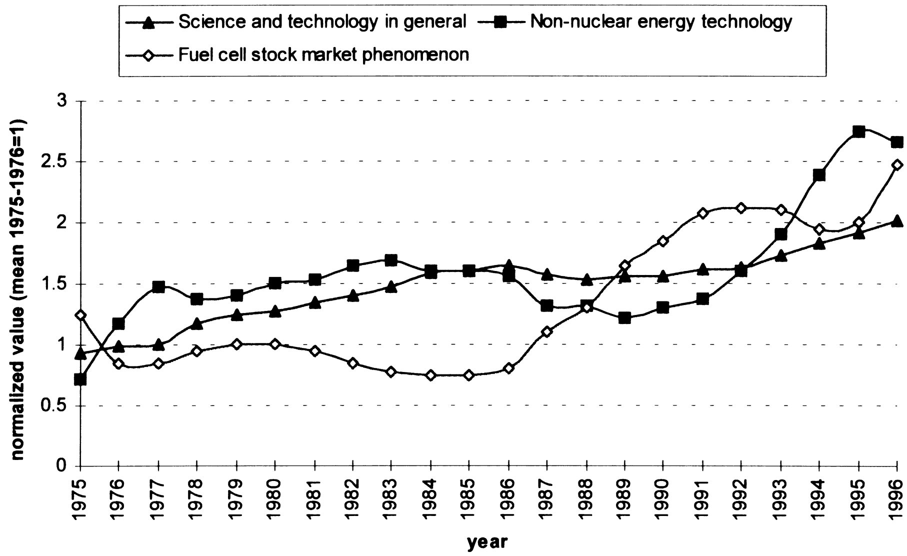

Fig. 3. Contribution to the value of fuel cells by the different layers of technological development on which the quasi-market value of fuel cells is based. The product of the three lines is the upper curve in Fig. 2.

Different technological options, once classified in a typology, often are related to each other in a 'prospective chronology'. A prospective chronology is an account, shared by the members of a technological community, that makes a statement about the 'sequence' in which the several types will enter the market in the future. The prospective chronology in the fuel cell community has been phrased in terms of 'generations' and is shown in Table 1. It was established in the second half of the 1970s, particularly strong during the 1980s and early 1990s, whereas today it might seem a little outdated.

Text analysis outside the scope of this paper shows that within the fuel cell community during the early 1980s speaking in terms of generations became linked with a very common sense idea about technological development that we will label as the 'sequential model'. Stated simply, this idea says that technological developments will occur in a certain sequential order: after the stage of science (basic research), an innovation will move to the stage of technology (applied research) before entering the market in the commercialisation stage. Although, especially in the case of fuel cells, very little empirical basis exists for this model, it is frequently used by actors in the field.[9] By linking the generation concept with the sequential model of technological development the term 'generation' received a very specific meaning within the fuel cell community. A 'newer' generation was necessarily in an 'earlier' state of development. Also the reverse became true. If a technology was seen as being in an 'earlier state of development', it would be labelled as a 'newer' generation. If a technology was seen as being in a 'later state of development' it would be labelled as an 'earlier' generation.[10] The latter happened to the alkaline fuel cell, the former to the solid polymer fuel cell.

Especially to new members of the fuel cell community as well as those on the 'fringes' of the community (the 'peripheral members'), this prospective chronology offers important information to base their strategic choices on. This way, the quasi-market value of the fuel cell types has considerably been influenced by the prospective chronology.

4.5. The effects of the fuel cell prospective chronology

One of the main effects of the fuel cell prospective chronology has been a shift in preference by the fuel cell community to the different types of fuel cells. This can be shown by Fig. 4. It has been constructed from the fuel cell database. In this graph the percentual distribution of papers on the five types has been calculated for each period of 2 years.

Several conclusions can be drawn from this graph. It clearly shows that the generations are not 'historical' in the sense that the first generations were developed first, the second generation was next, and finally followed by the third generations. On the contrary, papers on the third-

[9] As has been stated in a previous publication (Schaeffer and De Laat, 1996) [6] the sequential model of technological development is one of the narrative resources or 'myths of technology' that is used by actors in technological development practices.

[10] The generation concept is also used in other technologies, e.g. in the microprocessor industry. In this case, however, a 'next' generation was stated in performance characteristics, for instance a doubling in the number of bytes per chip or a halving of the costs per byte. This implies that for any actor a next generation necessarily follows the previous one (one cannot produce a 64 MB chip before having been able to produce a 32 MB one). In the case of fuel cells, however, developers of a third-generation technology (SOFC) do not have to be able to produce PAFCs or MCFCs first.

Table 1

The prospective chronology of fuel cells

Generation	Fuel cell types
First	PAFC (AFC added later)
Second	MCFC
Third	SOFC (SPFC added later)

generation technologies SOFC and SPFC have been published before papers on the first generation technology PAFC appeared. This shows the (socially) constructed character of the generation terminology.

Especially since 1983 there has been a clear-cut trend in shift of preferences. This shift complies with the prospective chronology that was one of the stable value-awarding accounts during the 1980s and the beginning of the 1990s. In our view the prospective chronology has been the source of the shift, rather than that the shift can be seen as a validation of the prospective chronology. Further research suggests that new and peripheral actors looking for a good strategic position within the fuel cell world tend, more than established actors, to choose the 'newer' technologies. Established actors soon follow, out of anxiety of missing some important developments. This means that shifts of preferences for technology types occur, 'because' of a shared prospective chronology and that this process will happen faster if more actors enter a technological community.

5. Conclusions

In this paper results have been presented from a social science study on the dynamics of technological developments for which the historical developments of fuel cells was taken as a case. Concepts have been introduced that make the changes in attention for fuel cells and the shift in preferences for the several fuel cell types more understandable. The idea that members of a technology community, in this case the fuel cell community, behave strategically, has been taken as a starting point for further development of concepts. Of these concepts the quasi-market of technological options and the value of technological options on such a quasi-market have been the most important ones. One of the aspects of this quasi-market is the stock-market phenomenon, indicating that the value of a technological option for an actor depends to a large extent on how other actors value the same option. Together with the idea that, also in the case of technological fields, there is a limit to growth, and that some actors award higher values to options if other actors do not value it highly (the high-risk/high-reward actors), the attention for a technological option, in this case fuel cells, is expected to vary in wave-like shapes over time.

At first sight a wave-like shape cannot be observed after 1976 for fuel cells. It seems as if the growth rate in attention for fuel cells only has increased since that time. However, if the change in attention for fuel cells is decomposed in three 'layers of technology', i.e. science and technology in general, the non-nuclear energy field and fuel cells, it appears that the attention for each layer has changed over time with wave-like characteristics. This means that the stock-market phenomenon applies to each layer of technological development and that their combined result has produced the observed growth in the case of fuel cells. Closer examination reveals that during a major part of the considered period, 'dips' of one of the technology layers have been counterbalanced by 'peaks' of other layers. At this moment all three layers seem to be more or less in phase with each other, while they all are attaining record heights. This illustrates how the current popularity of fuel cells can be understood. Another question which has been treated in this paper is why preferences for the several fuel cell types seem to shift over time. Since 1983, when speaking in terms of generations about fuel cells had been firmly established, the attention for the different types of fuel cells has been shifting according to the prospective chronology. Further research has revealed that this shift has been

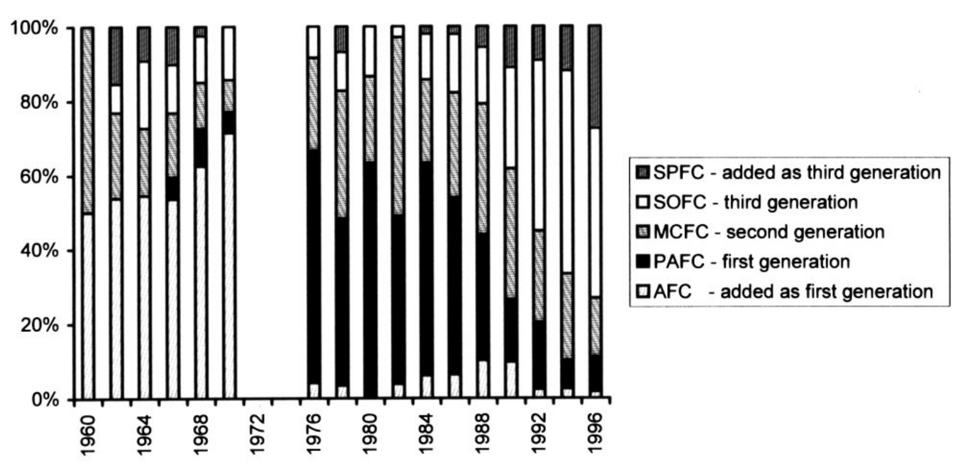

Fig. 4. Percentual distribution of papers published on the different types of fuel cells per period of 2 years.

triggered mainly by new and peripheral members of the fuel cell community. These actors shifted their attention first, soon followed by more established members of the community.

What is the use of this kind of analysis? As has been said in the background section of this paper, the research originally was intended to investigate whether this kind of study of technology could contribute to forecasting practices. Although the step to forecasting has not been taken yet, it is expected that concepts and analyses such as those presented in this paper will be helpful in improving forecasting methods. An important difference with current methods (for an overview, see Ref. [15]) such as trend extrapolation, is that trends are not prolonged without any insight into the underlying dynamics of the process. And what is more, these insights are based on empirical evidence, whereas traditional forecasting methods rely on concepts, such as the already mentioned sequential model of technological development, which lack such a base.

Another field of application might lie in research management. The trends observed by our analysis are of course also produced by many strategic decisions made by research managers. Showing them the aggregate effect of all these decisions and providing some insight into how decisions and aggregate effects are linked with each other, might function as a 'mirror' to their practices. This will allow them, if they wish, to act in a more 'reflective' way [16].

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