Mathematical Modeling of Innovation Dynamics

Final Report

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1 Abstracts

1.1 Abstract in English

The subject of this project is the empirical analysis of innovation processes in science-driven markets. A frequent state-of-the-art observation interprets the evolution of technology cycles in a typical form of two distinct waves. However, as only little is known about the reasons for the occurrence of this “double boom” pattern, the main goal of this project is to fill this gap.

The starting point in the project is the assumption that science-based technologies pass through two different development stages: the first stage corresponds rather with the assumption of the “science-push” model while the second conforms to the “demand pull” model. This basic assumption of the project made us to conduct an empirical investigation of 44 technologies for which science dependency is analyzed using non-patent citation (NPC) methodology. Indeed, 22 of these technologies developed according to a strong double boom pattern, for further ten fields at least a weakly formed double boom can be considered. Two fields seem to be in the first period of development only and only the remaining ten fields indicate no double boom course, but continually increasing scientific development. Still, not all science-driven technologies are subject to this wave development, but for a quite large share of these technologies this pattern seems to be appropriate.

The basic explanation is that in the development of science-based markets two quite different development phases due to basically different sets of determinants can be observed. An important aspect of this analysis is the clear distinction of technology, science and market activities and the analysis of their interaction. In order to understand the nature of market formation in science-based sectors three indicators are used: (1) measurement of scientific activities by publication statistics, (2) measurement of technological development by patent applications or patent grants, respectively, and (3) measurement of installed or sold (shipped, respectively) products to grasp diffusion. In order to get better insights into the structure of double-boom cycles, the four technology fields “robotics”, “immobilized enzymes”, “solar photovoltaic cells” and “fuel cells” are analyzed in more detail.

The application of different techniques of analysis proves to be very beneficial. For instance, the analysis of patent classification statistics is helpful to detect improved methods in particular technological fields. Application of time series analysis is meaningful to measure the reaction of markets on exogenous factors such

as the political, social or economic environment. Data envelopment analysis and a metric re-scaling approach to product characteristics can be used to analyze efficiency and technological improvement on the product level. Finally, social network analysis helps to display and analyze co-operative activities between market actors on different level of analysis. Analyzing co-author network some important changes can be identified: Firstly, the scientific network is growing rapidly, especially after 1991. Secondly, despite a trend toward increasing collaboration between researchers and "small-world"[3] development is observable. This tendency ensures quick information transfer, especially in the "demand pull" phase. Thirdly, regarding four scientific agent groups[4] significant changes in the network position of firms in the "demand pull" phase can be proven. In the "demand pull" phase firms do not take a central position in the co-author network any longer. A more detailed overview over the most important findings can be found in this summary of scientific results.

The implication of this project is that double-boom cycles are obviously characteristic for complex, science-based technologies. This characteristic has to be kept in mind in the support of promising fields. The quite long cycles imply that the support of a field may have a different impact, depending on the stage of development. Policy administrators often tend towards supporting new areas in the early stage of euphoria and are disappointed, if visible results are not achieved within short terms. However, new fields should be supported in particular in the stage of disillusion, when industrial firms decrease their activities. Firms should be careful with engaging too substantially in early stages and avoid the following, unrealistic euphoria. But they should recognize breakthroughs and must risk to invest in time before the second boom, in order to capture lucrative market segments.

The analysis of the long-term development of knowledge-intensive technologies at the meso level proves to be relevant for innovation theory in general, as the analysis in recent years increasingly deals with complex technologies. In this perspective, the findings of this project may be considered as a more concrete description of typical technological trajectories in science-based fields.

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[3] A small network is a network in which most nodes are not connected with each other, but the connected nodes can be reached from every other by a small number of steps.

[4] Universities, research institutes, firms, and others.

1.2 Abstract in German

Das Projekt beschäftigt sich mit der empirischen Analyse des Innovationsprozesses in einem wissensgetriebenen Markt. Dabei zeigt sich der typische Verlauf des technologischen Zyklus in Form von zwei Wellen. Gründe für das Auftreten dieses Verlaufes werden untersucht.

Dem Projekt liegt die Annahme zu Grunde, dass wissensbasierte Technologien in Ihrer Entwicklung zwei verschiedene Phasen durchlaufen: Die „Science-Push“- und die „Demand-Pull“-Phase. Grundlage dieser Annahme ist eine empirische Studie von 44 Technologien, deren Wissenschaftsbindung über die Analyse der Zitate auf die Nicht-Patent-Literatur untersucht wurde. Die Ergebnisse zeigen, dass die Entwicklung von 22 dieser Technologien einen stark ausgeprägten „Double Boom“ aufweist. Weitere zehn Technologien weisen einen schwach ausgeprägten Verlauf auf. Zwei Technologien scheinen sich in der „Science-Push“ Phase zu befinden. Die restlichen zehn Technologien weisen keinen typischen Verlauf auf, allerdings ist dort eine starke Zunahme der wissenschaftlichen Aktivitäten auffällig. Nicht jede Entwicklung einer wissensbasierten Technologie verläuft nach dem Zwei-Phasen-Modell, allerdings scheint doch ein großer Anteil der untersuchten Technologien dem „Double-Boom“ zu folgen.

Die diesem Projekt zu Grunde liegende Hypothese geht davon aus, dass in den zwei verschiedenen Phasen verschiedene Verläufe der beobachteten Variablen (Wissenschaft, Technik und Produktion) auftreten. Ein wichtiger Aspekt dieser Analyse ist die klare Trennung dieser Variablen und deren Interaktionen. Um die Entstehung eines wissensgetriebenen Marktes zu untersuchen werden folgende Indikatoren verwendet: (1) Messung der wissenschaftlichen Entwicklung durch Publikationen, (2) Messung der technischen Entwicklung durch Patentanmeldungen oder Patenterteilungen und (3) Messung der Produktion durch installierte oder verkaufte Produkte. Im Fokus stehen vier Technologien: Industrieroboter, immobilisierte Enzyme, fotovoltaische und Brennstoffzellen.

Die Anwendung verschiedener Analysetechniken erweist sich als sinnvoll. So zeigt die Analyse der IPC[5]-Statistiken die Entwicklung in speziellen Technologien auf. Die Zeitreihenanalyse macht die Reaktion des Marktes auf externe politische, soziale und wirtschaftliche Faktoren deutlich. “Data envelopment analysis“ (DEA) und der Ansatz des „Metric Re-Scaling“ von Produkteigenschaften können zur Effizienzanalyse und zur Messung der technischen Entwicklung auf Produktebene genutzt werden. Mit Hilfe der Netzwerkanalyse können Kooperationen zwischen

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[5] International Patent Classification

Akteuren visualisiert und analysiert werden. Analyse des Koautoren Netzwerkes zeigte wichtige Ergenisse: Erstens, ein rapides Wachstum in wissenschaftlichen Kooperationen konnte festgestellt werden. Das gilt insbesondere für Zeit ab 1991, also in der „Demand Pull“ Phase. Zweitens, trotz des schnellen Wachstums entwickelt sich das Koautoren Netzwerk zu einem „Small World“ Netzwerk. D.h. jeder Autor ist nur über wenige Links mit anderen Autoren verbunden, wenn auch der Anteil der verbunden Akteure relativ klein bleibt. Diese Veränderung ermöglicht schnelle Verbreitung von Informationen. Drittens, bei der Untersuchung von 4 Organisationstypen[6] ergibt sich eine signifikante Veränderung der Firmen innerhalb des Netzwerks. Besonderes in der „Demand Pull“ Phase stehen Firmen nicht mehr im Zentrum der wissenschaftlichen Kooperationen. Ein detaillierterer Überblick über die Ergebnisse findet sich in dem Abschnitt unten.

Ein Fazit dieses Projektes ist, dass die „Double-Boom“-Phasen offensichtlich charakteristisch für komplexe, wissenschaftsbasierte Technologien sind. Diese Charakteristik sollte bei der Unterstützung und Förderung neuer Technologien durch die Politik in den verschiedenen Phasen beachtet werden. Gerade in der ersten Phase neigen politische Entscheidungsträger beim Ausbleiben von vorzeigbaren Ergebnissen dazu, enttäuscht zu sein. Neue Technologien sollten vor allem in der Phase der „Desillusion“ unterstützt werden, wenn sich Unternehmen vorerst zurückziehen. Unternehmen sollten sich in frühen Phasen zurückhalten, um unrealistische Euphorien zu verhindern. Allerdings sollten sie mögliche „breakthroughs“ identifizieren und rechtzeitig vor dem zweiten Boom investieren, um sich lukrative Marktanteile zu sichern.

Die Analyse der langfristigen Entwicklung von wissensbasierten Technologien auf einem Meso-Level ist für die Innovationstheorie im Allgemeinen sehr relevant. In dieser Hinsicht können die Ergebnisse dieses Projektes auch als konkrete Beschreibung von typischen Pfadabhängigkeiten in wissensgetriebenen Technologien verstanden werden.

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[6] Universitäten, Forschungseinrichtungen, Firmen und andere.

2 Report on the Scientific Results

2.1 General findings

In case of complex, science-based technological fields, the technical activities (patents) and the scientific activities (publications) are closely linked over the whole observation period. The scientific activities start simultaneously with technical ones. For this reason they can be qualified as oriented basic or applied research. The most critical problem in the analysis is the access to suitable economic data on the level of meso technologies. In particular for more recent technologies, the “official” data sources do not offer suitable classifications; and if appropriate codes exist, inconsistencies in time are frequent. So the most relevant sources of economic data are market studies of private firms with their well known inaccuracies.

The characteristic double-wave cycle in technology development is not accidental. The large share of science-based technologies pass through two different development stages: the first boom can be associated with science/technology-push and the second with market pull phase. The market activities do not reach a substantial level until the beginning of the second technical boom. One of the most important finding of the analysis is the fact that technology and market activities have to be distinguish in a clear way. In our examples, the market activities are still in more or less continuous growth stage, even if technology activity passes through a distinct wave-like development.

The occurrence of this pattern can be explained by two main reasons.

Firstly, it is intrinsic characteristic of technologies that closely linked with its technological background. Crucial factor is the maturity of technological solutions for market needs. If new technological solution can be quickly adapted for new applications and the achieving of short-term market success is possible, then diffusion of technologies can proceed relatively quickly. Nevertheless, it should be kept in mind that development of these fields has a long-term perspective.

Secondly, the quite long cycles imply that the exogenous factors such as the political, social, economic environment can have different impacts, depending on the stage of development. The last can be estimated using patent and publication statistics. Surely, some particular factors like oil or finance crisis allow only limited control. But selection of financial support should be adjusted to the development stage of corresponding technological field.

The first boom can be described by a negative feedback loop: unsatisfactory research results are an incentive for increasing research activities. After the peak, the feedback turns into a positive characteristic. Unsatisfactory technological results trigger a decrease of research. So the characterization of the first boom as science/technology-push cycle does not imply a simple linear sequence.

The second boom is initiated by a solution of the crucial problems which led to the end of the first boom. Obviously, this solution is achieved in science, a development which is immediately recognized by other scientists. In contrast, the firms seem to be skeptical, against the background of the less favorable experiences of the first boom, and wait until the realization of the new solution proves to be reliable. The theory that they are not aware of this breakthrough is less probable. A closer look at citation data and a content analysis of publications and patents at different stages gives no indications that the change of trend in science and afterwards in technology are triggered by a single event, i.e. a discovery or an invention which revolutionizes the field. Rather, the breakthrough is the outcome of a systematic research program which yields relevant results for a broader application of the basic technology.

2.2 An In-Depth Empirical Analysis of Four Science-Based Fields

The investigated case studies of double-boom cycles of four science-based technological fields provide the following results:

2.2.1 Empirical Results for the Solar Photovoltaic (PV) Markets

The results of econometric and metric re-scaling approach were already discussed in the last interim report (December 2007). In the case of science-based markets, the scientific knowledge is an essential factor. The increasing complexity and interdisciplinary of science-based technologies lead to the fact that in these complex fields knowledge generation cannot be seen as the product of an individual person any more. For this reason, the social network analysis is used in order to investigate co-authors networks. The analysis is conducted on two aggregation levels: the level of individual authors and the level of organizations that these authors belong to. In this network the authors resp. organizations are the nodes and the joint papers are the links. The nodes are connected with each other if they have published a joint paper.

This part of project states two research questions: Are there significant differences in the network topology of the scientific community in the two periods of technological development (“science-push” period (1974-1990) and “demand-pull” period (1991-2005))? Are there changes in cooperative behavior of authors or organizations that can also explain the emergence of different phases in technology cycle?

The data for investigated co-author network is collected from the ISI Web of Science using the following keywords search strategy (solar cell or solar cells or photovoltaic#). The period from 1974 to 2005 is investigated.

The main results are:

The co-author network evolved rapidly. Especially after 1991 the total number of papers, authors, and organizations increased significant. This finding goes in line with the fact that in the last decade of the 20th century there were numerous promotion PV programs which have been introduced in various countries.

Analyzing the descriptive statistics of the collaboration network, some general trends in network topology can be identified. Firstly, the general trend toward a higher intensity of collaboration can be proven by different indicators like the average number of collaborators per author resp. organization, the relative share of isolated authors resp. organizations, and the average size of researcher groups published a paper in PV field. Thereby, in the second stage (“demand pull”) a statistical significant stepping up of collaboration efforts on the author’s and organization’s level can be revealed. Secondly, contrary to the network expansion only a moderate trend growth in the productivity of authors is measured. In the first phase (“science-push”) the productivity trend is even slight negative. In contrast, the productivity trend in the second phase is significant positive but moderate.

Thirdly, the investigated network demonstrates a tendency towards a broadening of giant component, a shorter average node to node distance, and a slight increase in clustering coefficient. This property is characteristic for small-world networks and is useful for knowledge creation and knowledge diffusion.

After regarding general tendencies in network development, the characteristic variability of individual actors in relation to their position in the network is investigated. Since intensity of collaboration activity reflects the objectives of organizations that authors belong to, four organizations types are considered: university, research institutes, firms, and others. The analysis of centralization scores (degree and betweenness centralization on the author and organizations level) reveals by and large a decentralized tendency of network development in the “science-push” phase. However, the picture changes in the “demand pull” phase. A continuous centralization tendency in the author and organization networks is identifiable.

The next research question is about changes in collaboration behavior of actors. Concluding the assumption that in the “science push” stage the innovative activity is more detached from market needs as in the “demand-pull” stage, the role and position of research units and industrial actors do not remain constant over time. Although the size of the groups stays nearly unchanged over all investigated period, a modification in position of each group is identifiable. According to size of groups, universities are the clearly dominating group (~50% of all organizations) in both phases of development. But regarding the group centrality score there is no dominating group in the “science-pull” phase. This result holds for both approaches: for degree centrality as a measurement of collaboration activity and for betweenness centrality as an indicator for control over information flow. For the “demand pull” stage the situation is different. The group betweenness and degree centrality scores of universities and research institutes are significantly higher as the corresponding group centrality values of enterprises. This finding supports the hypotheses that the position of firms concerning publication activity loses weight in the second phase. Private companies are more interested in fast product development and revenues than enhancing general knowledge.

To sum up, the results of this investigation indicate that the topological characteristics of PV co-author network have changed to ensure quick information transfer. Furthermore, there is a shift in the role and importance of research and industrial actors over the whole investigated period. These findings support the hypothesis that the structure and the behavior of actors in these phases change.

2.2.2 Empirical Results for the Technology Field “Robotics”

The results of the technology field “Robotics” follow a clear pattern of the “double-boom” -approach with a 20 year lag between the first patent activities and the second take-off. The publication activities began almost at the same time as the patent activities. It is interesting to note that the publication numbers enter a phase of stagnation about 3 years before the first patent peak, and that a new increase of publications commences already 4 years before the second growth of patents. The first economic activities begin almost in parallel with the technological and scientific activities and a certain stagnation of the sales appears in the stage of the technological decrease after the first boom. A real take-off in sales can be observed in parallel to the second boom of the technological cycle. So in the case of robotics, a certain relation between the technological and economic activities is visible, but only with regard to the growth rate of the sales.

In 1992 scientific activities display a distinct change of trend and the technological activities show a similar change about 4 years later. Obviously a breakthrough took place, triggering a general rise. A deeper analysis of the classification codes of patent applications shows that between the growth stages of the first and the second boom, the number of sub-classes is more than doubled. Beside, the scientific activities focus on the improvement of control issues which enable a broader application spectrum of robots.

To summarise, the improvement of the mechanical elements of robots is steadily going on, but the decisive change is due to a focus on control systems allowing for a better adaptation to the environment and external events. In this context, coping with fuzzy information is a major task. This change enables robots to deal with a broader spectrum of applications, and in particular, the way for service robots is opened up.

Figure 1: Number of EPO applications (by priority years), publications (by submission years)* and sales of industrial robots in Germany (in € bn), Sources: PLUSPAT (Questel-Orbit); SCISEARCH (STN), Schmoch (2007) (* 3-year moving average).*

2.2.3 Empirical Results for the Technology Field “Immobilized Enzymes”

The systematic use of enzymes in technical processes begins in the mid 1960s, but the use of immobilisation is introduced about ten years later. This is directly visible in a steep increase of the corresponding patent activities in 1978; publication activities commence to grow about one year earlier (see Figure 2). The peak of the first patent boom can be observed at the end of the 1980s; about 5 years previously, a stagnation period of the publications begins. Similar to robotics, the second increase of publications happens during the decline period of the first boom of the patent activities, and the lag between the turning points in science and technology is about five years.

The market introduction of immobilised enzymes begins in the second half of the 1980s, thus at the same time as the first patent boom, but a relevant level is only achieved at the beginning of the second boom.

Figure 2: Number of EPO applications (by priority years), publications (by submission years)* and worldwide sales (in $ bn) related to immobilised enzymes, Sources: PLUSPAT (Questel-Orbit); SCISEARCH (STN), Schmoch (2007) (* 3-year moving average).*

The change of content in the course of time was analysed by classification statistics of patent applications and keyword statistics. According to this, the major change are improved methods for fixing enzymes on a carrier, so that the enzymes are more stable and a broader variety of types of enzymes can be immobilised. Linked to this development, immobilised enzymes can be used for a much broader spectrum of applications. This is reflected in a steadily increasing set of patent classifications outside the core code for immobilised enzymes.

A second relevant aspect is the growing relevance of the use of enzymes in biosensors visible in the increased weight of related IPC sub-classes on the side of patents Again, the use of enzymes in biosensors requires methods for a permanent, stable fixing. As in the case of robotics, the science activities anticipate the technological ones.

2.2.4 Empirical Results for the Technology Field “Fuel Cells”

The principle of a fuel cell, firstly mentioned by Groove (1839), is the inversion of electrolysis: Oxygen and hydrogen create electricity by an electrochemical process. Over the years different types of fuel cells were developed, e.g. the Polymer Electrolyte Membrane Fuel Cell (PEM), the Direct Methanol Fuel Cell (DMFC) or the Solid Oxide Fuel Cell (SOFC) for different types of applications. As an all-rounder, the fuel cell is used in notebooks and cellular phones (portable application), for decentralised generation of electricity and heating (stationary applications) and for mobile applications e.g. cars, buses or planes. The focus of this research is set on the PEM fuel cell for mobile application. The contribution of this specific technology answering current and future challenges is undoubtedly. By means of fuel cell technology it is possible to face present and upcoming energy related challenges:

(1) Economic: The PEM fuel cell is benefiting, as a cross-sectional technology, due to its importance for different industries, especially for the German automotive industry, which is one of the most powerful sectors in Germany's economy. Current developments within the automotive sector (as a result of the financial crisis) show, that new ideas and future orientated solutions must be implemented in order to remain innovative and competitive. Besides, the limited range of fossil fuel will lead to dramatically increasing prices, which will harm the whole economy.

(2) Ecological: Fuel Cells are efficient and environmentally friendly. Their emission is zero, hence there is a chance to reduce local pollution in the area of high population density and, all in all, decelerate the global warming. In this context, the environmental friendly production of oxygen by regenerative energy sources becomes important. With the help of oxygen the fuel cell can build a bridge to a regenerative power supply in the future.

(3) Political: Fossil fuels, like oil or gas, are the most important energy resources so far. Most of them are located in the strategic ellipse, which ranges from the Near East over the Caspian Sea up to Siberia. Due to a possible political instability in these areas the peaceful accessibility of these recourses cannot be guarantied for sure. The interdependency must be minimized.

(4) Ethical: Ethical reasons play an important role in the question on how mankind treats fossil recourses – Are we allowed to use all fossil energy at once?

The results of the publication and patent analysis and shows the position of the PEM Fuel Cell within the Technology Cycle. The Technology Cycle consists of eight phases and three variables: science, technology and production. Publication data represent basic-orientated research (science), while patent data represent more market-orientated research (technology). Production is measured by produced units.

The bibliometric analysis was done with the online version of the ISI Web of Science. The date of query was February 2008. The search included all document types (but nearly 100% articles found), all years (1945 –2008) and all languages (but nearly 99% were written in English). The basis of the search strategy is a combination of keywords in abstracts. The additional search in the title of the publication did not point out more results.

Figure 3: Number of EPO and WIPO applications (by priority years), publications (by submission years)* related to PEM fuel cells, Sources: PATSTAT; ISI Web of Science; own computations; (* 3-year moving average).*

The source of patent data is the EPO Worldwide Statistical Patent Database version October 2007 (PATSTAT). The developed search strategy is based on the following components: (1) Complete technology classes (H01M – 008/22, H01M - 008/24) of the International Patent Classification (IPC, Version 8). (2) Additionally, a combination of classes (H01M -008) and keywords in abstract and title. The used keywords are similar to the keywords used in the bibliometric analysis. (3) Application authority: “Meta-Office”. This is a combination of the World International Property Office (WIPO) and the European Patent Office (EPO). But nearly 99% were filled in at the EPO. (4) The country assignment is done with the applicant, not with the inventor. If the patent filling has a German applicant, the application belongs to Germany.

Figure 3 illustrates the development of the patents and publication since 1980.

The numbers of patents and publications follow a similar development over time. It is interesting to see that patent activity started earlier than publication activity. Therefore, scientific activities slightly lag behind a bit. This fact was already identified on the PV market. In 2003, patent activity is dramatically decreasing. For this project the EPO Worldwide Statistical Patent Database version October 2007 (PATSTAT) is used. The decline in 2003 was a result of the 18 monthly publications deadline of the patent applications. So this is a normal fact due to data inconsistency because patent analysis is carried out using offline database. This change is not technology driven. A patent analysis with a similar search strategy in an online-database confirmed that assumption. After a stagnation between 2002 and 2005, the patent activity rise again in 2006.

According to PATSTAT, the position in the Technology Cycle is still before the “first boom”. So far, the Fuel Cell Technology is “science pushed”. There are useful scientific results and first technological solutions. But on the other hand, there are still a lot of unsolved technological problems, e.g. water-management or the cold-start of a Fuel Cell powered car. To start an efficient production of Fuel Cell cars, science and technology must be enormously improved.

As data on diffusion does not exist so far, a system dynamics model would be based on too many complex assumptions and in conclusion too difficult to calibrate. The contribution of such a simulation model is doubtful and the results would be too predictive. Another option is to deepen the research in the network evolution of the actors (see chapter below) with the help of an Agent Based Model. The outcome of this kind of model could be the relation of network evolution and market development.

Fuel Cell technology as a green technology in combination with regenerative produced hydrogen has the power to face energy related challenges and its consequences of the future. The results of the bibliometric and patent analysis with the focus on the PEM Fuel Cell make it possible to identify the position in the technology cycle. It shows that the development of the technology is still before the science push and therefore still in the invention phase. To reach a marketable product the knowledge base of the whole technology must be more mature and technological bottlenecks e.g. cost efficiency and reliability must be solved. This is a basic requirement for a solid solution and a broad market penetration.

2.3 Actors of the innovation process

According to Schumpeter, the innovation process consists of three phases: Invention is the first phase and stands for the creation of knowledge through scientific activities. The market realization of inventions is called innovation. The third phase is the diffusion phase, describing the market penetration of the innovation. This process is not linear and has interactions between the different phases.

The development of a science-based and young market is the subject of this project. The actors are the drives in these substantial technology activities. The identification of actors is based on publications and patent data that classify them into the following organisational types: Research Institutes, Firms, Universities, and Others (usually private persons).

The following line graph (Figure 4) depicts the share of the involved organisation types in basic research-orientated research. The number of publications is commonly used as an indicator for the scientific activities in that phase. The first publication activities came from Firms. Research Institutes started their scientific activities from 1992 onwards. Since 2000 Universities and Research Institutes have drawn near around a share of 40%.

Figure 4: Share of the organization types in the technological field Fuel Cell (Invention Phase), Source: Web of Science

The number of patents is used as an indicator for market-orientated research, and therefore represents the activities in the phase of innovation (see Figure 5). First patents come from firms. It is interesting to see that “Others” play an important role. This high contribution could be a result of University Professors or employees of firms and research institutes that are filled in as co-applicants. The role of Universities in the innovation phase is marginal.

Figure 5: Share of the organization types published in technological field Fuel Cell (Innovation Phase), Source: PATSTAT

Social network analysis is a powerful tool to examine the cooperation of the organization types and visualize the network of actors in the different phases of the innovation process. In the invention phase each organisation type cooperates with each other. It is interesting to see that within Germany the cooperation activity between Firms, Universities and Research Institutes are equal. In the innovation phase the cooperation between Firms and Others and Research Institutes and Others constitutes the strongest tie within Germany. German Research Institutes only cooperate with Others, and German Universities do not cooperate with foreign institutions at all. The social Network Analysis helps to understand the cooperation patterns of the young Fuel Cell market. Another interesting outcome of these networks is the internationalization of cooperation. There are international knowledge flows, and therefore, the innovation process cannot be treated isolated and must be open for foreign influence.

Summary Fuel Cell:

Fuel Cell technology as a green technology in combination with regenerative produced hydrogen has the power to face energy related challenges and its consequences of the future. The results of the bibliometric and patent analysis with the focus on the PEM Fuel Cell make it possible to identify the position in the technology cycle. It shows that the development of the technology is still before the science push and therefore still in the invention phase. To reach a marketable product the knowledge base of the whole technology must be more mature and technological bottlenecks e.g. cost efficiency and reliability must be solved. This is a basic requirement for a solid solution and a broad market penetration.

3. Self-evaluation in Comparison with the Original Objectives and Working Plan

We analyze new technological markets. That is why in many technological fields the data sets are only a few dozen years long. The limited size is the reason for the difficulty of the analysis. Next to the econometric time-series analysis, it proves helpful to also use other approaches (e.g. data envelopment analysis, metric rescaling, and social network analysis) to analyze the market development.

The system dynamic approach for investigation of diffusion process for fuel cells does not produce promising results. As data on diffusion does not exist so far, a system dynamics model would be based on too many complex assumptions and in conclusion too difficult to calibrate. The contribution of such a simulation model is doubtful and the results would be too predictive. Another option is to deepen the research in the network evolution of the actors with the help of an Agent Based Model. The outcome of this kind of model could be the relation of network evolution and market development.

The acquired experience in application of different analysis techniques will be used in further research projects. For instance, the combination of the social network analysis with bibliometric and patent data on different aggregation levels (regional, technological, etc.) reveals interesting insights into the nature of the innovation process.

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5. Tabular of the Report

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Theses written in the course of the project (Diploma, MA, MSc, PhD, Habilitation, including name of researcher responsible) Diploma: The Role of Institution in the Technological Innovation System of PEM Fuel Cells (Supervisor: Bjoern Bertram) Diploma: Actors and their Cooperation patterns in the Technological Innovation System of PEM Fuel Cells (Supervisor: Bjoern Bertram) Diploma: Barriers to the Concentrated Solar Power Industry. Integrated Market and Innovation Process Analysis (Supervisor: Inna Haller) Diploma: Analysis of the Geothermal Market in Germany. (Supervisor: Inna Haller)	
Publications related to the project: Schmoch, U.: Double-boom Cycles and the Comeback of Science-push and Mar-ket-pull. In: Research Policy 36(7) pp. 1000-1015. Haller, I.; Grupp H.: Demand by Product Characteristics: Measuring Solar Cell	

Quality over Time. In: Journal of Evolutionary Economics, forthcoming.

2nd Annual Conference of the EPIP Association, CIRCLE/Lund University – Sweden, September 20-21, 2007: Haller I: Mathematical Modelling of Innovation Dynamics: An Empirical Analysis of the Photovoltaic Market in Germany.

DIME Conference: Demand, Product Characteristics and Innovation, Jena, Germany, October 18-19, 2007: Grupp H.; Haller I.: Product Characteristics: Measurements by Metric Re-scaling.

DIME Workshop: Local and sectoral systems of innovations – Interdependencies and their development patterns over time, Karlsruhe, Germany, May 21-23, 2008: Fornahl D., Tran C. A., Haller I.: Knowledge Variety and Networks over time – how technologies and networks co-evolve in four German Biotechnology Cluster

Bi-Annual Conference of the International Schumpeter Society, Rio de Janeiro, July 2-5, 2008: Grupp H.; Haller I.: Product Characteristics: Measurements by Metric Re-scaling.

ASNA 2008: Dynamics in Science-Based Markets: Two Phases of Development, University of Zurich, 12-13 September 2008: Haller I.

DIMETIC 2008: The Innovation Process of Fuel Cell Powered Cars in Germany, Merit, Maastricht, 06-17 October 2008: Bjoern Bertram

Abstracts directly related to the project

Schmoch, U.: Double-boom Cycles and the Comeback of Science-push and Market-pull. In: Research Policy 36(7) pp. 1000-1015.

Abstract:

The discussion about the course of technology development began in the 1960s with linear science-push and market-pull models and received a decisive impetus in the 1980s with the introduction of non-linear, recursive models. The effect of these non-linear characteristics on the chronological development of a field is less clear, in particular as to science-based technology. Several authors discuss such developments of technologies, but with a focus on market activities. Some studies point to cyclical instead of logistic developments so that a closer look at the underlying mechanisms suggests itself. For an improved understanding, a clear distinction between science, *technology, and market activities proves to be important. A long-term analysis of the development of science based technology fields and related science fields leads to the discovery of typical double-boom cycles of technology, where the first boom can be associated with science/technology-push and the second boom with market-pull, but with feedback loops and non-linear characteristics. The scientific development shows two growth periods with an intermittent stagnation period where the turning points precede the referring technology developments, indicating a relevant impact of science on technology. In contrast, a cyclical development of the market activities in parallel to technology is not visible.*

Haller, I.; Grupp H.: Demand by Product Characteristics: Measuring Solar Cell Quality over Time, Journal of Evolutionary Economics, forthcoming

Abstract:

The purpose of this paper is to investigate the impact of innovation quality as a success factor of companies which satisfy demand in government-subsidized science-based markets. This paper focuses on the Photovoltaic market in Germany as a case study. It carries out the analysis in three stages. First, the efficiency of photovoltaic product characteristics is examined using the data envelopment analysis (DEA). Second, by means of a metric re-scaling approach, the technical improvement of solar modules offered on the German market is analyzed over time. Next, the results of the second stage are compared to demand growth (evolution of market shares). In conclusion, it can be shown that innovation quality in science-based markets is often an explanation of long-term growth, but occasionally a reduction of performance characteristics meets demand.

2nd Annual Conference of the EPIP Association, CIRCLE/Lund University – Sweden, September 20-21, 2007: Haller I: Mathematical Modelling of Innovation Dynamics: An Empirical Analysis of the Photovoltaic Market in Germany.

Abstract:

The objective of this paper is the analysis of dynamics of innovation processes in science-driven markets. In order to gain deeper insight in the science-based market formation different empirical studies are taken. The empirical investigations are summarised in a stylized model which provides the basis for the econometric analysis. This paper is focused on the interaction of particular variables in the model and its reaction to exogenous parameters. The photovoltaic market (PV market) in Germany is chosen as an example for econometric modelling. Using an error-correction model (ECM) short and long term effects in interaction between patent applications and scientific publications are analysed. The results verify empirical evidence of long-run equilibrium between publications and patents and confirm the basic hypothesis that two quite different development phases due to basically different sets of determinants can be observed in the development of science-based markets. In the first period from 1973 to 1990, the oil price development influences the interdependency between science and technology. In the second period from 1991 to 2001 the Renewable Energy Sources Act and *the Electricity Feed Act have significant effect on the development of science and technology.*

ASNA 2008: Dynamics in Science-Based Markets: Two Phases of Development, University of Zurich, 12-13 September 2008: Haller I.

Abstract:

The object of this study is collaboration networks of science-based technologies. Some empirical studies verify that a broad spectrum of these technologies passes through two different development stages: the first stage corresponds with the assumption of the "science-push" model, and the second conforms to the "demand pull" model. The study investigates the structure of scientific collaboration networks and examines the hypothesis that the changes in the network topology of the scientific collaboration community over time are jointly responsible for occurrence of two stages in technological development. As an example for science-based technologies the Photovoltaic market is chosen. The investigation period encompassed time from 1974 to 2005. The networks are derived from ISI Web of Science publication data using keyword searches. A set of topological metrics such as network density, average distance, different centralization measures, joint degree distribution etc., are used to characterize the changes in topological characteristics of collaboration networks.