Comparing innovation systems for solar photovoltaics in the United Kingdom and in China

N. Marigo, T.J. Foxon, P.J. Pearson

Imperial Centre for Energy Policy and Technology (ICEPT)
Postal address: Centre for Environmental Policy, Imperial College London,
South Kensington Campus, London, SW7 2AZ, UK
Telephone: +44 (0)20 7594 9306 Fax: +44 (0)20 7594 9334 Email: nicoletta.marigo@imperial.ac.uk

Abstract

Innovation in renewable energy sources (RES), such as solar photovoltaics (PV), can play an important part in CO_2 reductions for climate change mitigation, as well as contributing to economic development. With a production capacity growing by more than 70% per year over the last 7 years, China is rapidly emerging as an important player in the global PV market, with significant levels of exports to Western European countries. The country's low labour cost combined with the potentially huge internal market should enable it to contribute to technology learning processes, driving down costs and increasing market diffusion. By comparison, though the UK aims to show global leadership in climate change policy, e.g. by setting a legally binding target to reduce CO_2 emissions by 60% by 2050, it has been slow in developing either production capacity or markets for PV technology.

By adopting a national innovation systems framework of analysis, the paper identifies the different technological and institutional actors and relations of the innovation systems for PV in the UK and in China, and assesses the extent to which these are likely to encourage or constrain the technological development and the market diffusion of this technology in the two countries.

This novel effort to compare and contrast the innovation systems in the two countries combines information collected in both the UK and China and interviews with a sample of key actors in the PV sector. The comparison of the two countries' innovation systems both unveils striking differences from which valuable policy lessons can be derived for the management of innovation in the energy sector and helps understanding of how such innovation could contribute to economic development.

Introduction

This paper compares and contrasts the innovation systems for solar photovoltaic (PV) in the UK and in China, in order to see what lessons and insights might be gained from this analysis.

Innovation in renewable energy sources (RES), such as PV, could play an important part in CO_2 reductions for climate change mitigation, as well as contributing to economic development through the provision of valuable energy services and the creation of employment opportunities. Although several policies can be used to encourage the market diffusion of RES (Menanteau et al. 2003; Reiche and Bechberger, 2004), we suggest that better understanding is needed of the innovation process involved in these new technological systems.

Table 1 summarises the development (MW produced) and the diffusion (represented by MW installed) path of solar PV in China and in the UK. Data are provided for two points in time:

- early 1990s, when global PV was in a pre-commercial maturity phase and had a diffusion limited to niche markets such as space applications or off-grid stand-alone systems.

- 2005, when PV has entered a rapidly growing commercial phase supported by the incentives of many governments in Europe but also in Japan and the USA (Maycock 2004).

Table 1 Development and diffusion of solar PV in China and the UK

	MWp installed ***(cumulated)***		**MW produced** ***(modules)***	
	1992	*2005*	*1990*	*2005*
United Kingdom	0.2	10.9	1.2*	3.5
China	3	70	0.5	1850

Source: for China: Renewable Energy Development Program (REDP) (2004); Zhao, 2005. For the UK: Digest of United Kingdom Energy Statistics (2006).

* data refer to the production of Intersolar in 1997

Two observations can be made:

a. When compared to Germany, that in 2005 had a cumulated installed capacity of 1500MW (DENA, 2007), both China and the UK have been slow in diffusing PV despite the huge market potential of the former in both off- and on-grid applications and an ongoing public support for RES market development (Mitchell and Connor, 2004) coupled with a recent commitment to reduce CO_2 emissions by 60% by 2050 (Tempest, 2007) in the latter.

b. China has been particularly successful in the technological development and in establishing a strong industrial base for cell and module production with capacity growing by more than 70% per year over the last 7 years (Zhao, 2005). By contrast, the UK has made very little progress in manufacturing through time: there is only one small company (former Itersolar bought in 2003 by the Canadian ICP Solar) that produces 3.5 MW of thin-film amorphous modules[1].

This spurs some key questions that need to be addressed to better understand the present and future development of PV as well as to get insights into how new technological systems develop and diffuse in different economic contexts:

i. What factors are critical for the emergence, development and diffusion in the market of PV technology and how do they differ in the two different economic contexts?

ii. What is the role of knowledge (understood both as basic R&D in universities and in-house R&D in firms) in the innovation process and to what extent could differences in the R&D effort explain success or failure in PV in the two countries?

iii. What are the respective roles of government and market forces in promoting technological development and market diffusion?

To answer the previous questions the paper adopts a national innovation system (NIS) framework, which several authors have used to enhance understanding of the development and diffusion of RES in the UK and in other European countries (Foxon

[1] In 2004 Sharp – the world's largest PV manufacturers – opened a 20 MW assembly plant in Wrexham (but this is assembly, not production). In the upstream, Crystalox produces multi-crystalline silicon ingots.

et al., 2005; Jacobsson and Bergek, 2004; Jacobsson et al. 2004)[2]. Moreover, several scholars have used NIS as a framework for studying technological development and innovative capacity in developing countries, like China (Liu and White, 2001; Gu and Steinmueller, 1997).

The purpose of this exercise is: firstly to contribute to the current RES debate by adopting a systemic view to enhance understanding of how innovation for solar PV works. Second, by comparing and contrasting two economic contexts at a different level of maturity: China and the UK, useful insights into their technological and market efforts for PV can be provided. This appears to be particularly relevant in the case of China that, as a developing country, tends not to be associated with active technological development and innovation. Third, to derive policy recommendations for an improved development and diffusion of PV on the market.

The paper is organised as follows. Section 2 contains an overview of PV to provide a background on a rapidly growing economic sector and to the technology. Section 3 provides a brief introduction to the NIS approach and how it was applied to this study. Some methodological notes are also discussed in this section. Sections 4 and 5 present the main findings for China and the UK on innovation systems for PV. Section 6 compares and contrasts the findings for the two countries while section 7 discusses some emerging issues and put forward some policy recommendations.

PV market development and the technology

In the last five years PV has been one of the fastest-growing technological sectors in the world[3]. The most important market drivers behind this rapid growth have been public programmes to stimulate on-grid installed capacity in domestic markets, especially in Japan and Germany and, more recently, also in the US with the California Solar Initiative (California Public Utilities Commission, 2007).

A recently published study (Greenpeace and EPIA, 2006) highlights the contribution PV could make to future global electricity supply, climate change mitigation and employment. The study suggests that in twenty years' time enough solar power could be produced to satisfy the electricity needs of 20% of the entire EU-25[4]. This would imply a 353 million tonne reduction in CO_2 emissions, equivalent to the emissions of both Australia and New Zealand combined. On the supply side PV module shipments have been forecast to increase by a factor of 40 by 2025 and more than 3.2 millions jobs might be created along the PV value chain around the world (Greenpeace and EPIA, 2006).[5]

On the technological front, PV is associated with the high technology end of RE technologies. It can be divided into three main technological families:

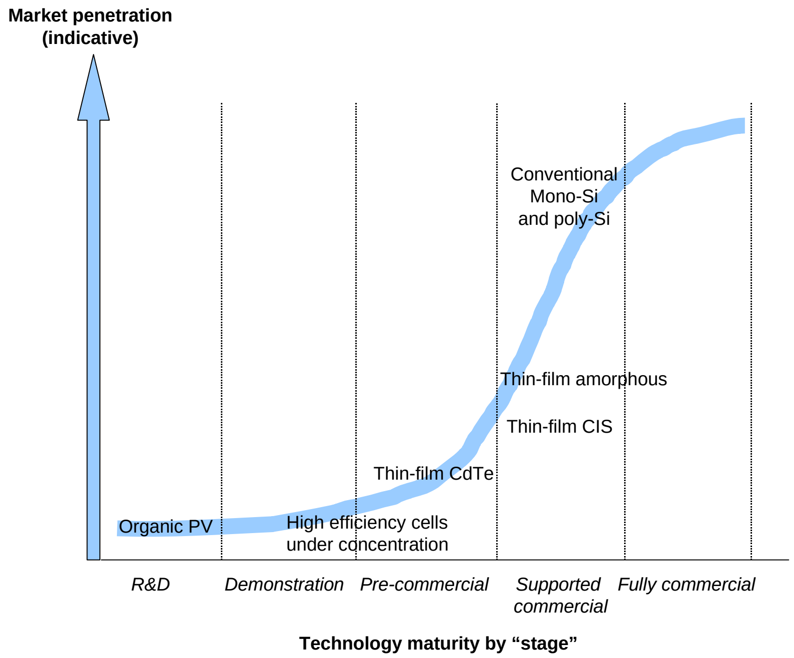
1. Conventional crystalline silicon wafer-based solar cells

[2] Jacobsson and colleagues have used a technological innovation system perspective, which is built around a specific technology rather than a country's national borders.
[3] Global demand for solar energy has grown at about 25% per annum over the past 15 years (Solarbuzz, 2007) while supply of PV cells and modules has been growing at an annual average rate of more than 35% over the past few years (Greenpeace/EPIA, 2006).
[4] Provide a number of conditions are met, such as the continuation of the existent (or the establishment of new) national and regional market support programs, …
[5] The largest employment opportunities are expected in the installation and marketing of PV systems (Greenpeace and EPIA, 2006).

2. Thin-film solar cells
3. New concepts, which include: thin-film high-efficiency solar cells under concentration and organic PV

More than nine tenths of the solar cells that are currently sold on the world market are based on crystalline silicon wafers while the rest is for thin-film solar cells[6] (Solarbuzz, 2007). Figure 1 employs a S-curve of technology adoption to illustrate the maturity and the market penetration of the different PV technologies. As shown in the picture, the different PV technologies differ greatly in terms of technological maturity and diffusion in the market, with several technologies being at the R&D and demonstration stages while others are at a pre-commercial stage. These differences in technological maturity are important factors to bear in mind when designing policy support to foster PV development. These policy implications will be discussed in more details in the final part of this paper.

Figure 1 The technological maturity of different PV technology families relative to market penetration



Source: Adapted from Foxon et at., 2005.

The national innovation systems approach, its application to this study and few notes on the methodology

This study shares the view that innovation proceeds through stages, from basic R&D to commercialisation, in a non-linear fashion where constant interactions between different agents (more details are given below) contribute in shaping and delivering innovation (Lundvall, 1992; Freeman and Soete, 1997).

[6] Several materials can be used for thin-film including amorphous silicon, copper-indium-diselenide (CIS) and cadmium telluride (CaTe), although thin-film cells based on CaTe are still in the pre-commercial phase.

In order to understand innovation better and to compare and contrast innovation in solar PV in China and in the UK, this study employs a national innovation systems (NIS) framework.

NIS is a conceptual device that focuses on the conditions that facilitate or hinder the generation and diffusion of innovation in a given economy. Different NIS differ in terms of economic structure and institutional set-up (Nelson, 1993). Central to NIS is the concept of *system* where different agents interact and influence each other to carry out the innovative activity. Innovation is delivered by a network of actors that include:

- those involved in creating and/or sharing knowledge (universities, research institutes, firms/technology developers),
- those disseminating and using the commercial products (project developers and end-users)
- those setting the framework conditions (government bodies, research funders, financial investors) (categories are taken from ICEPT and E4Tech, 2003).

By adopting a NIS framework this study:

a. identifies the key actors of solar PV in China and in the UK to understand the role they play in the emergence, development and diffusion in the market of PV.
b. Studies the interactions between the key actors to understand how these are affecting the functioning of the system.
c. Provides PV innovation maps for the two countries to offer an easy-to-refer-to overview of the system.
d. Analyses the innovation system in terms of three key issues[7]:
    - Primary determinants or drivers of innovation within the sector;
    - Knowledge creation, diffusion and exploitation;
    - Role of government and market forces in promoting technological development and market diffusion

The study combines information collected in both the UK and in China between 2003 and 2005. The evidence for the UK, based on a broader study (ICEPT and E4tech, 2003) of RE innovation systems undertaken for the UK Department of Trade and Industry (DTI) between March and June 2003, was collected through expert workshops and a series of semi-structured interviews with key actors from the RES industry (including PV), policy makers and the academic community.

Evidence for China was collected via fieldwork in the country from May to July 2005 while interviewing senior figures among the major Chinese wafer, cell and module manufacturers, along with policy makers involved in RES promotion and solar energy R&D representatives (Marigo, 2007).

China innovations systems for PV

With growing production capacity, China is an emerging player in the global solar PV industry (see Table 1). The innovation system for PV is mainly focused around conventional crystalline silicon technologies (both mono-Si and poly-Si) (see Figure 1).

[7] A richer analysis of the innovation system along six key issues was performed in the case of RES development in the UK (ICEPT and E4Tech, 2003).

R&D into solar PV in China started in the late 1950s under the close supervision of the central government (Dai and Shi, 1999). Today there are 30 research institutes and universities working in the development of the materials used in PV cells and in the accompanying manufacturing process (Zhao, 2001). The main focus is on wafer-based solar cells[8] but several institutes and universities are also active in research for thin-film solar cells (Yang et al., 2003; Zhao, 2001). There is no R&D underway in high-efficiency solar cells under concentration and organic PV.

On the technology development side, manufacturing of silicon cells started in the late 1970s/early 1980s with the establishment of five state-owned firms[9], one of which was a spin out from a research institute in Beijing (Dai and Shi, 1999). Domestic production is today present along the whole value chain of the crystalline silicon technology: from wafers, cells and modules production to PV system installation[10]. Domestic manufacturers of PV process equipment are also gradually emerging although key components along the production line are mainly sourced from mature economies in Europe or the USA.

A number of companies are responsible for PV system design, technology R&D, system integration, component manufacturing, sales and after-sales service. Some of them have been involved in key government programs for rural electrification (Ma, 2004a).

Industry networks tend to be strong especially between solar wafers and cell producers and their suppliers of silicon (mainly international) on the one hand and their domestic suppliers of PV process equipment on the other. These relationships proved to have a strategic importance in securing silicon in the presence of a severe silicon feedstock shortage and in obtaining customised PV process equipment at prices cheaper than those offered by foreign companies for standard PV process equipment.

In-house R&D, with firms devoting to it on average a tenth of their annual turnover, plays a key role in enhancing the technological capabilities and the competitiveness of firms (Marigo, 2007). Firms also tend to have links with universities and research institutes.

On the institutional front NDRC (the National Development Reform Commission) is the key body for policy promotion and has supported PV[11] (and indeed other RES like wind and small hydro) by subsidizing the capital cost of the equipment in remote rural areas in Western China. Provincial institutions that have been sharing the cost of capital grants for rural installations with NDRC (Ma, 2004) also influence the sector.

There are also a number of facilitating institutions whose role is to finance projects or to act as consultants/technical experts for project installations. These include the GEF, the World Bank, the UNDP and IT Power (UK).

Several energy institutes together with international (i.e.: Deutsche Gesellschaft für Technische Zusammenarbeit - GTZ) and local agencies are active in developing and implementing training programs for national and local level engineers and technicians.

---

[8] A particular emphasis is on high efficiency single-crystalline silicon solar cells (Zhao, 2001).

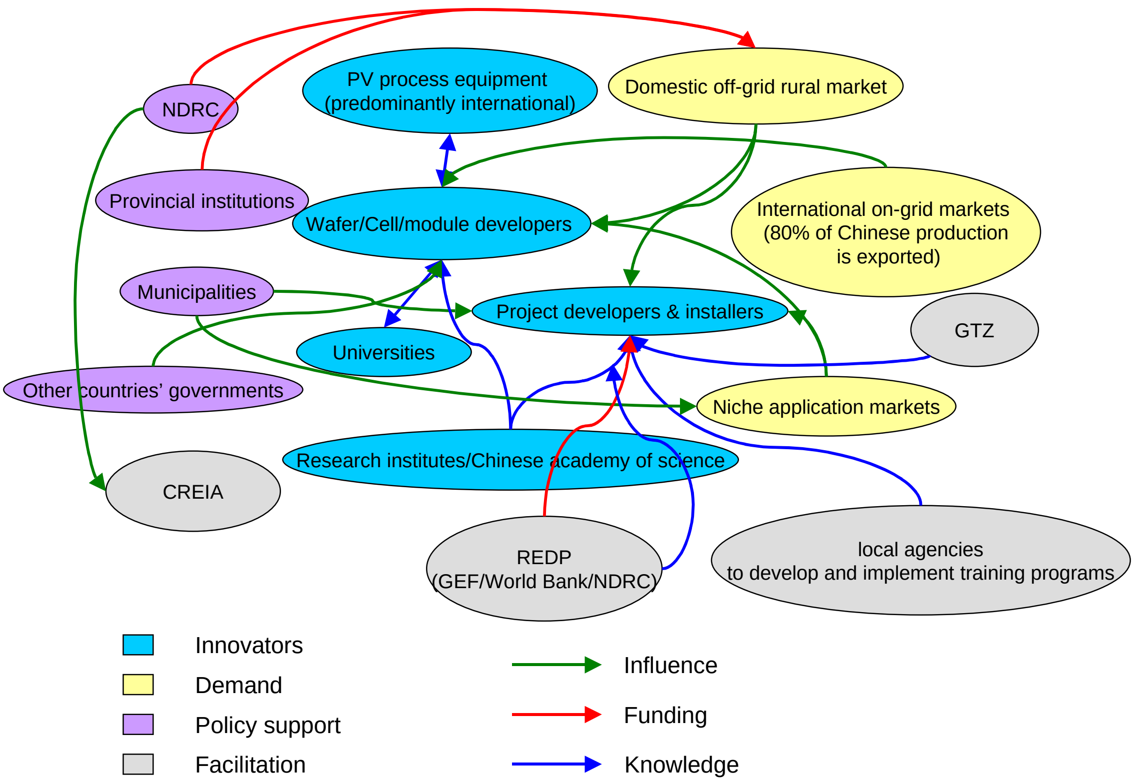
[9] In the same period a sixth firm emerged producing amorphous silicon solar cells.

[10] Production capacity is mainly concentrated in module production but new domestic actors are emerging in the higher value added sectors of the production chain (i.e.: wafer and cell production).

[11] The two main programs targeting rural electrification and aiming at RES market diffusion are the "Township electrification program" (2002-2004) and the "Village electrification program" (2006-2010).

Figure 2 presents an overview of the Chinese PV innovation system and of the systemic influences between the different actors.

Figure 2 The innovation system for PV in China



Source: adapted for Foxon et al. 2005

Although the internal market created by a massive government rural electrification program has been instrumental to the development of a few firms, especially the ones involved in the production of balance of system components, by far the most important innovation drivers are the export markets in Europe and in the USA, where highly subsidised installed capacity is providing Chinese firms with a strong innovation incentive.

UK innovations systems for PV

The UK is a small player in the fast growing PV economic sector both in terms of installed and (especially) production capacity (see Table 1).

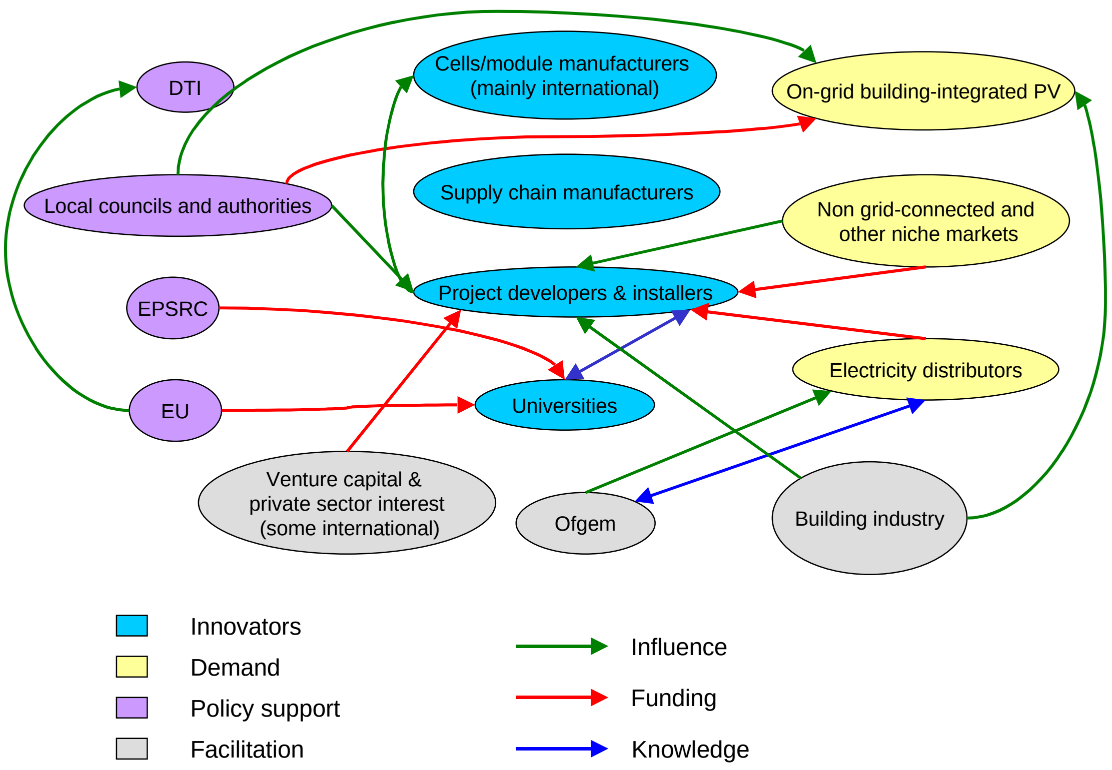
Industrial representation along the production value chain is highly fragmented with only one company producing crystalline silicon ingots and one producing thin-film amorphous modules. Several installers and system developers exist and are strongly focused on applications for the internal market where they are gaining technical expertise in PV building integrated (Earthscan 2006).

Such a fragmented industrial picture has not facilitated industrial networks, that remain weak (ICEPT and E4Tech, 2003).

There is world leading research in the UK with a wide range of skills and interests Several universities are active in R&D with a main focus on non conventional PV such as thin film technologies, high efficiency cells under concentration and organic PV (Table 1). Unfortunately, the UK research community is highly fragmented and few groups can claim to have reached critical mass (Infield, 2007).

R&D financing for universities is modest (Infield, 2007) and is largely sponsored by governmental programs (EPSRC) or by the EU, which has played a role in financing R&D for high-efficiency solar cells under concentration within the 6th framework program (i.e.: Full spectrum integrated project).

Figure 3 The UK innovation system for both conventional and novel PV



Source: adapted from Foxon et al. 2005

The absence of a strong manufacturing base and the relevance of R&D, make the UK PV innovation system highly oriented towards the national dimension. Both the research community and the system installers crucially depend on public funding and government's policies for market creation.

The prime driver behind the UK PV industry is the Department of Trade and Industry (DTI), with the promotion of capital grant schemes for the installation of PV systems. The sector is also affected by local councils and authorities that have the ability to mandate required quantities of RES in buildings. The EU, with the promotion of the Directive 2001/77/EC for electricity generation from RES, have an influence on UK national institutions and in particular on Ofgem that, in turn, can force network operators and suppliers to allow small distributed generators to connect to the grid (ICEPT and E4Tech, 2003).

Comparing and contrasting the PV innovation system in the UK and in China

Some interesting differences emerge in comparing the two innovation systems

Research vs industry

A first notable difference is the relative importance given to research and industrial production in the two countries. The UK has a strong research vocation with more than 20 universities working on several aspects of PV and with a wide range of skills and interests. Unfortunately, this strong science base has not been translated into commercial technologies as has been the case in other countries (including China) where PV manufacturers grew out of research institutes or universities[12] (Infield, 2007).

A number of factors explain this failure to move PV technologies from the R&D to the commercial stage:

1. The limited financing enjoyed by the UK R&D and first demonstration PV projects have hindered the scaling up to the next pre-commercial and supported commercial stages (Foxon et al, 2005).
2. The incentives offered by generic measures, such as the Renewables Obligation with its emphasis on quantitative targets, tend to promote those technologies that are already close to commercial maturity and cheaper to produce (i.e.: wind energy) but fail to attract investment into technologies that are in the early stages of development (i.e. PV) and that involve high risk and high costs (Helby, 2005; Foxon et al. 2005; Mitchell and Connor, 2004).
3. The UK research community is highly fragmented and few groups can claim to have reached critical mass. The lack of well focused research laboratories might have been responsible for the difficulties in mobilising financial resources and in legitimating PV, which is still perceived in the UK as a technology that only works in hot countries (Earthscan, 2006).

By contrast, the innovation system in China is largely commercially oriented with an industrial representation growing fast along all the steps of the value chain.

China's propensity towards industrial production dates back to the late 1970s/early 1980s when the strategic importance of PV for both space and terrestrial applications prompted the central government to establish a domestic industry by converting few semiconductors plants into solar cell and module production lines. Although only one of the six early established production lines still exists, this central government directed PV R&D and production were the starting point of the PV innovation system in China. A number of new silicon solar cell and module producers have emerged since the dismantling of the centrally planned economy and are rapidly expanding their production capacity. A number of factors have made this industrial dynamism possible:

- New entrepreneurs had built up their expertise over many years of research both domestically and abroad - and for production can count on the existing domestic knowledge.

[12] This has been for instance the case in Norway (Christinasen and Buen, 2002) and in Germany (Jacobsson et al., 2004)

- The government has set up a special innovation fund for SMEs and has provided seed capital for the establishment of some new cell and module plants.

Domestic market vs export

A second important distinction between the two innovation systems is the strong focus of the UK on the domestic market and a high propensity to export of China.

Although the UK research community draws upon a global community of researchers and ideas (ICEPT and E4Tech, 2003), it remains highly dependent on the national research councils (i.e.: EPSRC) for funding. Similarly, the fragmented representation of the UK companies in the PV industry with prevalence in the system development and installation areas, implies a strong focus on the domestic market and a dependence on specific government programmes to support PV[13].

China's research base and downstream industry similarly have a strong domestic focus but the manufacturing industry is heavily export oriented. 80% of Chinese cells and module production is exported to Europe and the USA because the internal market does not offer highly profitable market opportunities. It is interesting to note that if the government had a key role in the initial phases of PV development, it is now playing a much less active role. It has promoted rural electrification programs that have had only a limited impact on the domestic industry, but it is unwilling, at least for the time being, to provide a long term policy framework that could provide market opportunities and gain the domestic producers' confidence (Marigo, 2007).

In this way, the Chinese cell and module producers are relying on the high subsidies paid by the German and other European electricity consumers to increase PV installed capacity in their countries.

Similar system failures seem to have different impact in the two countries

The system failures that seem to hinder the development of PV in one country do not seem to be an obstacle in the other country.

In the case of the UK, a fragmentation of the research community and of the production has implied difficulties in legitimating the technology and in influencing the regulatory framework that affects PV. This, in turn, has resulted in limited policy support for PV technological development and market diffusion.

In China, a weak legitimacy of PV, to which other RES (i.e. wind and biomass) have been preferred during policy implementation and limited policy measures have not prevented a strong industrial base from emerging and to directing its attention to export markets.

Differences in the R&D effort

The UK is intensifying its R&D effort in the avant-garde of PV technologies (such as organic PV and high efficiency solar cells under concentration) that are still in the early phases of development (see Figure 1) but that show promising prospects for future development and diffusion. In this way a variety of design approaches are sustained in recognition of the nearly full maturity of conventional silicon

[13] It is for instance the case of the Major Demonstration Programme that offers grants to promote the use of PV in large projects and in small household applications.

technologies and of the great uncertainties over the performance and cost reduction potentials of different competing designs.

Although China is undertaking research in thin-film technologies that are currently in the pre-commercial phase of development, the R&D effort of both research institutes/universities and firms seems to be driven by the immediate need of the technology that is currently dominating the market: crystalline silicon.

Final discussion and policy implications

This paper, in aiming to compare and contrast the innovation systems for solar PV in the UK and in China, put forward at the beginning a set of key questions:

1. What factors are critical for the emergence, development and diffusion in the market of PV technology and how they differ in the two different economic contexts?
2. What is the role of knowledge (understood both as basic R&D in universities and in-house R&D in firms) in the innovation process and to what extent differences in the R&D effort could explain success or failure in PV in the two countries?
3. What are the respective roles of government and market forces in promoting technological development and market diffusion?

The analysis has shown that two issues are particularly relevant in the formation and diffusion of this technology:

a. *The role of R&D*

   R&D has played a key role in the initial phases of the technology's establishment in both the countries. However, while China's decision (under the central government close direction and supervision) to move from R&D to production in the late 1970s marked the beginning of the PV innovation system in that country, the UK failure to move technologies along the innovation chain (Foxon et al., 2004) has ended in a fragmented innovation system where the different actors do not co-operate to achieve a larger PV development and diffusion.

   R&D is also essential in the subsequent phases of the innovation process. The in-house R&D of the Chinese cell and module producers shows the relevance of this effort in enhancing technological capabilities and competitiveness of firms (Marigo, 2007).

b. *The role of policies*

   Policies are crucial in different moments of the technological development and market diffusion and can determine the failure or the success of an innovation system.

   Although not much PV has been installed in China (at least when compared to Germany or when considering the strong motivation China would have to promote a larger share of PV to meet its growing electricity needs by reducing CO_2 emissions), a significant industry has developed, stimulated by markets in Europe. Although China might be expected to be rewarded for its role in PV industrial development, as this might create the foundations for an even stronger export industry, the delay in promoting policies that can create larger opportunities in the domestic market (beyond the off-grid rural applications) means that the entrepreneurial spirit of the domestic industry is poorly mobilised and exploited to serve domestic environmental and development purposes.

By contrast the UK lags behind for both diffusion and PV industrial development. In failing to taking an active role in moving technologies from the demonstration to the pre-commercial and supported commercial phases, the UK makes a poor use of its creative and innovative effort. Moreover, it does not make good use of the money spent to support R&D because this is not translated into technologies that can meet society's needs in terms of clean electricity generation or employment.

The NIS approach we have adopted in this study has the merit of providing a framework to analyse the broad picture within which innovation for this technology unfolds. Moreover, by identifying the different agents of the system and studying their interactions, the importance of a shared vision between government, industry and research community can be appreciated.

This approach provides a much richer picture of the innovation process than the one offered by studies adopting traditional innovation indicators, such as R&D or the number of patents applied for by an industry or a country.

The adoption of the NIS framework has also allowed us to understand what special features of the national context have allowed a system to emerge and grow and another one to fall behind:

- In the case of China the role of the government under central planning has been crucial in the initial phase of the innovation system.
- In the case of the UK difficulties in establishing a productive base.

The systemic analysis has also unveiled, however, that the NIS for PV is affected by factors that go beyond national borders. Chinese producers, by exporting between 70 and 80% of their cells and modules to the highly subsidised markets in Europe and in other parts of the world, end up in being crucially dependent on the policies promoted in other countries and supported by the subsidies paid by the German or the American consumers.

The findings of this study also allow some policy suggestions for the further development and diffusion of PV in these two countries to be formulated.

For China:

▪ *Promote technological variety*

Putting all the eggs in the silicon basket might be a dangerous strategy. Si technology is certainly in high demand at the moment, but it is also very close to technological maturity and cost reduction opportunities and efficiency improvement are quite limited. Better prospects for a global larger scale PV adoption will possibly be provided in the mid-term by other technologies (i.e.: some thin film, PV under concentration or novel PV) where China is not focusing its R&D effort. Technological learning takes time and China might lose its current competitiveness should technologies that are now in the demonstration phase really take off. In this case countries where R&D in novel technologies is underway will possibly be advantaged.

The promotion of PV technological variety in the early stages of R&D would allow further technological learning away from a heavy reliance on international market pull.

- *Creation of opportunities in the domestic market*
  The promotion of sound and long-term measures for the development of the domestic PV market would permit a better use of the existent local industry together with improved opportunities for cleaner energy solutions and economic development.

For the UK:

- *Move technologies from the demonstration to the pre-commerciel and supported commercial phases*
  While the advantages of this policy option have already been discussed, opportunities to do this include providing seed capital for emerging enterprises venturing new PV technologies and creating niche markets for early stage technologies (Kemp et al., 1998; Foxon et al., 2005). As specified earlier, general measure for RES promotion are not effective enough to support immature technologies.
- *Broaden the range of possible PV applications*
  The UK is rapidly reaching the cutting-edge of building-integrated PV by marrying outstanding architectural design with RES generation (Earthscan, 2006). Specific policies, like that promoted by the Borough of Merton in London (TheMertonRule.org) aimed at promoting a larger use of PV in buildings, via for instance public procurement, would certainly contribute to the diffusion of the technology. However, as well as rooftop applications newer solutions like curtain walls should also be considered (Barnham et al. 2006). These new applications have the merit of optimising the economic value of a PV array by serving multiple functions like: energy supply, demand management (primarily, peak-shaving benefits, i.e., lower kW), emergency power (through the addition of some storage) and finally architectural value.

References

Barnham, K W, Mazzer, M, Clive, B (2006), "Resolving the energy crisis: nuclear or photovoltaics?", Nature Materials 5, March, 161-164

California Public Utilities Commission (2007), *The California Solar Initiative,* available at http://www.cpuc.ca.gov/static/Energy/solar/index.htm

Christiansen, A C, Buen, J (2002), "Managing environmental innovation in the energy sector: the case of photovoltaic and wave power development in Norway", *International Journal of Innovation Management* **6** (3), 233-256

Dai, Y, Shi, Z (1999), *Technological Innovation of the Chinese Photovoltaic Industry*, Centre for the Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, Beijing, Available at : http://www.andrew.cmu.edu/user/kf0f/Solar_PV_Report_8–99.pdf

Deutsche Energie-Agentur (DENA) (2007), *Renewables Made in Germany. The German Photovoltaic Industry*, available at http://www.renewables-made-in-germany.com/en/photovoltaics/

Digest of United Kingdom Energy Statistics (2006), URN No: 06/87, Department of Trade and Industry, Chapter 7

Earthscan (2006), *Guide to UK Renewable Energy Companies 2006*, James & James, London.

Foxon, T J, Gross, R, Chase, A, Howes, J, Arnall, A, Anderson, D (2005), "UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures", *Energy Policy* **33**, 2123-2137

Freeman, C, Soete, L (1997), *The Economics of Industrial Innovation* (Third Edition), Pinter, London

Greenpeace and EPIA (2006), *Solar Generation*, available at http://www.epia.org/05Publications/Solargeneration.htm

Gu, S, Steinmueller, W E (1997), "China's National Innovation System Approach to Participating in Information Technology: the Innovative Recombination of Technological Capability", *UNU/INTECH Discussion Paper* 9701, Maastricht

Helby, P (2005), "The role of technologies in policy design: does the Directive promote a national policy design favourable to technology development?", *FAVORES project report*. ALTENER project no. 2002-082, Lund University, Environmental and Energy Systems Studies, Lund, Sweden.

Imperial College Centre for Energy Policy and Technology (ICEPT) and E4Tech (2003), *The UK innovation systems for new and renewable energy technologies*, Report for UK Department of Trade and Industry, June, available at http://www.dti.gov.uk/energy/renewables/policy/iccept2003.pdf.

Infield, D. (2007), *A Draft Road Map for Photovoltaics Research in the UK*, report developed by the UKERC in conjunction with Photovoltaics Research Community.

Jacobsson, S, Bergek, A (2004), "Transforming the energy sector: the evolution of technological systems in renewable energy technology", *Industrial and Corporate Change* **13**, 5, 815-849

Jacobsson, S, Sanden, B A, Bångens, L (2004), "Transforming the energy system--the evolution of the German technological system for solar cells", *Technology Analysis & Strategic Management* **16** (Number 1/March), 3-30

Liu, Y (2005), "Shanghai embarks on 100,000 solar roofs initiative", *Worldwatch Institute*, November 10, available at: http://www.worldwatch.org/features/chinawatch/stories/20051110-2

Liu, X, White, S (2001), "Comparing innovation systems: a framework and application to China's transitional context", *Research Policy* **30,**: 1091-1114

Lundvall, B-A (ed.) (1992), *National System of Innovation: Towards a Theory of Innovation and Interactive Learning*, Pinter Publishers, London.

Ma, S (2004), "Renewable energy in China: brightness rural electrification program", *NREL Fact Sheets,* April. Available at http://www.nrel.gov/international/china/publications.html

Ma, S (2004b), "Renewable energy in China: township electrification program", *NREL Fact Sheets,* April. Available at http://www.nrel.gov/docs/fy04osti/35788.pdf

Marigo, N (2007), "The Chinese silicon photovoltaic industry and market: a critical review of trends and outlook", *Progress in Photovoltaics: Research and Applications* **15**, 143-162

Maycock, P (2004) *PV News*, March and April. Available at http://www.nrel.gov/ncpv/Maycock2004graph.pdf

Menanteau, P, Finon, D, Lamy, M-L (2003), "Prices versus quantities: choosing policies for promoting the development of renewable energy", *Energy Policy* **31**, 799-812

Mitchell, C, Connor, P (2004), "Renewable energy policy in the UK 1990-2003", *Energy Policy* **32,** 1935-1947

Renewable Energy Development Program (REDP) (2004), *Chinese PV industry development research report*, Report prepared for the NDRC/GEF/World Bank assisted renewable energy programme, Beijing, (cited 8 April 2005) Available at <URL: http://www.ndrcredp.com/id.asp?id¼1125> *(in Chinese)*.

Reiche, D, Bechberger, M (2004), "Policy differences in the promotion of renewable energies in the EU member states", *Energy Policy* **32,** 843-849

Solarbuzz (2007), *Solar Cell Technologies*, available at http://solarbuzz.com/Technologies.htm

Tempest, M (2007), “Climate change bill is revolutionary, says Blair”, *The Guardian*, Tuesday March 13, available at http://politics.guardian.co.uk/green/story/0,,2032710,00.html

Yang, H, Wang, H, Yu, H, Xi, J, Cui, R, Chen, G (2003), "Status of photovoltaic industry in China", *Energy Policy* **31**, 703-707

Wang, S (2005), *PV Situation in China*, Powerpoint presentation to N.Marigo at Beijing Jike Energy New Technology Development Company, May 2005.

Zhao,Y (2005), "Photovoltaic industry status and development trend in China", *Paper presented at the1st Workshop on the Future Direction of Photovoltaics*, 3-4 March, Tokyo, Japan

Zhao, Y (2004), "The present situation and future challenges of China’s photovoltaic industry", *Solar Energy (Taiyang neng)* **3**, 4-6 (*in Chinese*)

Zhao, Y (2001), "The present status and future of photovoltaic in China", *Solar Energy Materials and Solar Cells* **67**, 663-671

Zhu, L (2005), "China’s renewables law", *Renewable Energy World* (accessed 10 December 2005) Available at http://www.earthscan.co.uk/news/article/mps/UAN/432/v/1/sp/

Table 2 UK and China RES policy instruments and specific actions to promote PV

	RES policy instruments	PV specific policies
UK	*Main instrument* 2002-2026: Renewable obligation (RO), based on compulsory RES quotas and trade of certificates *Additional measures* Capital grants for earlier stage technologies	Up to March 2005: Major Demonstration Programme (MDP) for PV use in large and representative buildings +individual homeowner systems From April 2006: Low Carbon Building Programme (LCBP)
China	*Main instruments* 2006- ??: China Renewable Energy Promotion Law 1996–2010: Brightness Programme (focus on rural electrification): aims at providing 100 watts of capacity per person to ≈23 million people with de-centralised energy systems based on solar and wind	2006-2010 Village electrification programme (part of the Brightness programme) aims at electrifying (with PV and small hydro) 10.000-15.000 villages in China's off-grid western provinces. Demonstration systems for PV building integrated in selected cities On-grid PV in the Gobi desert (Gansu province): feasibility study under way for 8MWp to be installed PV for the 2008 Beijing Olympic Games. Road lamps, lawn lighting facilities, lamps for public lavatories and irrigation

Source: For the UK policy instruments: Mitchell and Connor, 2004; Foxon et al., 2005; Earthscan, 2006. For China's RES and PV policies: Ma, 2004a and 2004b; Wang, 2005; Zhu, 2005; Liu, 2005

Table 3 Summary table to compare different PV technological and institutional actors in both the UK and China

	UK	China
Innovators (i.e.: academic researchers, technology developers, knowledge-sharing networks)	Technology developers 1 company in the upstream (Crystalox, supplier of poly-Si ingots) 1 thin-film amorphous-Si module producer (ICP Solar) 2 module assemblers (Sharp and Romag) Several PV system designers and installers Academic researchers 20 universities mostly active in non-conventional, novel PV Knowledge sharing networks Relatively weak industry networks	Technology developers Several companies all along the production chain both upstream and downstream (module manufacturers are the most represented) Academic researchers 30 research institutes and universities mainly active in conventional Si technologies and thin-film. Very little R&D on novel PV Knowledge sharing networks Strong industry-universities links and industry networks
Demand	Electricity distributors for on-grid demand Off-grid demand and other niche markets New application markets (some BIPV)	70-80% of end-users are abroad off-grid demand for rural electrification and niche markets (i.e: consumers products like street/garden lighting)
Policy support and influence	Department of Trade and Industry (DTI); local councils and authorities; Ofgem	National Development and Reform Commission (NDRC - formerly the State Development and Planning) + local governments (i.e.: Shenzhen, Shanghai, Beijing) for local initiatives + policies for market pull promoted in other countries (mainly in Europe)
Facilitators (i.e.: research funders, financial investors; consultant/technical experts for project installations; industry associations)	Venture capital and private sector investment (some international) + national research councils (i.e. EPSRC)	Private sector investment and combination of private+public/local capital CREIA (China renewable industry association) GEF, the World Bank, the UNDP, IT Power (UK) and GTZ (D)