Success determinants for technological innovations in the energy sector – the case of photovoltaics

Nils Roloff, Ulrike Lehr, Wolfram Krewitt, Gerhard Fuchs, Sandra Wassermann, Wolfgang Weimer-Jehle, Bernd Schmidt

Nils Roloff, Ulrike Lehr*, Wolfram Krewitt: DLR, Institut für Technische Thermodynamik, Abteilung für Systemanalyse und Technikbewertung, Pfaffenwaldring 38-40, 70569 Stuttgart, first name.last name@dlr.de; Gerhard Fuchs, Sandra Wassermann, Wolfgang Weimer-Jehle: Institut für Sozialwissenschaft, Abteilung für Technik- und Umweltsoziologie, Seidenstr. 36, 70174 Stuttgart, first name.last name@sowi.uni-stuttgart.de; Bernd Schmidt: Juvenellstr. 45, 90419 Nürnberg, Schmidt.bernd@gmx.eu

Summary In response to the growing challenges of climate change and resource scarcity energy from renewable sources will have to play a significant role on future energy markets. Therefore, significant efforts from the industry will be necessary in terms of innovative processes and products to fulfill the needs of a future energy mix and the success determinants for these technological innovations are of considerable interest.

The paper outlines the results of a study that focuses on the different aspects of innovation in the photovoltaic industry. Innovation research suggests that innovation processes take place in systems of highly interdependent actors. Agent-based modeling provides a suitable tool for the analysis of the various effects of actors' choices, strategies and dynamic behavior. The study concentrates on the main actors within the innovation system "Production and Application of Photovoltaic Technology Systems": producers, PV system operators (households, farmers etc.), research institutes and universities, banks, interest groups and trade associations, installation firms, and government. Within these groups different characteristic features exist and each type is represented by one agent. Research institutes, for instance, can be oriented towards either applied or more theoretical research. This will affect their respective strategies on cooperativeness and knowledge generation. A variety of different types of producers is observable in the photovoltaic market, e.g. fast growing companies, new branches of established energy producers or off-mainstream innovative SMEs, which are characterized by different learning strategies and different goals. Households have different objectives and motives for the purchase of a certain type of PV system and their market behavior

* Since April 2008: Gesellschaft für Wirtschaftliche Strukturforschung mbH, Heinrichstr. 30, 49080 Osnabrück, lehr@gws-os.de.

feeds back to industry and research. Viewing innovation processes from an agent-based perspective allows innovative computational analysis of the organizational interdependencies between the relevant actors. It goes beyond standard analysis of innovation processes in that it tries to combine agent based and systemic considerations. In particular the response of actors to different energy policy measures, their dynamically emerging behavior and their related implications on innovation in the field of PV is described. The transferability and limits of the case study's results are analyzed.

Keywords: agent-based modeling, innovation, photovoltaics

1 Introduction

European energy markets currently undergo significant changes from centralized monopolistic markets to a more competitive environment with a lot of different participants. Additionally, the challenges from climate change and environmental issues have to be met. Renewable energy will play a significant role on future energy markets as the new targets from the European Commission show (KOM (2007) 1). To reach these targets several support mechanisms have been developed and have led to high dynamics in the renewable energy industry.

Apart from environmental goals, the support policies aim at economic development and technological change. The German feed-in law, for instance, has already triggered the rapid development in the German wind industry and in the photovoltaic industry. But it is widely agreed that still a lot of innovation is needed for technologies to provide clean electricity at affordable cost at a large scale for the future.

Success factors in an innovation system hinge on a wide array of determinants. They differ depending on the innovation phase, the technology and the actors, institutions and participants in the innovation system. The technological system for solar cells exhibits some very interesting characteristics: Firstly, the technology as such has been known for more than 100 years by now (Green 2000). However, the technological development was dominated by 'science-based experimentation' until the 1990s. Solar cells were first used for extraterrestrial applications during the so called 'Space Age' (1958 to 1973). Later on they were also used for consumer electronic products as well as for off-grid power systems (1974 until mid-1990s). Nevertheless the role of photovoltaics with regard to the supply of energy remained quite limited until Japan and Germany started their first demand-oriented programs during the 1990s. These initiatives and successive programs and regulative changes eventually led towards a significant growth of the PV-industry and therefore to an expansion of the whole technological system (Jacobsson et al. 2002). Secondly, as the technology evolved, the motifs of actors changed and new actors have been attracted to the field. This and the interdependence of political influence, consumer behavior, research and development led to the chosen modeling approach. Agent based modeling (ABM) seems to be a very

suitable approach in a highly interdependent system that evolves in a non-equilibrium and self-organizing fashion.
The structure of the contribution is as follows. After this introduction, chapter 2 outlines the theoretical background of the analysis. We have drawn from three disciplines – innovation research, agent based modeling and energy system analysis and technology assessment. Chapter 3 gives an overview of the model and first results will be presented in chapter 4. Chapter 5 concludes.

2 Theoretical Background

2.1 Innovation research

To capture the multi-faceted structure of the innovation system we work from a rather wide definition. Innovation in this analysis means all artifacts, processes, ideas and strategies that successfully change routines and are implemented in specific contexts of use, which can be changed in turn through the innovation. This definition is wider than some to be found in the literature in the sense that it not only comprises the invention of a new process or technology but also its diffusion . Therefore, the analysis does not stop at the mere analysis of patent data or the introduction of a new technology, but takes the whole innovation system with its intrinsic feed-back loops into consideration. The interdependence between actors, their co-operation and spill-overs play an important role (see e. g. Carlsson and Stankiewicz 1991, Edquist 2001, Lundvall and Johnson 2001 and Malerba 2006). Accordingly, the process of innovation is not understood as a linear sequence but rather as a non-linear, highly interactive process as proposed by Kline and Rosenberg (1986) or Rothwell (1995).
The importance of innovations for social change, international competition, structural change and economic growth has been analyzed quite successfully in the last decade. However, how and why innovation comes about and what triggers it or slows it down is still an open question. There is evidence, that knowledge is the most important input in the process of innovation; the importance of knowledge in certain innovative industries has been empirically shown (cf. Dosi 1988, Hullmann 2001). Sparks of innovation emerge through the interplay of different forms of heterogeneous knowledge: their confrontation, combination, fusion, transformation. Different schools of thought describe the accumulation and the distribution of knowledge within the firm, in the economic sector and in innovation system differently.
From an individualistic perspective the analysis focuses on the entrepreneur, who decides about access to knowledge in the firm (Hauschildt 2004). Evolutionary economics takes a more comprehensive approach and sees the firm as knowledge storage and as part of a wider organizational system (Fagerberg et al. 2005). The distribution of knowledge affects the innovativeness of a firm, but the type of knowledge in the firm and the innovation system also has a large influence. Argyris and Schön (1978) argued that the capacity to innovate would depend on the ability of organizations to bridge individual and collective forms of knowledge. Nonaka and Takeuchi (1995) proposed that the secret of the knowledge-creating company would reside in its capacity to master the different modes of conversion of tacit and codified forms of knowledge. Cook and Brown (1999) have suggested that the true spark of innovation lies in the ‘generative dance between possessing and practicing knowledge’.

As pointed out earlier, our approach takes the whole innovation system into account. The Innovation Systems approaches most clearly follow the principles of evolutionary economy. An "Innovation System" can be defined as the cluster of institutions, policies, and practices that determine a nation's, region's or sector's capacity to generate and apply innovations (Carlsson and Stankiewicz 1991, Lundvall et al. 2001, Malerba and Orsenigo 1997).

The Innovation Systems approach has achieved high visibility and political influence, but has been controversially discussed. Rammert (2002), for instance, argued that the approach lacked micro-foundations and would not reflect the path dependence of innovation formation due to habit, norms and institutions. Rammert argues further that innovation systems currently are undergoing a transition from sequentially organized systems to fractionally structured networks. Though such a system is different for each innovation – a thought that is reflected in the term "biography" of an innovation – Rammert, together with Hage and Hollingsworth (2000) or Amin and Cohendet (2004) assumes that the number of actors from different backgrounds enhance the likelihood of strong innovation activities and their success in the system. However, the more the analysis focuses on the individual biographies, the less the approach becomes suitable for more general recommendations and results. Therefore, in our approach we try to balance the analysis of individual motifs with more structural and systematic assessments. An additional challenge is to keep the structural approach sufficiently flexible to be able to answer the question "How are innovations generated, shaped and institutionalized by distributed innovative activities in heterogeneous innovation networks?"

2.2 Multi-agent based simulation

To analyze the innovation processes in the technological system for solar cells the agent based modeling approach is used. In contrast to the models of conventional simulation (e.g. system dynamics), in which participants are modeled in an aggregated top-down approach, agent based models consist of different individual decision-making agents. These bottom-up built agents interact with each other and thereby influence the development of the whole system. This allows modeling of distributed problem solving processes in a more realistic way. Hence, agent based simulation allows to transfer complex systems from reality into a model, which can be used to analyze dynamic processes and alternative strategies within the system.

Actors or rather stakeholders in the real world are represented as 'agents' in the respective model. Agents can represent individuals as well as entities on a higher aggregation level, like e.g. a company, a political party or a research organization. To make full use of the benefits of the agent-based simulation approach, actors and agents as their representatives in the model are described in terms of the following characteristics:

- *Dynamic environment*: actors live in a changing environment to which they adopt.
- *Individuality*: each actor is characterized by its own individuality, which means that he/she has its specific status, options for action and targets. The actor's status may change over time because of its own internal momentum or because of external constraints.
- *Goals and strategies*: Each actor has individual goals, which he/she strives to achieve. To achieve the goal, the actor has the capability to plan a course of events. The actor develops strategies for target-oriented action.

- *Communication and interaction*: Actors have the capability to communicate and to interact with one another, which can lead both to co-operation and competition.
- *Environmental model*: the environmental model describes how the actor perceives the real world. The environmental model is created by inputs from the real world and by cognitive processes. In general it reflects not only factual information, but also mental attitudes. An actor's action is always determined by his/her environmental model. An actor thus does not act on the basis of an 'objective' reality, but on how he/she perceives reality.

It is expected that agent based simulation offers distinct advantages in analyzing innovation processes, as it allows a specific and detailed representation of related actors and stakeholders. It thus facilitates the simulation of the dynamic processes resulting from interaction between actors with different sets of goals or values. Cooperation in complex adaptive systems can create emergent behavior, which occurs when the behavior of a system is more complicated than the simple sum of the behavior of its components. Traditional modeling techniques such as linear programming do not include emergent behavior. The ability to model emergent behavior is therefore considered a specific advantage of agent-based simulation to analyze innovation processes.

Regarding the analysis of innovation processes or rather innovation systems several theoretical studies already exist. These studies focus on different aspects related to innovation in general like e. g. the transfer of knowledge (März et al. 2006, Wersching 2007, Pyka et al. 2006), the diffusion of innovations (Steyer and Zimmermann 2001) or the effects of different diversification strategies of firms (Dawid and Reimann 2003). But nevertheless, very few attempts have been made so far to apply agent-based modeling to simulate the influence of multiple stakeholders on the innovation processes in a specific technological system. First examples are analyses of innovation processes in urban water infrastructure systems (Kotz and Hiessl 2005, Schwarz 2007) or the examination of the diffusion process of fuel cell vehicles (Schwoon 2003).

Because of the crucial importance of the interdependences between the relevant actors in innovation processes, and the dynamics of emergent behavior, we consider multi-agent based simulation as an innovative, promising and powerful computational analysis tool which can be successfully used in the field of innovation research. Open issues which still need further consideration are questions concerning the empirical validation of the models and how far multi-agent based systems can cope with the representation of medium to long term time periods (Richiardi 2004, Windrum et al. 2007).

3 The Model

3.1 Basic Assumptions

The success of an innovation depends on the one hand on an adequate configuration of people, objects and ideas and on the other hand on the combination of the personally embodied knowledge and the materially incorporated technological know-how (Rammert 2002). It is important to note that a realistic approach to the understanding of innovations has to be a dynamic, "biography" or "career" oriented one. Innovations are not a one stop affair. Rather innovations develop more or less quickly over time. Some innovations take their time. In certain sectors innovations are rather small scale and incremental while in others they may in fact be destroying old and creating new structures. The firm is without any doubt an important agent in the generation of innovations. Whether it is in fact the central agent is not so much a theoretical than an empirical question. The decisive impulses can result from producer-client/customer relations (e.g. von Hippel 1988, 2004) or can even be the product of public initiatives (Edquist 2004).

The types and structures of relationships and networks differ from sectoral system to sectoral system, as a consequence of the features of the knowledge base, the relevant learning processes, the basic technologies, the characteristics of demand, key links and dynamic complementarities. Thus, in a sectoral system perspective, innovation and production are considered to be processes that involve systematic interactions among a wide variety of actors for the generation and exchange of knowledge relevant to innovation and its commercialization. Interactions include market and non-market relations that are broader than the market for technological licensing and knowledge, inter-firm alliances, and formal networks of firms (Carlsson 1994, Breschi and Malerba 1997). Only recently a research tradition is slowly evolving that takes these sectoral characteristics of innovation processes at its heart.[1] The notion of a Sectoral System of Innovation (SSI) departs from the traditional concept of sector used in industrial economics because it examines other agents in addition to firms, places great emphasis on knowledge, learning and sectoral boundaries, focuses on non-market as well as market interactions, and pays much attention to institutions. Innovation is considered as a process that involves continuous and systematic interactions among a variety of actors.

A SSI is thus composed of a set of agents carrying out market and non-market interactions for the creation, production and sale of sectoral products (Malerba 2004:10):

(a) Any sector can be first of all characterized by its specific knowledge base, technologies and inputs. One way to categorize these elements was proposed by Malerba and Orsenigo (1997). They distinguish roughly between opportunity and appropriability conditions, degrees of cumulativeness of technological knowledge and characteristics of the knowledge base.

(b) Actors, Institutions, and Policies. A sector consists of a set of heterogeneous actors that are organizations or individuals (e.g. consumers, entrepreneurs, scientists). Organizations may be firms (e.g. users, producers and input suppliers) or non-firm organizations (e.g. universities, financial organizations, government agencies, trade unions or technical associations), including subunits of larger organizations (e.g. research and development – R&D – or production departments) or groups of organizations (e.g. industry associations). Actors are characterized by specific learning processes, competencies, beliefs, objectives, organizational structures and behaviors. They interact through processes of communication, exchange, cooperation, competition and command.

(c) Institutions. Actors' cognition, actions and interactions are shaped by institutions, which include norms, routines, common habits, established practices, rules, laws, standards and so on. They may range from the ones that bind or impose enforcements on actors to the ones that are created by the interaction among actors (such as contracts); from more binding to less binding; and from formal to informal (such as patent laws or specific regulations versus traditions and conventions). Many institutions are national (such as the patent system), while others may be specific to sectoral systems, such as sectoral labor markets or sector-specific financial institutions.

[1] see Malerba 2004 for a state of the art overview. For case studies see also Braczyk/Fuchs/Wolf 1999, Fuchs 2004, Fuchs and Koch 2005.

(d) Demand. The focus on users, customers, public procurement and regulation puts a specific emphasis on the role of demand in sectoral systems and in the innovation process. Demand is not seen as an aggregate set of similar buyers, but as being composed of heterogeneous agents the interaction of which with producers is shaped by institutions.

The starting point of the model development has been the definition of the actors that are relevant for the innovation system under scrutiny. The model at its current stage exhibits all the important characteristics with all the agents. As agents we include the most important actors in the innovation system: Producers of PV-systems, consumers/system operators, R&D-institutes, government, trades, interest groups and banks.

The agents „producer“, “R&D-institute“ and „consumer“ are at the core of the model. Producers not only produce, but also market and sell PV-systems. They observe the markets, build expectations on demand development and change their respective strategy according to their own market success. Likewise, investment follows expectations on market development. Furthermore, they have their own R&D departments and work on own innovations. For this purpose they make use of publicly-available knowledge and also buy knowledge externally, e. g. via licenses. Additionally, they contribute to the overall knowledge base by generating new knowledge within the course of their R&D-activities.

In addition to that, “producers” have the opportunity to use capital for three different purposes: they can improve the efficiency of production with respect to resources and/or labor, they have the possibility to invest in human capital and hire more skilled labor and they can acquire additional knowledge either from the market for licenses or from stepping up internal research and development expenditures. “Producers” try different investment measures and develop their strategy according to their market success.

Research and development institutes and firms receive funding from public budgets (agent “government”) and from private budgets, i.e. other firms. The R&D institutes produce knowledge. Public knowledge is disseminated via publications, conference contributions and other scientific exchange platforms. Proprietary knowledge is patented and then sold to firms. The amount of research results depends on the available capital, human resources, network activities and co-operations. With respect to human resources the research and development agents compete on the labor market with the producers for skilled and qualified labor.

Regarding the “consumers” of PV-modules, one could state that their respective motivation to buy a PV-system has changed considerably over time. 25 years ago, people who bought PV-modules were either enthusiastic about the technological aspects or convinced of the environmental benefits. Economic aspects did not – and could not, given the state of the technology at that point in time – play a role. Since then two developments occurred. Firstly, the effectiveness of the systems improved and the yields increased substantially. Secondly, the monetary returns have been improved by the market liberalization and the German feed-in tariff system (EEG). The liberalization of the German electricity market provided the legal framework for market access for independent producers. In addition to that, the German feed-in tariff system with the obligation of net operators to connect any producer of electricity from renewable energy sources (RES) to the grid and with fixed (profitable) tariffs for electricity from RES led to the development of a new, profit-oriented demand sector.

Therefore, the demand side agents have to reflect this variety of motifs. Accordingly, attainable return on investment, stable conditions from the legal framework, interest in environmentally safe investment, technological thrill and support of renewable energy are constituent parts of the utility function of the “consumers”.

The role of banks (as a subcomponent of the agent “producer”) and the trades is less active in the system. They are modeled as bottlenecks for capital and labor inputs in installation. Nevertheless, their activities influence the possibilities of supply and demand as well as the number of PV-systems that can be installed during certain time periods.
Due to the large influence of the (political) framework conditions at least for the German development, the agent “Government” is important in the model. However, the political decision process is not modeled as such. The government gives money for R&D, provides investment subsidies, sets the feed-in tariff and also grants credits with low interest rates. These variables are affected by the governments’ information level that is sustained by other departments (e.g. the targets for GHG), NGOs and trade associations and the firms. Additionally, the agents provide information themselves that facilitate trade activities. Figure 1 gives a schematic representation of the model.

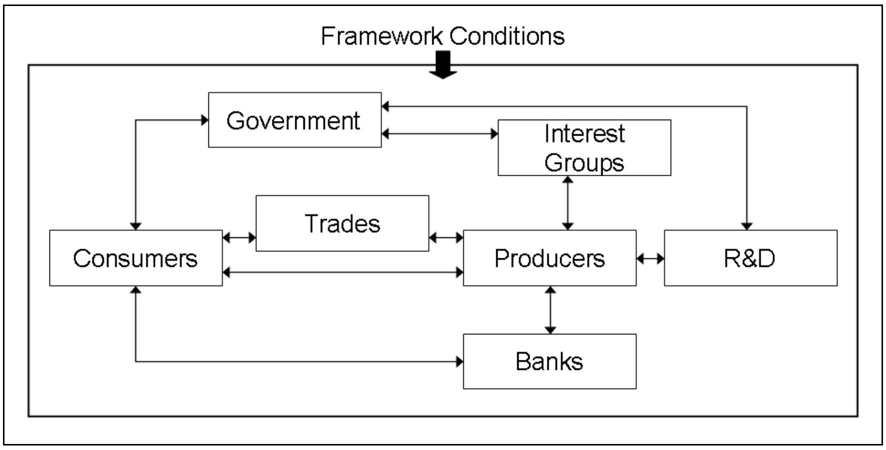

Fig. 1. Structure of the model

4 Results

The detailed structure of the single agents in the model allows for an analysis of their behavior in the light of different assumptions. However, thus far, our model only includes one agent of each type, therefore competition between, for instance, two different producers cannot be modeled as of yet. This is an issue of future research.
Nevertheless, individual strategies can be modeled and the agents individually exhibit plausible reactions. Furthermore, the interesting interactions and feed-back reactions can be modeled using different components together. The following firstly focuses on individual strategies of the “R&D-institute” agent and shows two experiments. Secondly, a small subsystem consisting of this agent, the firms’ agent and the consumers is used to validate the technology push effect that is well-known from the literature.

4.1 Individual strategies

As already mentioned, knowledge is a central element for innovation processes, especially with regard to science-based industries like the PV-sector. Accordingly, knowledge generating entities like R&D-institutes play a significant role in the technological system for PV systems. Hence, it is important to analyze the effects of certain biographic influences on knowledge output in the R&D-Institutes. Two R&D institutes with different focuses are considered. While the first one is more oriented towards applied research the other one leans towards basic research. Each is calibrated with the data of a relevant existing institute of the photovoltaic sector. In order to analyze the behavior of the R&D agent it is interpreted as an insulated system and is decoupled from the model as a whole. The structure of the agent is given in figure 2.

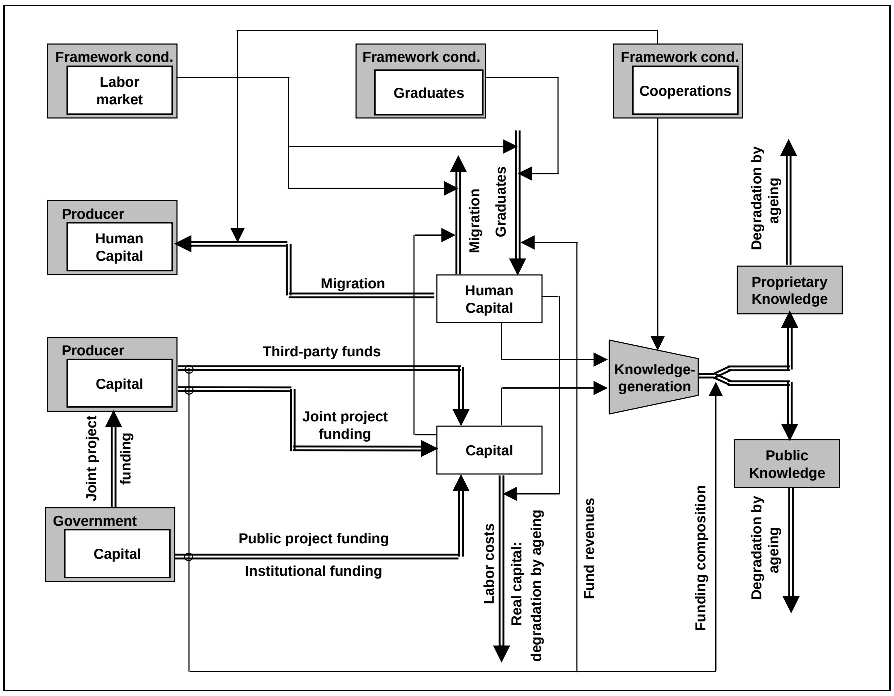

Fig. 2. Internal structure of the “R&D”-agent

The key process inside this agent is “Knowledge-generation”. The production rate depends on two prerequisites: “Human Capital” (workforce) and “Capital” (cash and equipment). “Capital” is fed by direct public funding, by company contracts and by indirect public funding via joint projects. “Capital” decreases due to the payment of wages and the ageing of equipment. The specific knowledge production rate increases if more equipment is accumulated. The agent employs additional workforce if sufficient funds are available, providing that there is no lack of interested graduates. On the other hand, employees are dismissed if funds are insufficient. With respect to workforce, the R&D institute competes with producers and the general labor market: graduates may prefer other employers if the labor market is in strong condition. Furthermore institute employees may migrate.

Two types of explicit knowledge are produced. Public knowledge can be used by every agent without any precondition. Proprietary knowledge must be bought by other agents, with the exception of the producer who funded the corresponding project. The shares of the knowledge types depend on the relations in funding: public funding produces public knowledge, third party funds generate proprietary knowledge and joint project funding yields a mixture of both.

Co-operation with producers, a major issue in innovation research, causes an ambivalent, complex impact on the agents. Strong co-operation increases the efficiency of knowledge production. On the other hand, it stimulates migration towards producers, hindering the R&D institute by moving away workforce and implicit knowledge, but at the same instant promoting producers.

The two experiments look at idealized biographic types of institutes. The first experiment takes the example of a large non-university research institute, created in 1985 on a low level. The following biographical characteristics were used as model input:

- focus on applied research,
- strong co-operation with industry,
- public funding has increased until 1990, then stagnated,
- increasing success in 1990's in raising industry funding and, later, joint project funding and
- a high scientific reputation, yielding unlimited availability of graduates.

The results of the simulation are given in figure 3. For a tentative calibration with empirical data we used data on the Fraunhofer-Institut für solare Energieforschung (Fraunhofer Institute for Solar Energy Systems - ISE) in Freiburg, Germany. Its structure resembles the idealized type.

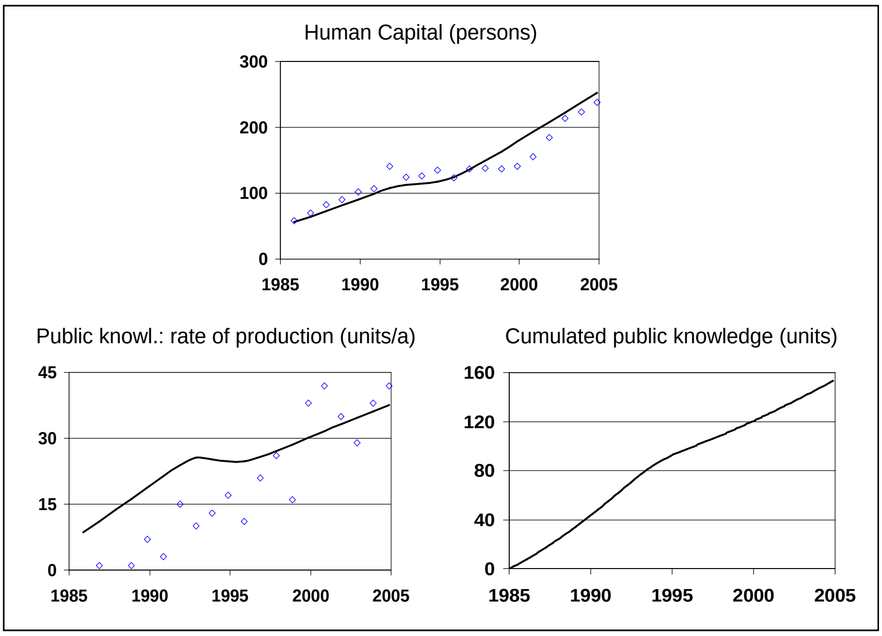

Fig. 3. Applied non-university research institute: model results (solid lines) and empirical data of the ISE (squares).

The model satisfyingly reproduces the data on the development of the workforce. Decreases in the workforce at the beginning of the 90s in the empirical data from ISE can be explained by a crisis in the institute (among other things a new competitor had been founded). So far the model does not include any of these changes.

The difference between the simulated data and the empirical measurements concerning the production of public knowledge until mid 90s result from the fact that the empirical data only include peer-reviewed articles. The model, on the other hand, purposefully includes any type of public knowledge, including research results that are published in reports and non-reviewed publications (discussion papers, gray literature). For later years data and simulated results merge, because international standards for publishing performance gradually catch on.

The second experiment analyses a middle-sized university institute with medium co-operation with the industry and a strong focus on basic research. As in the first experiment, we assume that the institute started in 1985 at a low level. Again a set of biographical characteristics was used as external drivers of the agent's development:

- strong focus on basic research,
- public funding increased first, then stagnated at the beginning of the 1990s,
- medium co-operation with industry,
- spin-off of an institute in the late 80s including staff transfer,
- acquisition of industry funding only started a couple of years ago, but took a very dynamic development,
- recruitment of new graduates is recently limited due to sharp competition from private firms and
- a recent shift of the institute's main working fields, including a policy of workforce reduction in the dropped fields.

Figure 4 shows the results of the simulation in comparison with empirical data. The empirical data for this tentative calibration are obtained from the Institut für physikalische Elektronik (Institute for Physical Electronics - IPE) at the University of Stuttgart, Germany, which resembles the idealized institute modeled.

The accordance of the calculated human capital with the empirical data is foremost due to the model input. It is not a test of the model quality, therefore. However, the good reproduction of the development of the knowledge production (number of peer-reviewed articles as empirical data) is encouraging. The observed decrease of the number of published articles in more recent times proved to have complex causes. Obviously the decrease of workforce plays a role, but it isn't sufficient to explain the whole effect. Sensitivity analyses showed that the production of public knowledge also considerably decreases if the workforce reduction policy is removed. Almost half of the effect is due to demanding tasks for the industry (competition with proprietary knowledge) and to the limitations of the institute to acquire new personnel in a sufficient amount.

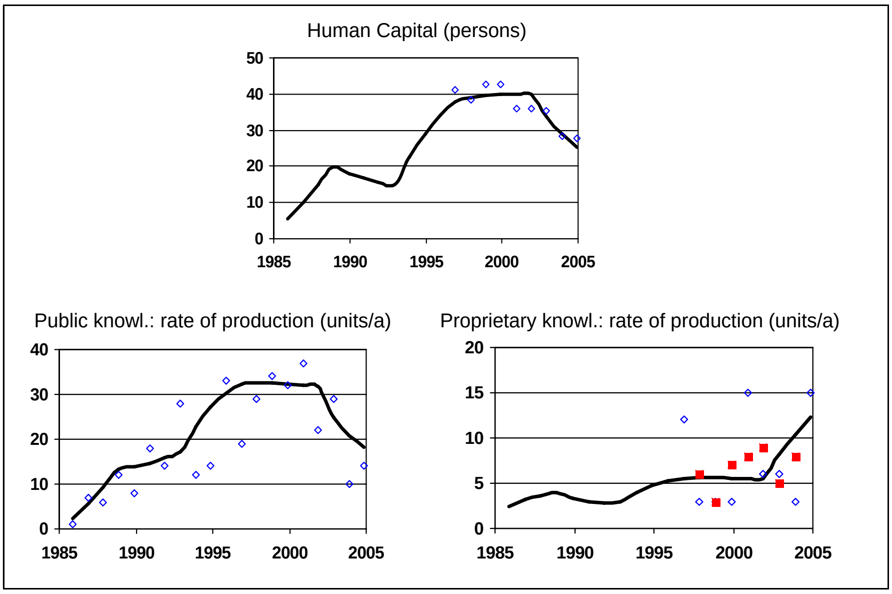

Fig. 4. Medium size university institute: model results (solid lines) and empirical data of the IPE (squares) (solid squares right bottom: 3-year average of the empirical data).

These experiments show that the R&D agent is suitable for modeling biographic determinants of different R&D institutes. The results allow for sensible deductions concerning the behavior of the R&D institutes. However, data for empirical validation and calibration currently are incomplete and rather sketchy. Future work will be dedicated to the strengthening of the empirical data base and will focus on more and different research institutes in the PV sector. As has been pointed out, the current status of the model does not allow explicit modeling of interactions of different types of the same agent. For future work, different cooperative strategies between agents will be interesting to model.

4.2 Interdependence between key agents

Based on the experience with the simulation experiments described above, prototypical elements of all agents were merged for simulations with the whole model. The following experiment is an example of the dynamic behavior of the model. The experiment analyses the "technology push" hypothesis. This hypothesis follows the assertion that increasing public funding for the support of research will lead to accelerated innovation activities. To verify the hypothesis, we need two simulation runs. The first run represents the reference, because we want to show changes from an increase of public support with respect to some status quo, i.e. a reference case. The second run of the model includes the increase and the system's reaction on this additional capital for research. Comparing the results of the two runs shows the effects of the technology support policy. Figure 5 shows the results.

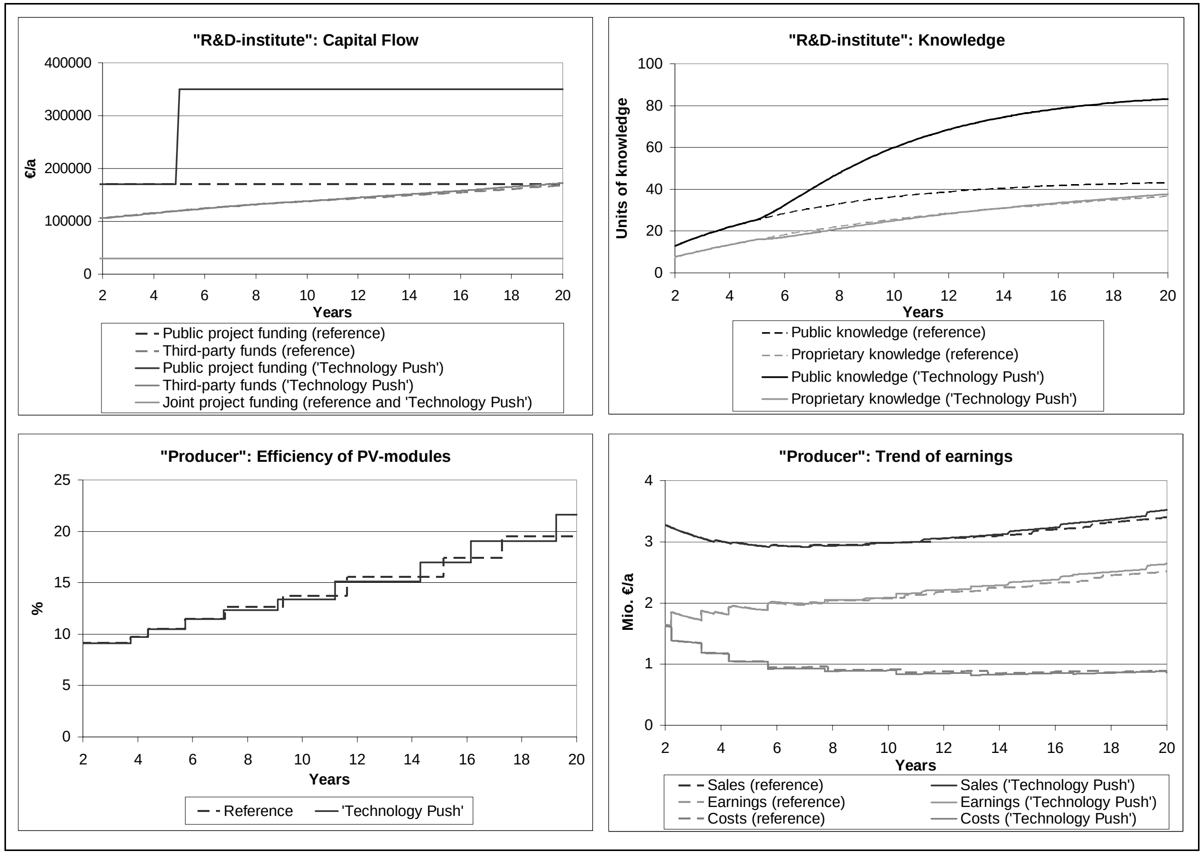

Fig. 5: Analysis of the 'technology push'-simulation experiment

The increase of public funding at T=5 leads to a significant increase in the production of knowledge compared to the reference case. Since public funding primarily enters the production of public knowledge, the R&D agents shift their preferences from the production of proprietary knowledge to the production of public knowledge. Therefore, proprietary knowledge decreases as a reaction to the monetary increase. However, the production of both types of knowledge increases on the long run due to more capital being available for both uses.

Producers profit from the increase in knowledge production, because they can use this knowledge as an input to their own R&D departments. The larger supply of (public) knowledge yields earlier product and process improvements compared to the reference case.

Technological change accelerates and yields increasing demand as the respective agent reacts to the improvement of the PV-systems. Furthermore, the producers react upon their market success and also obtain a larger profit due to process innovations which result in sinking productions costs. Capital stock increases at the producers and can be spent on the different uses described in chapter 3.

The experiment yields results that support the technology push hypothesis. Higher public funding accelerates the innovation activities. Additionally, a variety of feed-back loops reinforce the positive effect. The model reacts in a plausible way to an external shock that is modeled singular and discontinuous. The model is robust enough to deal with this type of external shocks and exhibits an acceleration of the innovation indexes.

5 Conclusions

The aim of this paper was to present an agent-based model for the analysis of innovation processes in the photovoltaic industry.

In order to be able to examine the success factors for innovations as well as the effects of policy measures it is necessary to understand how the innovation system under scrutiny is influenced by the behavior of different stakeholders and their respective interactions. Therefore, the stakeholders that are considered important are treated as agents in our model. Each agent is characterized by its individual goals, specific strategies and behavioral rules. The (dynamic) interdependences between the agents are also taken into account. After the implementation of the agents each one has been calibrated with empirical data.

As the first experiments on the basis of a decoupled agent ("R&D-institute") show the specific behavior of stakeholders can be modeled. Since the results of these simulation runs indicate that the model is already suitable for modeling biographic determinants of different R&D institutes the link between empirical research and agent-based modeling seems to be possible.

Apart from that the interactions between the agents and the respective influences on innovation processes can also be simulated on the basis of our model. Regarding the effects of discrete external influences the simulation model already generates plausible results as the outcomes of the simulation run described in chapter 4.2 illustrate.

Since the focus here was on the individual strategies of the different stakeholders and also on their non-market interactions our model only includes one agent of each type. Therefore, market processes as competition between different producers or technologies cannot be modeled adequately as of yet. Nevertheless, we believe that the first results discussed in this paper demonstrate that the effects of the dynamic interactions between stakeholders on innovation processes (in the photovoltaic industry) can be analyzed using agent-based simulation.

Given the already mentioned limitations of the current model there is still room for further improvements. Based on the developed structure more agents of each type have to be included such that analyses of the economic behavior of the agents as well as more detailed investigations of the non-market activities become possible. Additionally, the empirical validation of the model will be a key issue. Finally, the response of the stakeholders or rather agents to different policy measures will systematically be examined by simulating different scenarios on the basis of the calibrated model. These simulation runs will provide insights into the success determinants of innovation and will support the future development of innovation policies as well as their implementation.

Acknowledgements: This research has been supported by the VolkswagenStiftung, Germany in their program on “Innovation processes in the economy and the society”.

References

Amin, A.; Cohendet, P. (2004): The Architecture of Knowledge. Firms, Capabilities, and Communities. Oxford University Press, Oxford.

Argyris, C.;Schön, D. (1978): Organizational Learning: A Theory of Action Perspective. Addison-Wesley, Reading.

Breschi, S.; Malerba, F. (1997): Sectoral systems of innovation: technological regimes, Schumpeterian dynamics and spatial boundaries. In: Edquist, C. (ed.): Systems of innovation. Pinter, London.

Carlsson, B. (1994): Technological Systems and Economic Performance. In: Dodgson, M.; Rothwell, R. (eds.): The Handbook of Industrial Innovation. Edward Elgar, Aldershot/Brookfield, pp. 13-24.

Carlsson, B. and R. Stankiewicz (1991): On the nature, function and composition of technological systems. In: *Journal of Evolutionary Economics*, 1(2), pp. 93-118.

Cook, S. D. N.; Brown, J. S. (1999): Bridging Epistemologies: The Generative Dance between Organizational Knowledge and Organizational Knowing’. In: *Organization Science*, 10(4), pp. 381-400.

Dawid, H.; Reimann, M. (2003): Diversification: A Road to Inefficiency in Product Innovations?, CEM Working Paper 2003/63, University of Bielefeld.

Dosi, G. (1988): Sources, Procedures, and Microeconomic Effects of Innovation. In: *Journal of Economic Literature*, 26, pp. 1120-1171.

Edquist, C. (2001) The System of Innovation Approach and Innovation Policy: An account of the state of the art. Lead paper presented at the DRUID Conference, Aalborg, June 12-15, 2001. Online: http://www.druid.dk/conferences/nw/paper1/edquist.pdf (accessed: 06-02-2007).

Edquist, C. (2004): The Fixed Internet and Mobile Telecommunications Sectoral System of Innovation: Equipment Production, Access Provision and Content Provision. In: Malerba 2004, pp. 155-192.

Fagerberg, J.; Mowery, D. C.; Nelson, R. R. (eds.) (2005): The Oxford Handbook of Innovation. Oxford University Press, Oxford.

Green, M. A. (2000): Photovoltaics: technology overview. In: *Energy Policy*, 28(14), pp. 989-998.

Hage, J.; Hollingsworth, J. R. (2000): Idea Innovation Networks: A Strategy for Integrating Organizational and Institutional Analysis. In: *Organization Studies*, 21(5), pp. 971-1004.

Hauschildt, J. (2004): Innovationsmanagement. Vahlen, München.

Hippel, E. von (1988): The Sources of Innovation. Oxford University Press, Oxford.

Hippel, E. von (2005): Democratizing Innovation. MIT Press, Cambridge, M.A..

Hullmann, A. (2001). Internationaler Wissenstransfer und technischer Wandel (Dissertation). Physica-Verlag, Heidelberg.

Jacobsson, S.; Andersson, B. A.; Bångens, L. (2002) Transforming the energy system - the evolution of the German technological system for solar cells. SPRU (Science and Technology Policy Research), University of Sussex: *Electronic Working Paper Series*, No. 84. Online: http://www.sussex.ac.uk/Units/spru/publications/imprint/sewps/sewp84/sewp84.pdf (accessed: 05-14-2007).

Kline, S.; Rosenberg, N. (1986): An overview of innovation. In: Landau, R. (ed.): The positive sum strategy: Harnessing technology for economic growth, pp. 275-306.

Kommission der Europäischen Gemeinschaften (KOM) (2007): KOM 2007, 1, Eine Energiepolitik für Europa. Online: http://eurlex.europa.eu/LexUriServ/site/de/com/2007/com2007_0001de01.pdf (accessed: 03-10-2007).

Kotz, C. and Hiessl, H. (2005): Analysis of system innovation in urban water infrastructure systems: an agent-based modelling approach. In: *Water Science & Technology*, 5(2), pp. 135-144.

Lundvall, B.-A.; Johnson, B.; Andersen, E. S. and Dalum, B. (2001): National systems of production, innovation and competence building. In: *Research Policy*, 31, pp. 213-231.

Malerba, F. (2004): Sectoral Systems of Innovation. Concepts, Issues and Analyses of Six Major Sectors in Europe. Cambridge University Press, Cambridge, UK.

Malerba, F. (2006): Innovation and the evolution of industries. In: *Journal of Evolutionary Economics*, 16, pp. 3-23.

Malerba, F.; Orsenigo, L. (1997): Technological Regimes and Sectoral Patterns of Innovative Activities. In: *Industrial and Corporate Change*, 6(1), pp. 83-117.

März, S., Friedrich-Nishio, M.; Grupp, H. (2006): Knowledge transfer in an innovation simulation model. In: *Technological Forecasting and Social Change*, 73(2), pp. 138-152.

Nonaka, I.; Takeuchi, H. (1995): The Knowledge-Creating Company: How the Japanese Companies Create the Dynamics of Innovation. Oxford University Press, New York.

Pyka, A.; Gilbert, N.; Ahrweiler, P. (2006): Simulating knowledge-generation and -distribution processes in innovation collaboration and networks. Volkswirtschaftliche Diskussionsreihe des Instituts für Volkswirtschaftslehre der Universität Augsburg, No. 287.

Rammert, W. (2002): The Cultural Shaping of Technologies and the Politics of Technodiversity. In: Sorensen, K.; Williams, R. (eds.): Shaping technology, Guiding Policy: Concepts, Spaces and Tools. Elgar, Cheltenham, pp. 155-172.

Richiardi, M. (2003): The promises and perils of Agent-based Computational Economics. Working Paper No. 29, LABORatorio R. Revelli, Centre for Employment Studies, Turin, Italy.

Rothwell, R. (1995): The fifth generation innovation process. In: Oppenländer, K.H.; Popp, W. (eds.): Innovationen und wirtschaftlicher Fortschritt: betriebs- und volkswirtschaftliche Perspektiven. Bern, pp. 9-26.

Schwarz, N. (2007): Agent-based Modelling of the Diffusion of Environmental Innovations – An empirical approach. Paper presented at the 5th International EMAEE Conference on Innovation: “Globalisation, Services and Innovation: The Changing Dynamics of the Knowledge Economy”, 17-19 May 2007, Manchester, UK.

Schwoon, M. (2006): Simulating the Adoption of Fuel Cell Vehicles. In: *Journal of Evolutionary Economics*, 16(4), pp. 435-472.

Steyer, A.; Zimmermann, J.-B. (2001): Self Organised Criticality in Economic and Social Networks - The case of innovation diffusion. In: Kirman, A.; Zimmermann, J.-B. (eds.): Economics with Heterogenous Interacting Agents. Springer, Berlin, pp. 27-42.

Wersching, K. (2007): Agglomeration in an Innovative and Differentiated Industry with Heterogeneous Knowledge Spillovers. Online: http://www.insme.org/documenti/kspillovers.pdf (accessed: 02-23-2007).

Windrum, P., Fagiolo, G.; Moneta, A. (2007): Empirical Validation of Agent-Based Models: Alternatives and Prospects. In: *Journal of Artificial Societies and Social Simulation*, 10(2, 8).