MODELLING THE EFFECTS OF TECHNOLOGY-PUSH AND DEMAND-PULL POLICIES ON TECHNOLOGICAL CHANGE IN THE ENERGY SECTOR - THE CASE OF PHOTOVOLTAICS

Nils Roloff, German Aerospace Center, +49-711-6862-545, Nils.Roloff@dlr.de
Ulrike Lehr, Gesellschaft für Wirtschaftliche Strukturforschung mbH, +49-541-4093328, lehr@gws-os.com
Wolfram Krewitt, German Aerospace Center, +49-711-6862-766, Wolfram.Krewitt@dlr.de

Overview

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. However, in order to fulfil the needs of a future energy mix enormous efforts from the industry will be necessary in terms of both innovative processes and products. Therefore, analyses focusing on the success determinants for these technological innovations and on the influence of policy measures gain increasing importance. In particular, the effects of 'technology-push' and 'demand-pull' policies on the rate and direction of technological change are of considerable interest. This paper outlines the results of a study focusing on the process of technological change in the German photovoltaic industry. Furthermore a new approach of simulating the development of technological innovation systems based on the concept of agent based simulation is presented.

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 public policy measures still had a strong focus on the support of R&D activities. Until Japan and Germany started their first demand-oriented programs during the 1990s the role of photovoltaics with regard to the supply of energy thus remained quite limited. These initiatives and successive programmes 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). 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 behaviour, research and development led to the chosen modelling approach. Agent based modelling (ABM) seems to be a very suitable approach in a highly interdependent system that evolves in a non-equilibrium and self-organizing fashion. Although agent based modelling gains increasing importance within the field of innovation research a large part of the existing models is oriented towards theoretical issues. Consequently, there still remains a gap between the theory oriented agent based models and the empirical analyses of innovation systems. This contribution is thus in line with the so called history-friendly modelling approaches which try to fill this gap.

The structure of the paper 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 modelling 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 and methodological 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 artefacts, 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 interrelations between actors, their co-operation and spill-overs play an important role (see e. g. Carlsson and Stankiewicz 1991, Edquist 2001, Lundvall et al. 2001 and Malerba 2006). 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). Hence, emphasis is placed on the fact that both technology push as well as market pull factors influence the generation and diffusion of innovations (Mowery and Rosenberg 1979, Pavitt 1984). As a consequence we do not treat the demand side as an passive element but rather try to take the diverse interdependencies between firms and their (potential) customers into account (cf. Adner and Levinthal 2001).

The importance of innovations for social change, international competition, structural change and economic growth has been analysed 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). Additionally, the different knowledge generating processes at the level of the firm like learning by searching, learning by doing or learning by interacting and their respective impact on innovation processes are taken into consideration (Malerba 1992). With regard to renewable energies there are however just a few studies which analyse the influence of these different learning mechanisms (see e. g. Miketa and Schrattenholzer 2004) as most analyses are based on the well-known single learning curve approach. We therefore differentiate between the learning mechanisms mentioned above in order to gain new insights into their respective effects on innovation processes.

As pointed out earlier, our approach takes the whole innovation system into account. The Innovation Systems approaches most clearly follow the principles of evolutionary economics. 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. Even though this approach places a certain emphasis on the importance of both technology push and demand pull factors it has to be stated that up to now “demand related aspects still play a minor in the innovation literature” (Edler et al. 2006). But given the fact that the potential of demand-oriented policy measures is increasingly recognized analyses of customer behaviour gain more and more importance. Especially, the modelling of the various interdependencies between firms’ dynamics, demand dynamics and technology dynamics is considered to be a challenging but crucial task (Malerba 2005). We thus aim at developing an appropriate model that incorporates the most important links between the just mentioned dynamics such that the effects of technology push and demand pull policy instruments on technological change can be explored.

Considering the Innovation Systems approach it has moreover been argued that the approach lacked micro-foundations and would not reflect the path dependence of innovation formation due to habit, norms and institutions (see e. g. Rammert 2002). 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.

2.2 Multi-agent based simulation

To analyse the innovation processes in the technological system for solar cells the agent based modelling approach is used. In contrast to conventional simulation (e.g. system dynamics), in which participants are modelled 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 modelling 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 analysing 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 behaviour, which occurs when the behaviour of a system is more complicated than the simple sum of the behaviour of its components. Traditional modelling techniques such as linear programming do not include emergent behaviour. The ability to model emergent behaviour 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 particular 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 (Janssen and Jager 2002; Steyer and Zimmermann 2001) or the effects of different diversification strategies of firms (Dawid and Reimann 2003). Within these models innovations are often abstract commodities such that only few references to reality exist. Hence, not many attempts have been made so far to apply agent-based modelling 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 (Schwarz 2007; Kotz and Hiessl 2005) or the examination of the diffusion process of fuel cell vehicles (Schwoon 2006). As some of these studies are primarily focussed on questions regarding future development paths the empirical base of the respective model parameters is comparatively weak. The so called history friendly models are therefore the only agent based models that explicitly deal with innovation processes which take or took place in a particular industrial sector. However, up to now just the computer and the pharmaceutical industry have been analysed this way (Malerba et al. 2001; Dominguez Lacasa 2005).
Given the crucial importance of the interdependences between the relevant actors in innovation processes, and the dynamics of emergent behaviour, multi-agent based simulation can thus be considered as an innovative, promising and powerful computational analysis tool which can be successfully used in the field of innovation research. Open issues which apparently 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 configuration a certain constellation 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 (Innovation as creative destruction according to Schumpeter). 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, 2005) or can even be the product of public initiatives (Edquist 2004).

The types and structures of relationships and networks differ between the economic sectors, 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. The notion of a Sectoral System of Innovation (SSI) extends the traditional concept of sector used in industrial economics by including other agents in addition to firms, placing great emphasis on knowledge, learning and sectoral boundaries, focusing on non-market as well as market interactions, and paying 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):

(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 behaviours. 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 labour markets or sector-specific financial institutions.

(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 and production equipment suppliers, consumers/system operators, R&D-institutes, producers of PV-inverters, government and banks. Furthermore, the influence of foreign producers of PV-systems is also taken into account. Figure 1 gives a schematic representation of the model.

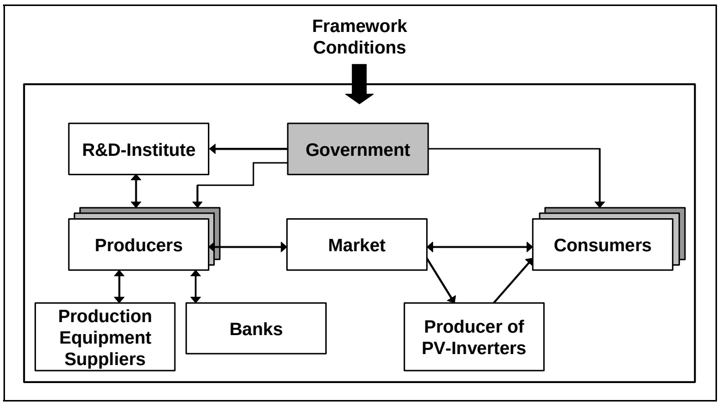

Fig. 1: Structure of the simulation model

The 'producer' and 'consumer' agents plus the agent 'R&D-institute' are at the core of the model. 'Producers' not only produce, but also try to enhance the PV-systems they sell. Hence, they have their own R&D departments and work on technological improvements. With regard to the firms that are observable in the photovoltaic market a variety of different types of producers exists, e.g. fast growing companies, new branches of established energy producers or electronics companies and off-mainstream innovative SMEs. As these different types are characterised by individual goals, learning strategies and cost structures these characteristic features are also incorporated into the model.

The 'research and development institute' as well as the firms receive funding from public budgets (agent 'government') and from private budgets, i.e. other firms. The 'R&D institute' produces knowledge and tries to improve the PV-technology itself as well as the related production technologies. Public knowledge generated by the institute is disseminated via publications, conference contributions and other scientific exchange platforms. Proprietary knowledge is patented and then sold to firms.

As far as the demand side is concerned, people can be differentiated with regard to their innovativeness. In addition to these individual differences concerning the adoption or rejection of innovations people also have different objectives and preferences when purchasing a certain type of PV system. Therefore, the demand side agents have to reflect this varieties.

The role of 'production equipment suppliers', 'producers of PV-inverters' and 'banks' is less active in the system. The 'production equipment suppliers' just react to the investment behaviour of the 'producers'. Depending on the rate of capacity expansion of the 'producers' the 'equipment suppliers' start to improve the production equipment which normally does not match the industrial state of the art. They thereby alter the conditions of market entry for potential newcomers. The same holds true for the 'producers of PV-inverters' as they constantly enhance the inverter efficiency and also reduce their costs the more PV-systems are sold. Hence, the 'producers of PV-inverters' contribute to price reductions of PV-systems. The 'banks' are modelled as simple bottlenecks for capital. Nevertheless, their activities also affect the possibilities of new entrants.

Due to the large influence of the (political) framework conditions at least for the German development, the agent 'government' is important in the model. The government gives money for R&D, provides investment subsidies, sets the feed-in tariff and also grants credits with low interest rates. However, the political decision process is not modelled as such.

A brief history of the German photovoltaic industry

The second important step for the development of the model has been the analysis of the evolution of the German photovoltaic industry. In brief, the history of this industry can be divided in four eras (also see Dewald 2007). The so called pioneer phase was dominated by 'science-based experimentation' and lasted until the mid-1980s. Although first public support programmes were implemented as a reaction to the oil crises in the 70s no market for PV-systems emerged. As PV-related activities were more or less limited to the space-oriented R&D projects conducted by electronics companies like Siemens and AEG/Telefunken this period is not our analysis focuses on the following phases. The second era covered a time span of about ten years and began with the realisation of several demo projects. Additionally, the 1,000-roofs-programme was launched. It enforced the installation of small grid-connected PV systems and offered firms the opportunity to gain operational experiences. Nevertheless the German PV market stagnated after the end of this programme. The third era (mid-1990s to 2005) was characterised by further regulative changes and the implementation of successive demand-oriented policy measures like the 100,000-roofs-programme (1999 to 2003), the renewable energy act (2000) and its amendment (2004). These targeted market introduction instruments led to a significant growth of the PV market in Germany and encouraged the formation of new firms like Q-Cells and Ersol. The fourth era is the current one. In addition to a further growth of the PV market a trend towards internationalisation and an increasing technological diversification can be observed nowadays.

3.2 Basic structure of the agents

Due to space constraints this section just contains a simplified description of our model which is an extension of an existing agent based model (Roloff et al. 2008). At the core of the model are the processes that lead to technological improvements of PV-systems and to the diffusion of this technology. PV-systems are defined by three characteristic features: price, efficiency and long-term stability or rather guarantee period. Furthermore the diversity of photovoltaic technologies is incorporated into the model. PV-modules can thus be produced using two different technologies, characterised by the major types of PV cell materials: 'traditional' crystalline or thin-film.

R&D-Institute

The development and production of PV-systems is a science based industry where technological progress is mainly driven by advances in basic science (Grupp et al. 1995). Consequently, institutions conducting basic research activities play a major role with respect to the innovation process. It can thus be considered as an advantage that German university institutes and research centres like the Fraunhofer Institute for Solar Energy Systems have reached a comparatively high scientific level throughout the last decades.

Within the model the R&D institute generates public as well as proprietary knowledge depending on the funding it receives. As equation (1) indicates the production of knowledge which is made publicly available (K_t^{publ}) is directly driven by the budget the R&D-institute gets from the government ($C_{\text{Gov}\rightarrow\text{R\&D},\,t}$) where $\lambda_{\text{R\&D}}$ is a scaling parameter. Accordingly, the proprietary knowledge $K_{\text{R\&D}\rightarrow j,\,t}^{\text{prop}}$ generated for producer *j* is proportional to the amount of research contracts received from the respective producer ($C_{j\rightarrow\text{R\&D},\,t}$).

$$(1)\quad K_t^{\text{publ}} = \frac{1}{\lambda_{\text{R\&D}}} \cdot C_{\text{Gov}\rightarrow\text{R\&D},\,t}$$

$$(2)\quad K_{\text{R\&D}\rightarrow j,\,t}^{\text{prop}} = \frac{1}{\lambda_{\text{R\&D}}} \cdot C_{j\rightarrow\text{R\&D},\,t}$$

$$(3)\quad T_{\text{R\&D},\,t} = (1-\beta)\cdot T_{\text{R\&D},\,t-1} + K_t^{\text{publ}} + \sum_{j=1}^{N} K_{\text{R\&D}\rightarrow j,\,t}^{\text{prop}}$$

$$(4)\quad \tilde{\eta}_{\text{R\&D},\,t} = \tilde{\eta}_{\text{R\&D},\,t-1} + \varphi_{\text{R\&D},\,\eta,\,t} \cdot \left(\frac{T_{\text{R\&D},\,t}}{\tilde{\eta}_{\text{R\&D},\,t-1}}\right)$$

$$(5)\quad \varphi_{\text{R\&D},\,\eta,\,t} = \begin{cases} 1 & \text{if} \quad \varphi_{\text{R\&D},\,\eta,\,t}^{\text{pot}} > \varphi_{\eta,\,t}^{\text{limit}} \\ 0 & \text{else} \end{cases}, \text{with } \varphi_{\eta,\,t}^{\text{limit}} \sim U(0,1)$$

$$(6)\quad \varphi_{\text{R\&D},\,\eta,\,t}^{\text{pot}} = \exp\left(-\frac{\tilde{\eta}_{\text{R\&D},\,t} + \dfrac{\tilde{\eta}_{\text{R\&D},\,t}}{T_{\text{R\&D},\,t}}}{\gamma_{\text{R\&D},\,\eta}}\right)$$

$$(7)\quad \eta_{\text{R\&D},\,t} = \tilde{\eta}_{\text{R\&D},\,t} \cdot \eta_{\max}$$

Based on this knowledge the institute builds up its technological capability $T_{\text{R\&D}}$.[1] Considering this process, equation (3) takes into account that technological knowledge can be accumulated but also has a certain 'half-life'. Thus it gets obsolete after a certain time period depending on the rate of degradation β. Furthermore, the uncertain or rather stochastic nature of innovation processes is also incorporated into the model. On the one hand the ability of the R&D institute to improve the (normalised) efficiency of photovoltaic cells $\tilde{\eta}_{\text{R\&D},\,t}$ increases with its technological capability but decreases with the level already achieved (4).[2] Hence, opportunities for technological advances decrease as technological limits are approached. On the other hand technological improvements just take place if the value of the potential innovation probability $\varphi_{\text{R\&D},\,\eta,\,t}^{\text{pot}}$ exceeds the random variable $\varphi_{\eta,\,t}^{\text{limit}}$ (5). As equation (6) shows the potential innovation probability also declines with increasing technological level. Finally, variable $\tilde{\eta}_{\text{R\&D}}$ just indicates the level achieved compared to the technological limit. The actual efficiency of laboratory PV-cells has therefore to be calculated with (7).

[1] The following equations used for modeling the innovation process are a modification of the model developed by Lehmann-Waffenschmidt (2008).

[2] Please note that the structure described here is on the one hand the same for innovations regarding long-term stability as well as process innovations. On the other hand is also the same for both technologies considered in the model.

Producers

Concerning the producers of PV cells and modules it can be stated that their activities are not limited to the production processes. In fact, they play an important role with respect to the technological progress. Given the comparatively high costs of this renewable energy technology the producers constantly seek to reduce materials consumption as well as processing costs and simultaneously improve the performance of the PV-systems. With regard to these industrial learning strategies we pay special attention to the relative impact that different learning processes such as 'learning by searching' and 'learning from experience' have on the technological progress. Additionally, the effects of intra-industrial knowledge spillovers are incorporated into the model.[3]

The innovative activities of the firms are driven by their respective R&D budgets. As the firms receive public funding from the government their total R&D budget is the sum of these grants plus their own R&D expenditures. While parts of the R&D budget are spent for contract research (see $C_{j \to R\&D, t}$ in the previous section) the largest part ($CR_{j,t}$) is used for own R&D activities. Concerning these activities three different ways of knowledge creation are distinguished: 'learning by searching', 'learning by doing' and the strategic use of knowledge spillovers. Thus, the knowledge $K^{int}_{j,t}$ generated through 'learning by searching' is proportional to the share k^{int}_j of $CR_{j,t}$ that firm *j* spends for this kind of innovative activity (8). The remaining part of $CR_{j,t}$ is used in order to build up the technological capabilities $K^{AC}_{j,t}$ that are necessary for the interpretation of externally available knowledge (9). Parameters β and λ_P are the above mentioned technology specific rate of degradation and a scaling parameter, respectively.

$$(8) \quad K^{int}_{j,t} = (1-\beta) \cdot K^{int}_{j,t-1} + \frac{k^{int}_j \cdot CR_{j,t}}{\lambda_P}$$

$$(10) \quad K^{LbD}_{j,t} = K^{LbD}_{j,t=0} \cdot \left(\frac{\left(\hat{x}_{j,t-1} + x_{j,t}\right)^{\ln(LF)/\ln 2} - \left(\hat{x}_{j,t-1}\right)^{\ln(LF)/\ln 2}}{\left(\hat{x}_{j,t=0}\right)^{\ln(LF)/\ln 2}} \right)$$

$$(9) \quad K^{AC}_{j,t} = (1-\beta) \cdot K^{AC}_{j,t-1} + \frac{\left(1-k^{int}_j\right) \cdot CR_{j,t}}{\lambda_P}$$

$$(11) \quad \hat{x}_{j,t=k} = \sum_{t=0}^{k} x_{j,t}$$

Equation (10) is derived from the well-known learning-curve approach and describes the way learning from experience contributes to expansions of the technological knowledge base. Accordingly, the amount of knowledge $K^{LbD}_{j,t}$ processed on the basis of 'learning by doing' is first of all determined by the cumulative volume of production $\hat{x}_{j,t=k}$ (11). In addition to that, variable LF denotes the learning factor which is set to values greater than 1. A value of 1.2, for example, implies that each doubling of the cumulative volume of production results in an expansion of knowledge of 20%.

In addition, learning through intra-industrial knowledge spillovers is modelled as follows: First the amount of knowledge that a single firm *j* potentially can absorb is calculated based on the publicly available knowledge generated by the R&D institute and the level of technological capability that firm *j*'s competitors have reached (12). Parameters σ^{publ} and σ^{comp} are for scaling and represent the degree of complexity and/or tacitness of the knowledge base. As equation (13) shows the amount of external knowledge a firm actually absorbs depends on the externally available knowledge as well as on the absorptive capacity $AC_{j,t}$ (14) and the relative technological position $R_{j,t}$ (15) of the respective firm where σ^{AC} and $\sigma^{Spillover}$ are scaling parameters.

$$(12) \quad K^{ext.}_{j,t} = \sigma^{publ} \cdot K^{publ}_t + \sigma^{comp} \cdot \left(\sum_{\substack{k=1 \\ k \neq j}}^{N} T_{k,t-1} \right)$$

$$(14) \quad AC_{j,t} = 1 - EXP\left(-\frac{K^{AC}_{j,t}}{\sigma^{AC}} \right)$$

$$(13) \quad K^{Spillover}_{j,t} = \frac{1}{\sigma^{Spillover}} \cdot K^{ext.}_{j,t} \cdot AC_{j,t} \cdot EXP\left(-\frac{1-R_{j,t}}{\sigma^{P}} \right) \cdot \left(1 - R_{j,t}\right)$$

$$(15) \quad R_{j,t} = \frac{\eta_{j,t}}{\eta_{R\&D,t}}$$

Taking all together, the technological capability of firms is build up on the basis of the knowledge generated through 'learning-by-searching' and 'learning-by-doing' as well as through the use of knowledge spillovers and contract research (16).

[3] The structure described here is again the same for innovations regarding long-term stability as well as process innovations and also for both technologies considered in the model.

Here the parameters ω^{int}, ω^{LbD}, $\omega^{\text{Spillover}}$ and ω^{Contract} are used for weighting in order to adjust the relative contribution of the respective learning processes.

$$\text{(16)} \qquad \mathrm{T}_{j,\,t} = (1-\beta)\cdot \mathrm{T}_{j,\,t-1} + \omega^{\text{int}}\cdot \mathrm{K}^{\text{int}}_{j,\,t} + \omega^{\text{LbD}}\cdot \mathrm{K}^{\text{LbD}}_{j,\,t} + \omega^{\text{Spillover}}\cdot \mathrm{K}^{\text{Spillover}}_{j,\,t} + \omega^{\text{Contract}}\cdot \mathrm{K}^{\text{prop}}_{\text{R\&D}\to j,\,t}$$

The firms then make use of their technological capability in order to achieve advances with respect to the efficiency and the long-term stability of the PV-modules they sell (product innovations) and to improve their production processes (process innovations). The process of technological progress is again modelled on the basis of the ‘innovation lottery’ mechanism already described above.

As a result of these technological advances the PV-modules offered by the producers are heterogeneous. But nevertheless they are close substitutes. Hence, the producers are considered to be price setters with limited market power depending on their market share. Accordingly, prices are set by adding a mark-up to costs. In order to take into consideration the market power of the firms and the supply-demand relation the mark-up parameter varies with the firms’ respective market shares and the quantities demanded compared to the production capacities. Supply and demand is then matched as follows: Producers set prices first but only produce as many PV-systems as consumers order. Thus there is no excess supply and inventories are not considered.

As far as the production costs of PV-modules are concerned it can be stated that they are mainly influenced by the material cost. Due to the fact that an increase of the module efficiency results in a decrease of materials consumption product innovations affect the level of manufacturing cost (also see Nemet 2007 for a detailed analysis). As figure 2 shows total manufacturing cost are therefore influenced by process innovations as well as by material prices and product innovations.

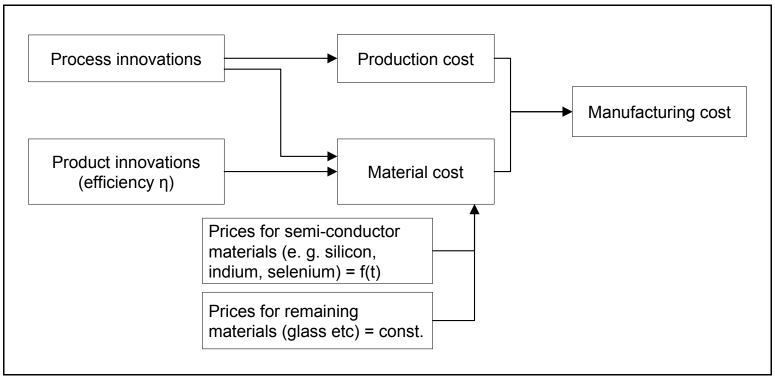

Fig. 2: The impact of process and product innovations on cost reductions

Given the levels of manufacturing costs and prices the firms’ profits are calculated on the basis of the number of produced and sold PV-modules. Profits are then used in different ways. As mentioned above firms invest a certain fraction of their profits in R&D. Furthermore they expand their production capacity when a certain degree of capacity utilisation is exceeded. In the same way they also have the possibility to sell production equipment if their profit should be negative. Thus profitable firms have the possibility to expand while unprofitable ones are forced to shrink or even go bankrupt. In addition to that, newcoming firms use a certain share of their profits to amortise their initial debts (see below). Finally, any remaining capital is kept as a ‘reserve’.

For reasons of simplicity, market entry decisions are not yet incorporated into the current version of the model. Rather the points in time at which firms enter into the market are exogenously set. Hence, just two firms exist at the beginning of each simulation run. As these two firms represent the PV-branches of the electronics companies Siemens and AEG/Telefunken they start with positive initial savings plus certain amounts of technological knowledge. Compared to that, the process of market entry is modelled in a quite detailed way for newcoming firms. Given a pre-defined market share they shall achieve when entering the market the necessary production capacity is calculated first. Based on information about material and equipment prices and about the estimated production costs given the technological level of the production equipment offered by the suppliers the newcomers then apply for a credit at the bank. This credit has to be repaid within a certain period of time, otherwise the firm is forced to exit the market again. In addition to that, it is assumed that firms normally possess comparatively little technological knowledge when entering the market. But even so, producer agents representing academic spin-offs that aim to commercialise new technological alternatives (CIS, CdTe) are initialised separately such that they are equipped with relevant know-how right from their beginning.

Consumers

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.

Although economic aspects were not that important at the beginning the return on investment (ROI) which can be achieved through the use of a PV-system is a major determining factor with regard to the diffusion process. The demand side agents are thus modelled as price-takers that make use of a separate module for the calculation of the attainable ROI. This module is based on formulas to be found in common software tools ('solarcalculators'). Accordingly, the attainable ROI is calculated for each PV-system offered on the market on the basis of the following parameters and variables: price, average solar irradiation, inverter efficiency, public investment subsidies, feed-in tariff, average annual degradation, interest rates demanded by the bank as wells as by the government and expected rate of inflation. As the diffusion process depends on the general price level rather than on particular system prices a weighted average is calculated in (17), where $\vartheta_{j,\,i,\,t}$ is the market share that firm j achieved at time t with the PV-system based on technology i and $\mathrm{r}_{j,\,i,\,t}$ is the ROI that can be attained with the respective product. In addition, the value of this weighted average is transformed according to equation (18) in order to rescale its range.

$$(17) \qquad \bar{\mathrm{r}}_t = \frac{\sum_{j=1}^{N}\sum_{i=1}^{2}\left(\mathrm{r}_{j,i,t}\cdot\vartheta_{j,i,t}\right)}{\sum_{j=1}^{N}\sum_{i=1}^{2}\vartheta_{j,i,t}}$$

$$(18) \qquad \tilde{\bar{\mathrm{r}}}_t = \begin{cases} 1 & \text{if } \bar{\mathrm{r}}_t > \mathrm{r}_{\max} \\ \frac{1}{\mathrm{r}_{\max}-\mathrm{r}_{\min}}\cdot\left(\bar{\mathrm{r}}_t - \mathrm{r}_{\min}\right) & \text{if } \mathrm{r}_{\min} < \bar{\mathrm{r}}_t < \mathrm{r}_{\max} \\ 0 & \text{else} \end{cases}$$

The normalised ROI directly affects the total budget to be spent on PV-systems during a simulation period. The total budget moreover depends on the number adopters $\mathrm{D}_{d,\,t}$, the average budget per adopter b and the group specific sensitivity parameter ε_d (19). Note that the demand side is not regarded as a homogenous group. Rather we differentiate between five groups (innovators, early adopters, early majority, late majority and laggards) according to the innovativeness of the respective individuals (Rogers 1995). Consequently, the social process of technology diffusion is modelled separately for each group.

Equations 20a, 20b and 21 are a modification of a simple diffusion model. The original model developed by Bass takes into account that the decision of individuals concerning the adoption or rejection of an innovation is first of all influenced by their neighbours' (friends, relatives, colleagues) buying decisions and additional factors like mass media coverage or similar stimuli (Bass 1969). However, the diffusion process of PV-systems is mainly driven by 'word-of-mouth' such that the so called external influences caused by advertising and the media can be omitted. We thus concentrate on the social processes that take place within as well as between the above mentioned adopter groups.

As far as the beginning of the diffusion process is concerned it can be stated that the different groups start buying PV-systems when certain thresholds with regard to the price level ($\tilde{\bar{\mathrm{r}}}_d^{\mathrm{limit}}$) and the prevailing social pressure ($\mathrm{NB}_d^{\mathrm{limit}}$) are met (20a). Here NB_t denotes the social pressure generated by all adopters together (neighbourhood effect). Therefore, the value of NB_t depends on the total number of people or rather households already using PV-systems (22) and on the group specific parameter $\mathrm{q}_d^{\mathrm{active}}$ which describes how much members of the different adopter groups are motivated to actively influence the behaviour of others (21).

Regarding the diffusion process itself the group specific growth in the number of adopters is driven by the just mentioned 'global' neighbourhood effect as well as by influences that primarily occur within the individual adopter groups (20b). The relative impact of these two effects thereby hinges on the so called coefficients of imitation $\mathrm{q}_d^{\mathrm{passive,\,ext}}$ and $\mathrm{q}_d^{\mathrm{passive,\,int}}$. Additionally, the speed of diffusion is also affected by the ROI that generally can be achieved by investing into PV-systems. Finally, the variable MP_d denotes the market potential which is the total number of people or rather households that will eventually buy a PV-system.

$$(19) \qquad \mathrm{B}_{d,t} = \begin{cases} \mathrm{POW}\left(\tilde{\bar{\mathrm{r}}}_t, \varepsilon_d\right)\cdot \mathrm{b}\cdot \mathrm{D}_{d,\,t} & \text{if } \hat{\mathrm{D}}_{d,\,t-1} > 0 \\ 0 & \text{else} \end{cases}$$

$$(21) \qquad \mathrm{NB}_t = \sum_{d=1}^{D}\mathrm{q}_d^{\mathrm{active}}\cdot\hat{\mathrm{D}}_{d,\,t}$$

(20a) $$\mathrm{D}_{d,t} = \begin{cases} \Psi_{d,t} & \text{if } \widehat{\mathrm{D}}_{d,t-1} > 0 \\ 10 & \text{if } \widehat{\mathrm{D}}_{d,t-1} = 0 \text{ and } \mathrm{NB}_t > \mathrm{NB}_d^{\mathrm{limit}} \text{ and } \tilde{\bar{\mathrm{r}}}_t > \tilde{\bar{\mathrm{r}}}_d^{\mathrm{limit}} \\ 0 & \text{else} \end{cases}$$

(22) $$\widehat{\mathrm{D}}_{d,t} = \widehat{\mathrm{D}}_{d,t-1} + \mathrm{D}_{d,t}$$

(20b) $$\Psi_{d,t} = \mathrm{POW}\left(\tilde{\bar{\mathrm{r}}}_t, \varepsilon_d\right) \cdot \left[\mathrm{q}_d^{\mathrm{passive,ext}} \cdot \left(\mathrm{MP}_d - \widehat{\mathrm{D}}_{d,t-1}\right) \cdot \mathrm{NB}_t \cdot \left(\sum_{e=1}^{D} \mathrm{MP}_e\right)^{-1} + \mathrm{q}_d^{\mathrm{passive,int}} \cdot \left(\mathrm{MP}_d - \widehat{\mathrm{D}}_{d,t-1}\right) \cdot \left(\frac{\widehat{\mathrm{D}}_{d,t-1}}{\mathrm{MP}_d}\right) \right]$$

In order to take into consideration that individuals who are part of the same adopter group nonetheless buy different products a modified love-for-variety approach is used (also see Wersching 2007). Hence, the representative consumers of the different adopter groups have the utility function (23). As the PV-modules offered by the producers are close substitutes the degree of complementarity α is set close to 1 in this case. However, the adopter groups are heterogeneous with respect to their preferred product characteristics. Therefore the variable A_d represent the total preference of group *d* for the available product variants. Here the total preference for a PV-system processed by firm *j* with technology *i* depends on the attainable ROI and on the total efficiency of the system which is a product of the module and the inverter efficiency (24). Parameters $\mathrm{w}_d^{\mathrm{ROI}}$ and w_d^{η} are group specific and denote the characteristic preferences with regard to economic (ROI) as well as technological (efficiency η) aspects.

(23) $$\mathrm{u}_{d,t}\left(\mathrm{y}_{\mathrm{D}_d \to 1,1,t}, \ldots, \mathrm{y}_{\mathrm{D}_d \to N,2,t}\right) = \left[\sum_{i=1}^{N}\sum_{j=1}^{2}\left(\mathrm{A}_{d,j,i,t} \cdot \mathrm{y}_{\mathrm{D}_d \to j,i,t}\right)^{\alpha}\right]^{1/\alpha}$$

(24) $$\mathrm{A}_{d,j,i,t} = \mathrm{POW}\left(\mathrm{r}_{j,i,t}, \mathrm{w}_d^{\mathrm{ROI}}\right) + \mathrm{POW}\left(\left(\eta_{j,i,t} \cdot \eta_t^{\mathrm{BOS}}\right), \mathrm{w}_d^{\eta}\right)$$

(25) $$\mathrm{B}_{d,t} \geq \sum_{i=1}^{N}\sum_{j=1}^{2}\left(\mathrm{P}_{j,i,t} \cdot \mathrm{y}_{\mathrm{D}_d \to j,i,t}\right)$$

Given their preferences consumers buy a mix of products that maximises their utility subject to their budget constraint (25). Since we model consumers as price-takers straight-forward calculations then lead to the following demand curve, where $\mathrm{y}_{d \to j,i,t}$ is the quantity of PV-system based on technology *i* that the adopter group *d* would buy from producer *j*:

(26) $$\mathrm{y}_{d \to j,i,t} = \mathrm{B}_{d,t} \cdot \left(\sum_{k=1}^{N}\sum_{s=1}^{2}\left(\mathrm{P}_{k,s,t} \cdot \left(\frac{\mathrm{A}_{k,s,t}}{\mathrm{A}_{j,i,t}}\right)^{\alpha/(1-\alpha)} \cdot \left(\frac{\mathrm{P}_{j,i,t}}{\mathrm{P}_{k,s,t}}\right)^{1/(1-\alpha)}\right)\right)^{-1}$$

Government, Bank, Production Equipment Suppliers and Producer of PV-inverters

As the political decision making process is not explicitly modelled the ‘Government’ agent acts as an exogenous driver. Accordingly, the agent is used to feed time series data on federal R&D funding expenditures as well as information on demand-oriented policy measures into the model. In the same way time series data on interest rates is integrated into the model with the help of the ‘Bank’ agent. Furthermore this agent governs the issuance and the repayment of credits.

As mentioned above the role of ‘Production equipment suppliers’ and the ‘Producer of PV-inverters’ is also less active in the system. The ‘Production equipment suppliers’ agent simply reacts to the development of the ‘producers’’ investment behaviour. It is assumed that suppliers usually offer equipment which does not fully meet the state-of-the-art with regard to the achievable product quality (module efficiency, long-time stability) when their market is stagnating. However, the suppliers begin to improve the equipment they offer in a step-process when the rate of capacity expansion of the ‘producers’ exceeds certain limits. Even so, this is without importance for incumbent firms since they set up the production equipment themselves. But compared to that the market conditions for potential newcomers are directly altered by this process.

The price and the efficiency of PV-inverters considerably influence the total system price and the overall performance of PV-systems such that the producers of PV-inverters and their behaviour had to be integrated into the model. Nevertheless, we tried to keep complexity at a reasonable level and therefore applied a simple learning curve approach in order to model the development of the inverter efficiency and cost.

4 Results

Simulation Setup

History-friendly models aim to capture qualitative theories about mechanisms underlying technological change and factors affecting the evolution of industries in stylised form. So in order to analyse the evolution of the German PV-sector the model is calibrated such that it is able to replicate the history of this industry. However, a major problem with calibration in the context with agent-based models is that a large fraction of parameters cannot be estimated on the basis of statistical methods as much of the information required is not (publicly) available. Therefore, many parameters have to be chosen based on 'educated guessing' such that the model is able to generate reasonable and robust results. Even so, it was possible to compile a considerable amount of information from literature reviews, expert judgements and publicly available databases.

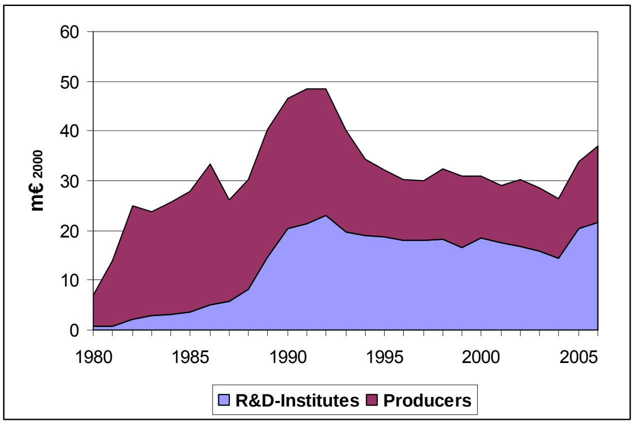

Fig. 4: Public funding of PV-related R&D in Germany

With regard to public R&D funding the database of the ministry of education and research ('Förderkatalog') provides very extensive information on single projects such that data on the funding of the different technological alternatives as well as on the respective recipients could be processed (see fig. 3). In the same way, detailed information about the demand-oriented policy measures was integrated into the model, e.g. the level of the subsidies granted to the operators of PV-systems during the so-called 1,000-roofs-programme or the interest rates of the low-interest loans provided by the state-owned KfW-bank in the context of the 100,000-roofs-programme. The same holds true for the development of the PV-specific feed-in tariffs.
As far as the technological development of photovoltaic cells and modules as well as the cost structures of the PV firms are concerned much data could be obtained from market surveys, industry reports and expert judgments. In addition the financial reports published by companies listed on the stock exchange were analysed. Given the fact that information on the diffusion process and the motifs of (potential) customers was scarce we interviewed firms, citizens' initiatives, energy consulting centres and craftsmen ('solarteurs') on this subject.
Finally, time series data on the development of interest and inflation rates as well as on prices of semi-conductor materials and production facilities could be gathered from data-bases and industry reports.

Results of the simulation runs

As a first step it was necessary to develop a parameter setting - the 'standard set' - that is based on the empirical data and enables the model to reproduce the history of the German PV-industry. Then the robustness of the model was assessed by performing systematic parameter analyses. After that, first simulation experiments were conducted in order to analyse the effects of 'technology-push' and 'demand-pull' policies on the development of the innovation system under scrutiny. In order to demonstrate the dynamic behaviour of the model an experiment which studies the effects of 'demand-pull' policy measures is described in the following paragraphs.
For the analysis two simulation runs are needed. The first run or rather scenario represents the history-friendly base case. Compared to that the second scenario includes systematic variations of certain parameters such that the effects of these variations can then be examined by comparing the two runs.
In the experiment described here we focus on the influence of the PV-specific feed-in tariff. As illustrated in figure 5 feed-in tariffs were first introduced in Germany in the 1990s on the basis of the Energy Feed-In Law. The Renewable Energy Act replaced this law in 2000 and the compensation rates for photovoltaic energy were substantially increased. In the following

years the feed-in tariffs have been reduced step by step. However, an amendment to the EEG was made in 2004 in order to compensate the phase-out of the 100,000-roofs-programme. For the simulation experiment this amendment was omitted in the second simulation run (scenario 2).

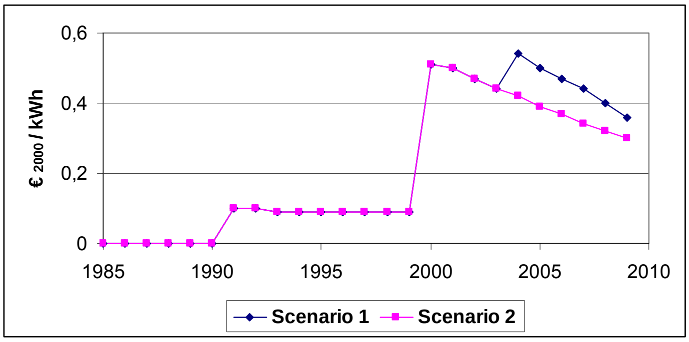

Fig. 5: Development of the PV feed-in tariff in scenarios 1 & 2

Figures 6 to 10 show the results. As can be seen in figures 6 and 7 the results from scenario 1 fit the real development of the German PV-market well. In addition the effect of the reduced feed-in tariffs in scenario 2 on the total number of PV installations becomes obvious. With respect to the average price it can be observed that the greater reduction of the compensation rates in the second scenario forces the producers to lower their prices at a comparatively faster rate. Nevertheless the average price reaches a somewhat lower level in scenario 1 at the end of the simulation period. This deserves some further investigation.

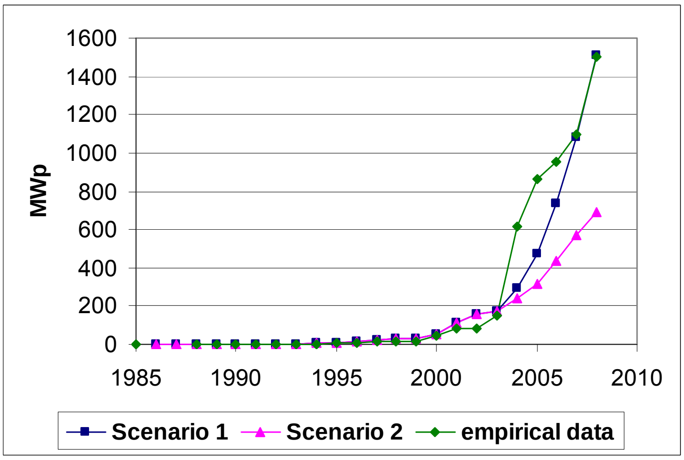

Fig. 6: PV installations per year

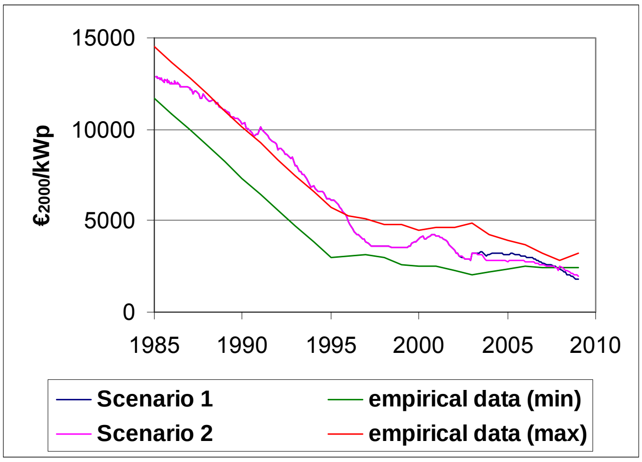

Fig. 7: Development of PV panel prices (weighted average)

Hence, one has to consider the factors influencing the prices of PV-modules: process as well as product innovations, market concentration, demand-supply relation plus external influences like the silicon price. Given this multitude of influences, diverse interacting mechanisms exist which together affect the price development.

The faster reduction of the feed-in tariff in scenario 2 induces a relative decrease of demand compared to scenario 1. As a consequence firms lower their prices in order to keep sales up. Even so, the sales volumes remain significantly lower than in the base case, as figures 6 and 8 illustrate. Due to these reductions of sales and profit margins the firms’ R&D budgets are also smaller. Additionally, the possibilities for ‘learning by doing’ are reduced. Technological progress thus is comparatively slowed down thereby limiting the potential for further cost reductions (see fig. 9).

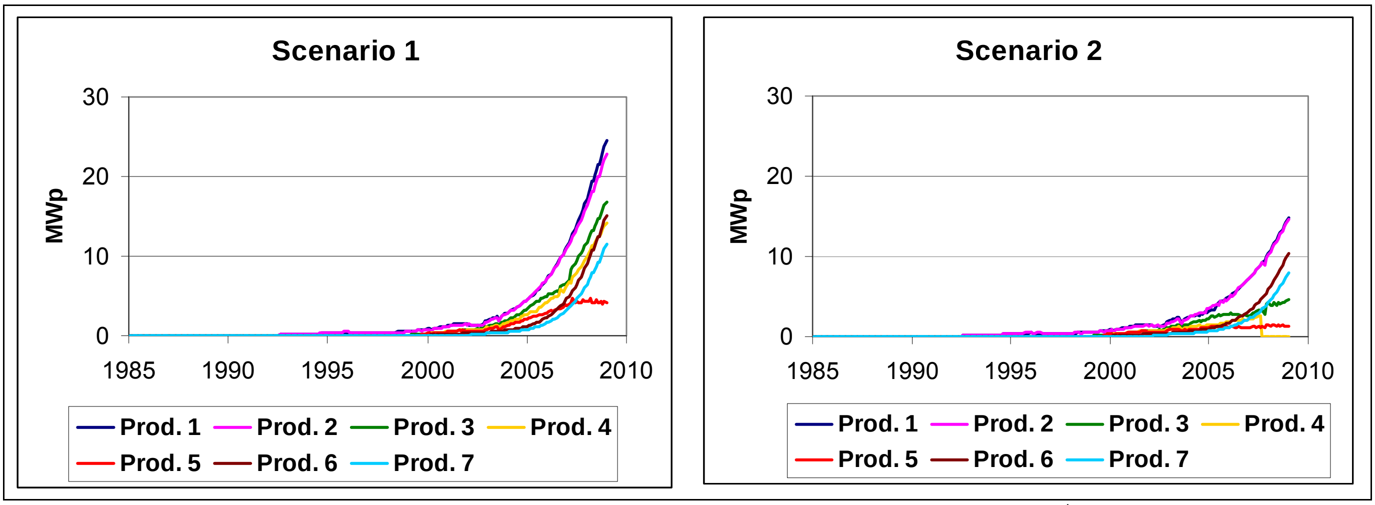

Fig. 8: Comparison of producers' PV module production (per simulation period) in scenario 1 & 2[4]

Figure 8 shows the impact the variation of the demand-oriented policy measure has on the different PV-firms. Here, the agents 'producer 1' and 'producer 2' correspond to the pioneering firms AEG/Telefunken and Siemens Solar whose PV-related activities are now part of Schott Solar and SolarWorld, respectively. Producers 3 to 5 stand for the second generation companies like Q-Cells and Ersol which entered the market in the late 1990s. In addition, the firms that try to commercialise thin-film PV technologies (CIS, CdTe) are represented by 'producer 6' and 'producer 7'.

With regard to scenario 1 it can be stated that the agent 'producer 5' is the only one that does not successfully expand. However, this agent was deliberately set to spend a 'less than average' fraction of its capital on R&D in order to demonstrate the importance of persistent R&D strategies in the photovoltaics industry. In comparison to 'producer 5' all other newcoming firms are characterised by dynamic growth rates. As a result, the market shares of the pioneering firms decline despite their first-mover advantages.

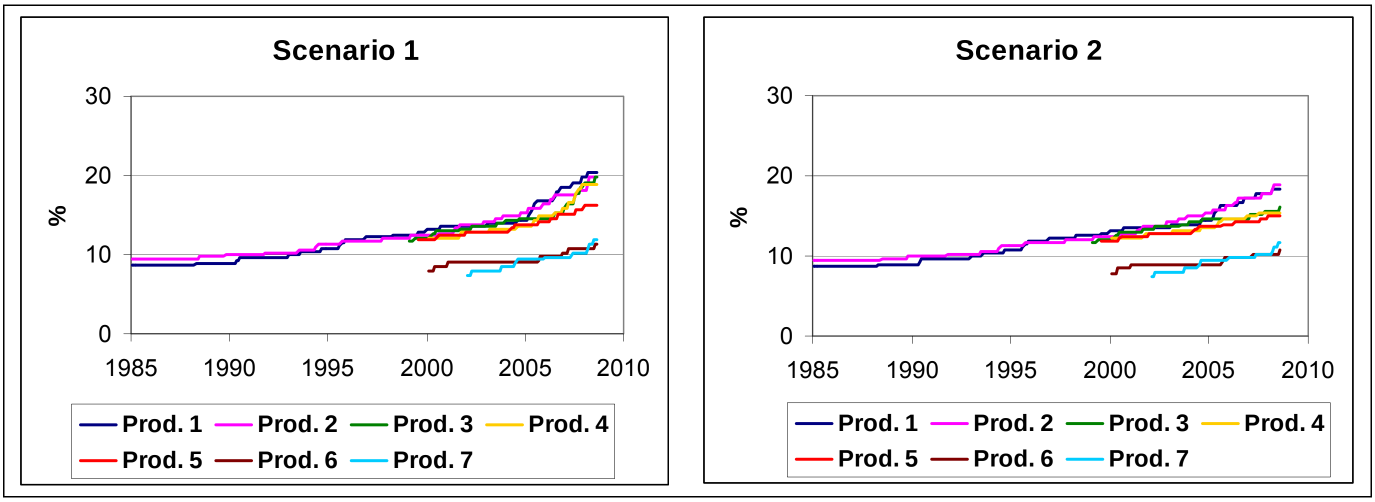

Fig. 9: Comparison of the efficiencies of the PV-modules offered by the producers in scenarios 1 & 2

It can be seen from figure 8 that the lower compensation rates in scenario 2 do not affect all 'producers' in the same way. Rather the newcomers 3, 4 and 5 encounter problems entering the market and eventually even go bankrupt like 'producer 4' at the end of year 2007. Comparing the two simulation runs market concentration is higher in scenario 2 which leads to increased prices. The sudden increase of the firms' profit margins right after the bankruptcy of 'producer 4' illustrates this effect best (see fig. 10).[5]

[4] One simulation step corresponds to one tenth of a year in reality. Therefore the values of ten sub sequent simulation steps have to be summed up in order to calculate yearly values.

[5] Please note that profit margin is here defined as sales minus manufacturing costs divided by sales. Investments in production facilities and R&D as well as expenses for administration and marketing are thus not taken into account.

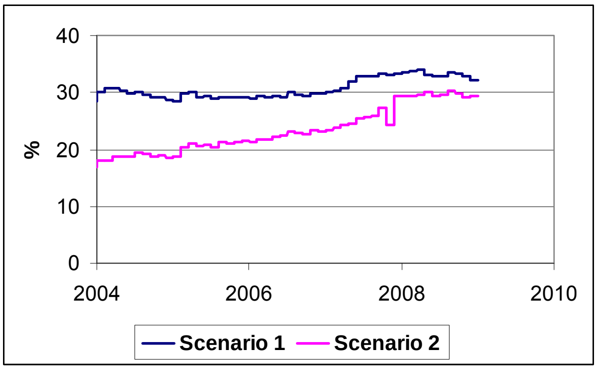

Fig. 10: Profit margin (weighted average) in scenarios 1 & 2

As a result, the simulation experiment described here demonstrates that decreases of the feed-in tariff might trigger price reductions. Nevertheless, the complexity of the diverse cause-effect relationships has also to be taken into consideration in order to avoid unplanned long-term effects. In addition to that other simulation runs showed that high levels of demand-oriented policy measures can potentially also lead to unintended consequences. For example, there exists the risk of increased first-mover advantages such that newcomers are not able to compete with the pioneering companies. This effect can even be intensified by the behaviour of the demand-side agents. When they do not have a certain 'love-for-variety' and rather focus on the best products available a clear trend towards technological lock-in and higher levels of market concentration can be observed in the respective experiments.

5 Conclusions

Although the model in its current version is still work in progress the interactions between the agents can be simulated. 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 illustrate. Furthermore, multi-agent based systems can obviously deal with the representation of long-term periods and dynamically evolving systems.

Viewing innovation processes from an agent based perspective hence allows for innovative computational analyses of the interdependencies between the relevant actors. It goes beyond standard analysis of innovation processes by attempting to combine agent based and systemic considerations. In particular, the response of actors to 'technology-push' and 'market-pull' policy measures, their dynamically emerging behaviour and their related implications on innovation processes as well as the development of the PV market can be examined. But it also has to be considered that the calibration of the different agents necessitates a great amount of empirical data which may not always be available. Nevertheless the results of the first simulation runs demonstrate that agent based modelling seems to be a promising approach for model-based analyses of innovation support policies.

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