Three generations of solar cell technologies in Japan – a Functions of Innovation Systems analysis

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Abstract
This paper looks into the development and implementation of photovoltaic energy (PV) in Japan from the Functions of Innovation Systems perspective. It regards the current three generations of PV separately and looks at each generation within its own innovation system. The functioning of the innovation systems is analysed with special attention for virtuous and vicious cycles; and the competition between the three generations of PV within Japan is analysed. From the case studies, it appears that both second generation thin film PV and third generation organic solar cells are thriving in virtuous cycles of high expectations, knowledge development and entrepreneurial activities. Second generation CIS PV is locked in a vicious cycle of high investment costs and little knowledge exchange, whereas the high growth of first generation PV is slowed down by a vicious cycle triggered by silicon shortages and reduced market prospects. Competition between the generations is found to revolve around two resources: company investments (on a small scale) and physical resources (silicon), market investments (they mostly aim at the same market) and market subsidies (on a larger scale).

Keywords: Functions of Innovation Systems, PV generations, Japan, competition

1. Introduction

For years, Japan has been a frontrunner in both research and development (R&D) into and production and implementation of photovoltaic solar cells (PV). Currently, all three generations of PV are being developed in Japan. This paper looks into the development and implementation of PV from the Functions of Innovation Systems perspective. For the period 2000-2008, it investigates for each of the three PV generations in Japan the functioning of the innovation systems, and the presence of virtuous and vicious feedback cycles. It also compares the innovation system functioning for the three generations of PV and looks into competition between the PV generations. These latter two aspects make the paper highly original.

The research question is:
How do the innovation systems for first, second and third generation PV in Japan function and to what extent do these innovation systems compete?

The paper is structured as follows. Sections 2 and 3 describe the theoretical framework and the methodology. Section 4 shortly introduces the three generations of PV. Section 5 offers the empirical analysis. Section 6 will draw conclusions.

2. Theoretical framework

The theoretical framework used to compare PV in Japan and in the Netherlands is that of an emerging Innovation System (IS). There are several definitions of innovation systems mentioned in literature, all having the same scope and derived from one of the first definitions (Freeman, 1987):

> "…systems of innovation are networks of institutions, public or private, whose activities and interactions initiate, import, modify, and diffuse new technologies".

The idea of the IS approach is that innovation and diffusion is an individual as well as a collective act. This approach understands the technological change through insight in the innovation system dynamics (Hekkert, Suurs et al., 2007).

In order to make the dynamic analysis feasible, the solution is to analyse the dynamics in a Technological Innovation System (TIS). A TIS is not bound by e.g. a geographical area or an industrial sector, but by a technology, it is defined by Hekkert and Negro (2008):

"…a network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilise technology."

A well functioning TIS is a prerequisite for the technology in question to be developed and widely diffused, but it is difficult to determine whether or not a TIS functions well. Therefore, the factors that influence the overall function – the development, diffusion, and use of innovation – need to be identified (Edquist, 2004). Jacobsson and Johnson (2000) developed the concept of system functions, where a system function is defined as "…a contribution of a component or a set of components to a system's performance". They state that a TIS may be described and analysed in terms of its 'functional pattern', i.e. how these functions have been served (Johnson and Jacobsson, 2000). The functional pattern is mapped by studying the dynamics of each function separately as well as the interactions between the functions. The system functions are related to the character of, and the interaction between, the components of an innovation system, i.e. agents (e.g. firms and other organisations), networks, and institutions, either specific to one TIS or 'shared' between a number of different systems (Edquist, 2001).

Recently a number of studies have applied the system functions approach, which has led to a number of system functions lists in the literature (a.o. Jacobsson and Johnson, 2000; Liu and White, 2001; Rickne, 2001; Bergek, 2002; Carlsson and Jacobsson, 2004; Jacobsson and Bergek, 2004; Hekkert et al., 2007; Negro et.al 2007; Kamp, 2008). This paper uses the list of system functions, recently developed at Utrecht University (a.o. Hekkert et al., 2007) that will be applied to map the key activities in innovation systems, and to describe and explain the dynamics of a TIS.

Function 1: Entrepreneurial Activities

The existence of entrepreneurs in innovation systems is of prime importance. Without entrepreneurs innovation would not take place and the innovation system would not even exist. The role of the entrepreneur is to turn the potential of new knowledge development, networks and markets into concrete action to generate and take advantage of business opportunities.

Function 2: Knowledge Development

Mechanisms of learning are at the heart of any innovation process. For instance, according to Lundvall: "the most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning" (Lundvall, 1992). Therefore, R&D and knowledge development are prerequisites within the innovation system. Four types of learning processes were distinguished by Kamp et al. (2004); learning by searching[1], learning by doing[2], learning by using[3] and learning by interacting[4]. This function encompasses 'learning by searching', 'learning by doing', and 'learning by using'.

Function 3: Knowledge Diffusion through Networks

The fourth learning process that was identified was learning by interacting, or knowledge diffusion. It entails the transfer of knowledge between different linked actors, which is commonly known as a network. According to Carlsson and Stankiewicz (1991) the essential function of networks is the exchange of information. This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors and market.

Function 4: Guidance of the Search

Resources are limited making it necessary to effectively distribute them by focusing, or guiding them, on specific paths. There are several ways in which such guidance can be established. If a technology has proven itself, this will give the technology a higher level of credibility, which will propel development into this area. Similarly a technological breakthrough can motivate actors to focus on a specific field of study, given that it creates high expectations in the future abilities of the technology. Guidance can also be initiated by institutions such as the government through goal setting.

Function 5: Market Formation

A new technology often has difficulties to compete with incumbent technologies. Therefore it is important to create protected spaces for new technologies. A possibility is the formation of temporary niche markets based on financial incentives, or based on specific applications of the technology (Schot, Hoogma et al., 1994). This can be done by governments but also by other agents in the innovation system.

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[1] Learning by searching entails the creation of new knowledge at research institutes or companies.
[2] Learning by doing consists of production skills which increase the efficiency of production operations.
[3] Learning by using activities deliver specific production-related knowledge such as feedback on the performance of the system in an actual application, as well as gaining experience with placing or installing the innovation.
[4] Learning by interacting entails the transfer of knowledge between different actors.

Function 6: Resource Mobilisation

Resources, both financial, human and physical, are necessary as a basic input to all the activities within the innovation system.

Function 7: Support from advocacy coalitions [5]

Since a new technology has to become part of an incumbent regime, parties with vested interests will often oppose this force of 'creative destruction'. In that case, advocacy coalitions can function as a catalyst to create legitimacy for the new technology and to counteract resistance to change.

Virtuous and vicious cycles

Both the individual fulfilment of each system function and the interaction dynamics between them are of importance to the functioning of the TIS. Positive interactions between system functions could lead to a reinforcing dynamics within the TIS, creating *virtuous cycles* that promote the development and diffusion of the technology. Vicious cycles on the contrary, which result from negative interaction between the system functions, lead to reduced activities in relation to other system functions, thereby slowing down or even stopping the progress.

3. Methodology

This paper assesses the functions of the TIS for each PV generation through the evaluation of the system functions. Table 1 shows the indicators for the functions that were used. The data were collected through interviews with key actors, document search and literature review. The interviews were conducted in English by a Dutch researcher in Japan. Respondents came from a variety of organisations: companies (Sharp Corp., Showa Shell Sekiyu K.K., Kaneka Corp., Suntech/MSK), (semi-)government organisations (NEDO[6], ANRE[7]), universities (TUAT[8],

[5] This function is sometimes called 'creation of legitimacy/counteract resistance to change'. The terms are used interchangeably. We chose 'support from advocacy coalitions' as it is the clearest description.
[6] The New Energy and Industrial Technology Development Organization (NEDO) is the subsidy provider of the Japanese government
[7] Agency for Natural Resources and Energy, subdivision of Ministry of Economy, Trade and Industry (METI) responsible for the national energy policy
[8] Tokyo University of Agriculture and Technology

Tokyo University of Science, Kyoto University), research institutes (AIST[9], PVTEC) and others (ULVAC[10], Misawa Homes[11], JPEA[12], RTS[13]). After data collection the interrelation between the system functions was investigated per PV generation. By observing positive and negative interactions we determined the presence of virtuous and vicious cycles and their main causes. Lastly, we compared the innovation system functioning for the three generations of PV and looked into competition between the PV generations.

Table 1: Indicators of each function

Function	Indicator
Function 1: Entrepreneurial activities	Type of entrepreneur
	Change in the number of entrepreneurs
	Recent activities
	Future (announced) activities
Function 2: Knowledge development	Type of organisation performing research
	Type of research activities (basic/applied)
	Start of national research project
	Start of production
	Production cost changes
	Market size indication
	Feedback from market
Function 3: Knowledge diffusion through networks	Collaboration between organisations on R&D
	Formalised exchange methods
Function 4: Guidance of the search	Targets set by government or industry
	Type of targets (research/ market/ installation)
	Support for goals
	Technological expectations
	Technological background

[9] National research institute of Advanced Industrial Science and Technology (AIST)
[10] Supplier of manufacturing equipment, in particular vacuum technology
[11] Housing construction company
[12] PV branch organisation
[13] PV market analysis and consultancy firm

	Expected continuation of development and diffusion
Function 5: Market formation	Market size developments
	Consumer motivation
	Financial market incentives
	Technology specific applications
Function 6: Resources mobilisation	Availability of venture capital
	Availability specialised financial institutes
	Availability of (research) employees
	Availability specialised education programs
	Availability of raw materials
Function 7: Creation of legitimacy	Existence of advocacy coalitions
	Activities of coalitions
	Recent results of activities

4. Technology

PV works by absorbing the solar radiation and transforming it into an electric current. There are several varieties of solar cell designs with different performance and cost features. These varieties are generally divided into three generations, each in a different phase of development. First generation solar cells have been developed for decades and are widely implemented. Second generation solar cells have just entered the market. Third generation solar cells are still in the R&D phase and have not entered the market yet. The market we will focus on in our analysis is the power application market.

4.1 First generation

First generation solar cells are all crystalline silicon solar cells (c-Si). These are the most well-known solar cells, and also the most well researched. Nearly all solar cells currently being produced are of this type. They hold 90% of the total market and compared to the other technologies crystalline silicon have a high efficiency of around 15%. (Branz et al., 2008).The main problem lies in their relatively high silicon usage. As there is currently a silicon shortage, other technologies which use less or no silicon are becoming more attractive.

4.2 Second generation

The second generation of solar cells consists of a variety of solar cell technologies which have recently entered the market. We will focus on thin-film silicon solar cells, which includes amorphous silicon, Tandem and Hybrid solar cells, and on CIS solar cells.

4.2.1 Thin-film silicon solar cells (tf-Si)

Thin-film solar cells were created to reduce the amount of silicon per solar cell. Current products are becoming increasingly thin, up to 1/100th the thickness of conventional crystalline silicon solar cells. (ECN, 2008b) Current research is aimed at determining the optimum structure of the solar cell. Another major research point is making the wafers stronger as waver breakage is a big problem.

4.2.2 Copper Indium di-Selenide/di-Sulfide solar cells (CIS)

CIS does not incorporate silicon. There are not many manufacturers of CIS solar cells yet as it was commercialised only recently. Many companies are upscaling their test installation into full production. Current research aims at increasing the conversion efficiency from 12% to 15%, determining the optimal composition of the solar cells, and switching from cell to module without high efficiency losses. (Powalla, 2008)

4.3 Third generation

The third generation solar cells is still in the R&D phase and consists of a large range of technologies in varying stages of development. We will focus on organic solar cells, in particular dye-sensitised solar cells and polymer ‘plastic’ solar cells, as they are the furthest in development.

4.3.1 Dye-sensitised solar cells (DSC)

DSC use chemical dyes to capture the light and convert it into electricity. DSC are very cheap to produce (20-30% of production costs of first generation solar cells). (Arakawa, 2008) The main problems now are long-term stability, and material sealing to prevent oxidation. DSC can be used flexibly and can be made in many different colours. Commercial production of DSC solar cells for consumer products started at the end of 2008. (Prent & Stroeks, 2008)

4.3.2 Polymer solar cells

Polymer solar cells consist of special plastic composites. This technology is in an early stage of development (ECN, 2008a) but research is progressing rapidly. Current research focuses on finding new materials, improving the structure of the cells, and resolving stability issues, to ensure sufficiently long lifetimes for practical use. (ECN, 2008a)

5. Functional analysis of Japanese PV innovation systems, per generation

5.1 First generation PV

Function 1: Entrepreneurial Activities

Crystalline silicon solar cells (c-Si) are produced by four Japanese companies: Mitsubishi Electric, Kyocera, Sharp and Hitachi. (RTS, 2008) As part of large groups they have capital available for research and production expansion. However the market is fairly established and highly competitive so no new entrepreneurs have entered.

Most likely due to the silicon shortage interest from the current companies appears to be waning. One company has decided to sell its activities (Hitachi) and one is focusing increasingly on its thin-film activities (Sharp). The remaining two companies (Mitsubishi Electric and Kyocera) show dedication and have announced production expansions of up to 3 times their current production volume to supply the growing international market. (RTS, 2008)

Function 2: Knowledge Development

The main organisations performing research into c-Si are: AIST, Mitsubishi Electric, Kyocera, Hitachi and Sharp Corp. (RTS, 2008) Japan has performed research into c-Si since 1974, when the government started the Sunshine Project[14]. Currently, most research is performed by the large companies, sometimes in collaboration with manufacturing equipment companies.

Sharp started mass-production in 1963. Since then, large cost reductions have been achieved (learning by doing). System price per kW dropped over 80% between 1993 and

[14] The nation's first national research program into solar energy.

2006. (Watanabe, 2007) As the main technology on the market c-Si has benefited a lot from the government's installation test projects, the Field Test Projects[15] (learning by using).

Function 3: Knowledge Diffusion through Networks

C-Si is a very mature technology, which makes the companies unwilling to cooperate. (Sharp, 2008) However collaborative research between research institutes, and between research institutes and companies, does exist. (NEDO, 2008) Also much information is exchanged through formalised exchange methods (meetings, conference, etc.). Most of this relates to patents or new products and production technologies.

Function 4: Guidance of the Search

An important source of guidance is the much cited document on the future of PV in Japan: the PV2030 Roadmap. This Roadmap was created by a committee consisting of representatives from government, industry and academia. (NEDO, 2004) According to the Roadmap, PV is expected to fulfil 50% of Japan's residential energy demand (approximately 10% of total energy consumption). (NEDO, 2004) The Roadmap's main goal is to lower the cost of PV to 7 yen/KWh by 2030. These cost goals are transformed into specific efficiency targets for each technological field.

C-Si has been used for a very long time and has gained a lot of credibility. Therefore, it is expected to remain an important type of solar cell in the industry, despite the current silicon shortage. (Sharp, 2008) However interest from entrepreneurs and researchers is shifting more and more to the second and third generation solar cells.

Function 5: Market Formation

The residential market for PV has increased enormously under the government's installation subsidy, the 'Residential Dissemination Programme' (1993-2005). It provided home owners with an installation subsidy that decreased as production costs decreased. Therefore, the price that home-owners had to pay for a PV installation has barely changed under the scheme. Since the end of the 'Residential Dissemination Programme' the Japanese have lost their position as the country with the largest installed capacity of solar cells in the world to

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[15] In the Field Test projects half the installation costs of innovative modules and/or systems is reimbursed in exchange for feedback from users including performance evaluation up to 4 years which is released to the public. [NEDO, 2007; Ikki & Matsubara, 2007]

Germany. (PVPS, 2007) Foreign markets like the German are becoming more and more important for Japanese manufacturers. (PVPS, 2007)

C-Si roughly has a 90% share of the total Japanese PV market. Though PV experts expect c-Si cells will remain the dominant PV technology in the coming years due to their high efficiency and proven reliability, it is expected to lose a large share of the market (some estimates go up to 50%) in the near future as other technologies will improve their efficiency.

Function 6: Resource Mobilisation

C-Si is investigated by large group companies that can bear the burden of R&D, as well as the training of new researchers. Many companies and research institutes are involved and therefore many specialists in the industry are available. The main problem lies in the silicon shortage which forces technical innovations and a move towards thinner technologies. Some factories are not producing at full capacity due to shortages, and getting a steady supply of silicon is one of the major challenges currently facing manufacturers. (AIST, 2008) However there are good prospects in this regard as the number of silicon manufacturers is increasing. It is expected that there will be a sufficient amount of silicon on the market around 2010. (Suntech/MSK, 2008)

Function 7: Support from advocacy coalitions

Government regularly receives input from actors like industry and academia through advisory committees. Working together to achieve a common goal is considered very important in Japan. (JPEA, 2008) The government's goals and policies in general are not top-down but are made together with industry and academia. While the guidance for PV research activities is strong there is a distinct lack of market guidance and support since the end of the Residential Dissemination Programme in 2005.

Virtuous and vicious feedback cycles

Until 2006, Japan was ranked top one in the world in terms of production volume. However, since then, crystalline silicon PV development in Japan has been slowed down due to a vicious cycle (see Figure 1). The silicon shortage has led to problems for entrepreneurs. This has pushed entrepreneurs away from this technology towards technologies that use less or no silicon. Even though the silicon supply is expected to increase within a few years, entrepreneurs that have already shifted are not expected to return as developments in the other types of solar cells are making them competitive with crystalline silicon solar cells. The relative decrease in production of crystalline silicon PV has led to reduced market shares prospects; combined with the highly competitive market there are less prospects for potential new entrepreneurs.

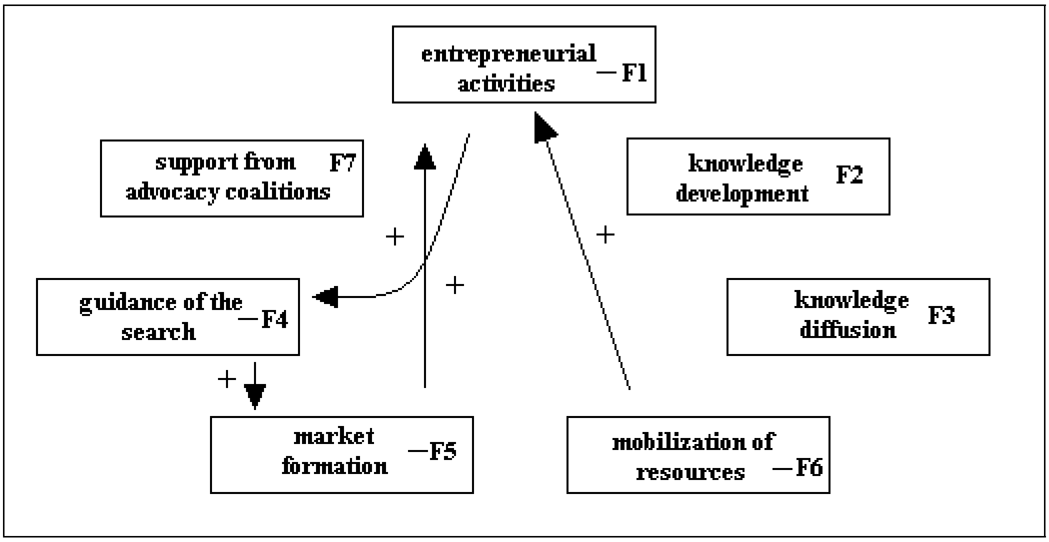

Figure 1: Crystalline silicon vicious cycle

5.2 Second generation PV

Function 1: Entrepreneurial Activities

Worldwide, many companies have started thin-film silicon (tf-Si) production due to the silicon shortage and the ease with which one can start. Thin-film solar cells use only 1/100th of the amount of silicon as the first generation PV. [ECN, 2008b] Furthermore, as tf-Si technology is very similar to LCD, it is easy for LCD companies, with their large consumer appliance business units, to move to the production of tf-Si solar cells. In Japan, several new companies have started production of thin-film silicon: Sanyo (1997), Mitsubishi Heavy Industries (MHI) (2002) and Fuji Electric Systems (2006). These companies are very active and many of them expect to put new multi-junction products on the market in the near future. [RTS, 2008]

There are only two *CIS* manufacturing companies in Japan; Showa Shell (2008) and Honda Soltec (2008). Matsushita was involved but has abandoned CIS development. [Prent & Stroeks, 2008]

Function 2: Knowledge Development

Of all PV technologies currently the most popular research field is thin-film PV. Research into thin-film started in 1977 and is still mainly basic research; however companies are switching from basic to applied research. Thin-film silicon solar cells have been in production for quite some time. Companies have gained a lot of experience in producing them (learning by doing). They also benefit from the Field Test Projects to test their solar cells and gain experience with usage (learning by using).

The *CIS* research community is fairly small. Only three universities participate in NEDO research (Kushiya, 2008). Only two companies are doing research into CIS: Honda and Showa Shell. Both these companies are fairly small and therefore limited in their research abilities. (Kushiya, 2008) There are also some problems with ‘learning by doing’. Although CIS shows great potential to achieve large cost-reductions (Iken, 2004), there are currently only few research institutes which can actually fabricate CIS cells. (Kushiya, 2008; Imoto, 2008) The most likely cause is the high cost of the required vacuum equipment. (Derbyshire, 2008) However the government aims to incorporate all research groups into large research centers. (Kushiya, 2008)

Function 3: Knowledge Diffusion through Networks

For tf-Si many collaborative efforts exist, especially between companies and research institutes. A network of institutions keep in touch in this field and exchange information. Academic conferences take place twice a year. (Kaneka, 2008) Here research results and patents are presented.

For CIS, knowledge exchange is difficult. The research groups are all very small and focus on different parts of the cell. (Kushiya, 2008) Research institutes and universities do collaborate. However the two companies producing and researching CIS have very little collaborative activities. Honda Soltec has developed their main product by themselves, the only major Japanese PV company to do so. (Tanaka, 2007) Showa Shell has been researching CIS the longest but does not collaborate with any other institute as it considers its own knowledge level too advanced. (Kushiya, 2008) Formalised exchange methods that specifically target CIS are limited too.

Function 4: Guidance of the Search

The industry sees great promise in tf-Si as efficiency improvements and cost reductions are expected and tf-Si has the benefit of lower module weight. Tf-Si is used in calculators and in TFT so there is confidence in the continued development of this type of cell.

CIS is not regarded as promising by the large companies like Sharp and Mitsubishi. This is most likely a combination of three factors: high R&D costs (Kushiya 2008), concerns about the Indium supply which is making those currently dealing with a silicon shortage nervous (Smets, 2008), and the expected increase in silicon production by 2009-2010 making the need to develop a technology which differs from the tried-and-tested semi-conductor technologies not so urgent.

Function 5: Market Formation

Tf-Si is drastically increasing its market share. However due to the lower efficiency than crystalline silicon, manufacturers are aiming at specific applications, mainly building integrated PV[16]. Fuji Sun Energy created a lightweight flexible solar cell which can be integrated into non-straight roofing material, or even tent-cloth.

CIS is competing directly with crystalline silicon in that they are aiming at standard rooftop applications. However the highly competitive market makes it difficult to enter and compete with the silicon-based technologies. CIS holds no clear advantage yet over crystalline regarding pricing and efficiency. However there is currently only a limited supply of CIS PV modules in the world wide so it could be considered a status symbol. (Kushiya, 2008)

Function 6: Resource Mobilisation

Tf-Si does not have problems in mobilising resources, as a lot of large companies are involved.

With the small research and production base the number of CIS experts in Japan is limited. However since companies and universities train new employees themselves this is not an issue. (Kushiya, 2008) The main problem for CIS manufacturers lies in ensuring a sufficient Indium supply. The companies appear confident this will not form a problem however if many companies suddenly start CIS production it will still become an issue.

[16] Solar cells integrating into buildings or building materials e.g. windows, roof tiles, walls, etc.

Function 7: Support from advocacy coalitions

Government regularly receives input from actors like industry and academia through advisory committees.

Virtuous and vicious feedback cycles

A virtuous cycle was found for the development of thin film silicon solar cells (see Figure 2). The silicon shortage has increased attention for tf-Si. The overlap with other technologies like LCD benefits its further development and allows new players to enter production and research fairly easily. The large Japanese market has attracted several new thin-film silicon solar cell manufacturers.

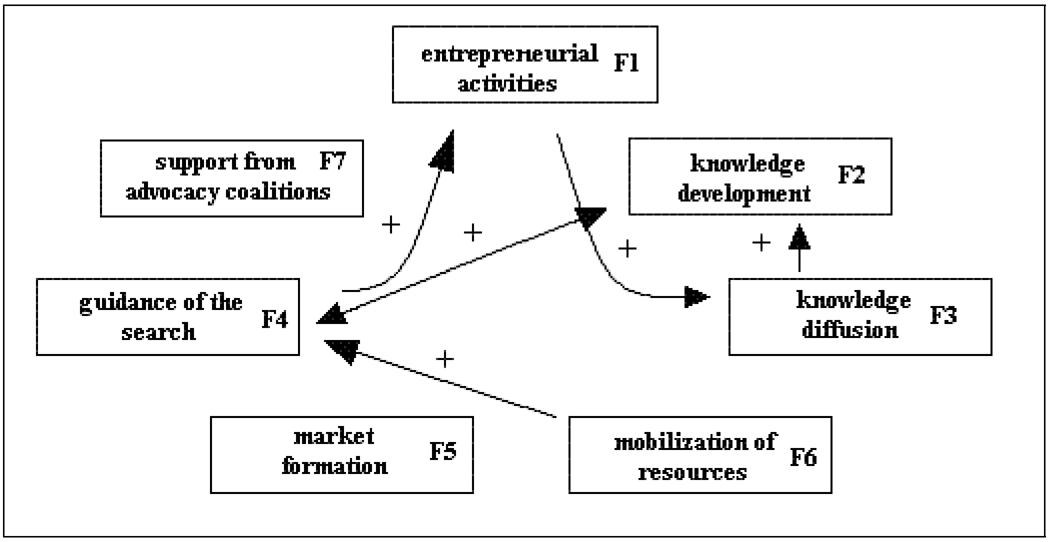

Figure 2: Thin-film silicon virtuous cycle

We can find a vicious cycle for CIS where the small scattered research community does not allow good knowledge diffusion (see Figure 3). This causes problems with the perception of the technology and scares off potential new entrepreneurs. However there are some good prospects as the small research groups are expected to be combined into larger groups which should facilitate knowledge creation and diffusion.

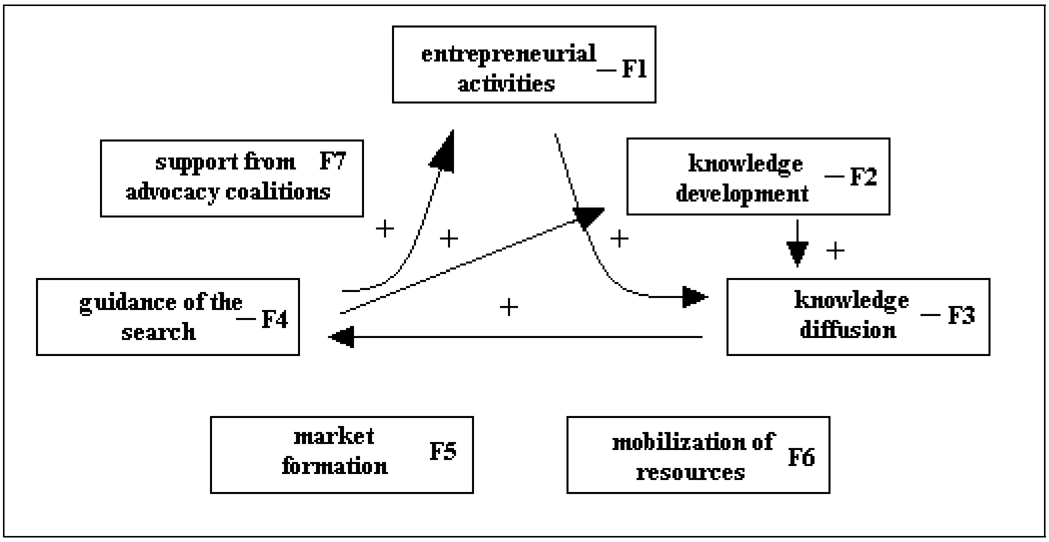

Figure 3: CIS vicious cycle

5.3 Third generation PV

Function 1: Entrepreneurial Activities

A large variety of companies is involved in the production and development of organic solar cells. These include both small companies such as Chemicrea Inc. (chemical company), and large companies such as: Sharp Corp., Fujikura, Nippon Sheet Glass Co., Nippon Steel Chemical Co., Ltd., Toyo Seikan Kaisha, Ltd. (container and package company), Koa Corp. (electronic parts manufacturer), and Hodogaya Chemical Co., Ltd. (NEDO, 2008) Many companies new to the solar cell industry are involved, as this involves a different type of industry; chemical, instead of the electronic appliances sector of the first generation. (Arakawa, 2008) Three to four years ago about 50 companies were involved in DSC research. However some have left since their research was not successful. Others have successfully adapted and continue R&D. (Yoshikawa, 2008) Companies attached to large groups have an established knowledge base which is necessary in order to perform the research. (Yoshikawa, 2008; JPEA, 2008)

Function 2: Knowledge Development

Many research institutes are involved in research into organic solar cells. Since the main problems with organic cells concern their stability, power applications which require long term stability (15-20 years for rooftops) will require much research. (Arakawa, 2008) Many scientists work on improving the efficiency of organic solar cells, however the cells are not yet in full scale production. (JPEA, 2008) DSC solar cells can easily be made. Therefore, production experience can easily be gained to improve the production process (learning by doing).

Function 3: Knowledge Diffusion through Networks

Many companies and research institutes are involved in organic solar cell research and are collaborating quite heavily. Some small companies have grouped together to start research into polymers and some small companies collaborate with universities. (Yoshikawa, 2008) However knowledge exchange will become more difficult in the near future, especially for DSC as it gets further towards commercialisation. (Yoshikawa, 2008) A special group for organics meets once every 3 months and exchanges research information. The conferences are a major source of information. Also there are journals such as 'Solar Energy and Materials' though none are specialised for organic solar cells. For polymers there are conferences and related journals such as 'Electronic Devices', which also discuss DSC. (Yoshikawa, 2008)

Function 4: Guidance of the Search

There is mixed confidence in organic solar cells for use in power applications. In general it is expected that it will take about ten years before they are ready for long-term applications. (Arakawa, 2008) Organic cells are fairly unstable as the materials oxidise in air and therefore require some advanced lamination technology. They also have a very short lifespan. For these reasons some believe they might never be able to be used in power applications. (Smets, 2008)

Function 5: Market Formation

The main advantages of organic solar cells are the potentially low production costs, high efficiency and diversity in colour. In general, many consumer applications are possible for DSC and worldwide many companies are planning innovative DSC products. However the focus of the Japanese government and thereby the research in Japan is on rooftop applications. Therefore, companies will most likely not receive much governmental aid for R&D into consumer applications. As such, PV manufacturers doubt what to do with organic solar cells right now. Sharp "still needs to decide a final application as the market is very uncertain at the moment. A power plant is our final application but we are also considering other applications. We can't set a date yet for market introduction." (Sharp, 2008)

Function 6: Resource Mobilisation

The organic research field is large; there are a large number of research groups and companies involved. As such we can assume there is enough human capital present. The problem apparently lies with access to financial capital. Many small companies have reportedly stopped due to financial difficulties in researching and developing a new product. They are mainly dependent on NEDO research projects for financing. (Arakawa, 2008)

Function 7: Support from advocacy coalitions

Government regularly receives input from actors in industry and academia through advisory committees.

Virtuous and vicious feedback cycles

A virtuous cycle was found for organic solar cell development (see Figure 4). Organic solar cells show a lot of potential to achieve the target of grid parity through the reduction of production cost. This mobilises resources for R&D. Most of the research is only in the basic research stage which is the field of academic research. As such its inclusion in the PV 2030 Roadmap is an important factor stimulating development of the technology though it is still far from power-type applications. The combination of a new technological field and ease-of-production is what has attracted many companies and research institutes to this type of solar cell. Collaboration between companies is common place, to share the costs of research and development and lobby for government support.

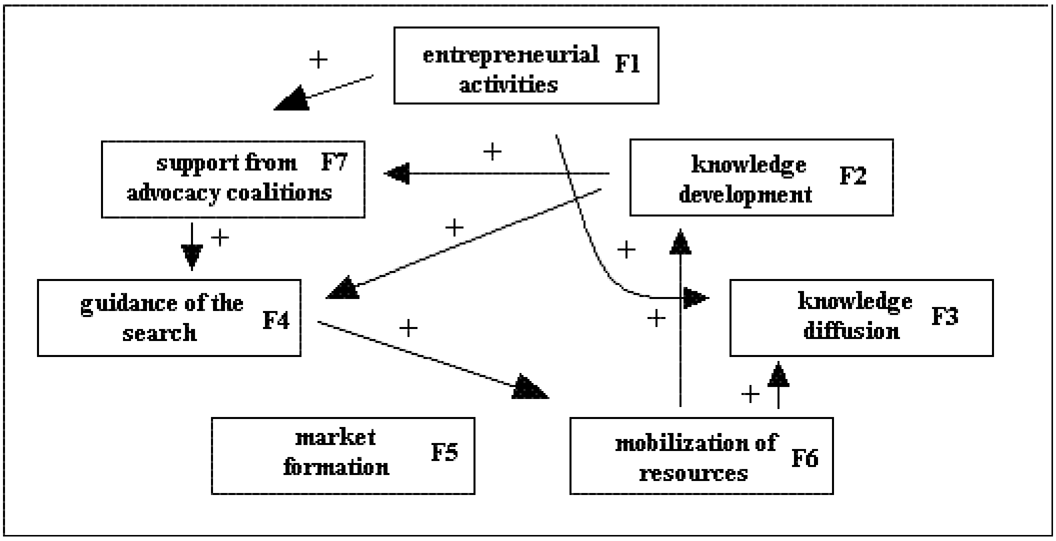

Figure 4: Organic solar cells virtuous cycle

5. Conclusion and discussion

The research question of this paper was:

How do the innovation systems for first, second and third generation PV in Japan function, and to what extent do these innovation systems compete?

We will answer the two parts of this question in the following two sections.

5.1 The functioning of the innovation systems for the three generations of PV in Japan

The case study has revealed large differences in the functioning of the innovation systems for the three generations of PV in Japan. The first generation – crystalline silicon solar cells – has thrived for decades. Japan has developed a large industry and a large installed capacity of PV. Until 2006, Japan was number one ranked in production volume. However, this positive situation has slowed down since 2006. Now, a vicious cycle appears, triggered by silicon shortages and the abandonment of market subsidies. These have pushed entrepreneurs away to other technologies that use no or less silicon and/or to markets outside Japan, like Germany.

The second generation solar cells shows both a virtuous and a vicious cycle. Thin film silicon PV prospers from a virtuous cycle. Entrepreneurial activities are increasing because companies make the step from first generation PV or from the LCD industry to second generation PV. The technology shows great promise because it uses less silicon and worldwide markets are growing. Also a lot of knowledge is exchanged by all actors involved, which is guided by the Roadmap from the Japanese government. The other second generation solar cell technology, CIS, is locked into a vicious cycle of high investment costs, small groups of actors involved and little knowledge exchange.

Third generation solar cells find themselves in a virtuous cycle of high expectations, large R&D investments, and knowledge exchange. The end goal for this generation of PV is to contribute to electricity production, but currently developers aim at consumer appliances.

5.2 Competition between the three generations of PV in Japan

The three generations of PV in Japan can compete for three types of resources: physical resources, human resources and financial resources. Financial resources can come from companies, from government or other policy bodies and from the market.

Competition for physical resources is an important factor in the different functioning of the TIS. The current silicon shortage poses a problem for first generation PV (crystalline silicon) producers. These entrepreneurs have to compete for the scarce silicon resources with producers of thin film PV who are rapidly expanding their production activities, and with computer chip manufacturers. Also indium, which is used in the production of second generation CIS solar cells, is a scarce resource.

Human resources do not appear to be a big source of competition. The three generations of PV are all produced with different production processes that ask for different types of knowledge and know-how. Therefore, human resources cannot easily make the switch from one generation of PV to another.

Financial resources are an important factor. Not so much investments from companies, however as these are fairly separated. Each PV generation requires totally different production processes and knowledge bases. Second generation PV entrepreneurs, both thin film and CIS, only focus on thin film or CIS respectively, with their specific production processes. LCD companies do make the step to thin film PV, because they use a very similar production process. Third generation PV attracts still another type of entrepreneurs, mainly from the organic chemistry industry. What does take place is the ousting of first generation crystalline silicon PV by second and third generation. Sharp is involved in all generations, except for CIS, and has largely made the step from first generation PV production to thin film PV production. Hitachi was producing first generation PV but has totally stopped its PV production (although it is involved in third generation PV R&D on a very small scale). Mitsubishi is involved in both first and second generation PV but divides this over two different subsidiaries: Mitsubishi Electric (first generation) en Mitsubishi Heavy Industries (second generation).

Financial resources from the government and other subsidy providers form a different story. Here competition definitively takes place. Within the Roadmap, different goals are set for each PV technology. Also R&D subsidies are allocated per technology, although it is very unclear how the budgets per technology are determined. Market subsidies are for renewable energy or for PV in general, so here the different generations have to compete for the subsidies.

The three generations of PV also have to compete for financial resources from market parties. They largely aim at the same market – both first and second generation PV aim at electricity production, mainly on rooftops. This market is highly competitive and first generation PV still holds the advantage regarding price and efficiency. Second generation CIS clearly looks different – black instead of blue – and therefore CIS entrepreneurs compete in this highly competitive market by putting CIS on the market as a status symbol. Second generation thin film PV aims at specific applications like building-integrated PV, non-straight roofing material or even tent cloth. Third generation solar cells – organic PV – ultimately aims at the electricity market too, but for now focuses on the market of consumer appliances. Here the competition is less fierce.

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