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A Road Map for Photovoltaics Research in the UK

Research Report

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Developed by the UKERC in conjunction with Photovoltaics research community

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Executive Summary

This document provides a road map for Photovoltaics (PV) research in the UK. It covers PV materials, cell and module design and manufacture and applications including BOS components. It is specific to the UK and reflects the strengths and weaknesses of the research base in the UK, although it is compatible with the roadmaps of other countries, particularly the one recently developed for the European Community. Its primary aim is to identify priority areas for UK PV research and assist the research funding agencies, particularly EPSRC, DTI and the Carbon Trust, in developing their research programmes, but it also considers the need to develop UK capacity, both in terms of expertise and research facilities.

Research cannot take place in a commercial vacuum, and although not its primary function, the road map will outline the context for PV research in the UK. The potential for market growth in the UK and more widely is outlined and the need for market stimulation in the UK discussed.

The road map reflects the outcomes of a two day PV road mapping exercise, organised by the UKERC Meeting Place, that took place in Edinburgh in July 2006, together with inputs from a number of the attendees over the following weeks and subsequently contributions from the wider researcher community in response to an initial draft. The road map has also been subject to international peer review, and we indebted to these reviewers for their input.

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1 Context for UK PV Research

Renewable energy technologies are becoming an ever more important part of the energy supply portfolio and photovoltaics, the direct conversion of light into electricity, is making a rapidly growing contribution to the renewable energy sector. Worldwide module shipments in 2005 were around 1.4 GWp, up about 34% on the previous year and continuing the impressive growth trend of recent years.[1] Whilst the market in the UK is presently modest by European standards, the installed capacity has quadrupled in the last four years and was 10.9 MW at the end of 2005.[2] To maintain this expansion and encourage more UK companies to participate requires a strong and suitably targeted R&D programme aimed at increasing performance and reducing manufacturing costs as well as the introduction of market stimulation policies like those already introduced in other European countries and elsewhere. Japan in particular has been leading the way towards competitive PV with a reduction in their subsidies from 3.22 $/Wp in 1997 to zero by 2005. At the same time their internal market has continued to grow by more than 30% per year.[3] Figure 1 highlights the very different rates of growth in Japan, Germany and the UK, and emphasises the importance of appropriate market stimulation. It is useful to note that over 42 thousand people were directly employed in the PV sector in Germany by the year 2004.

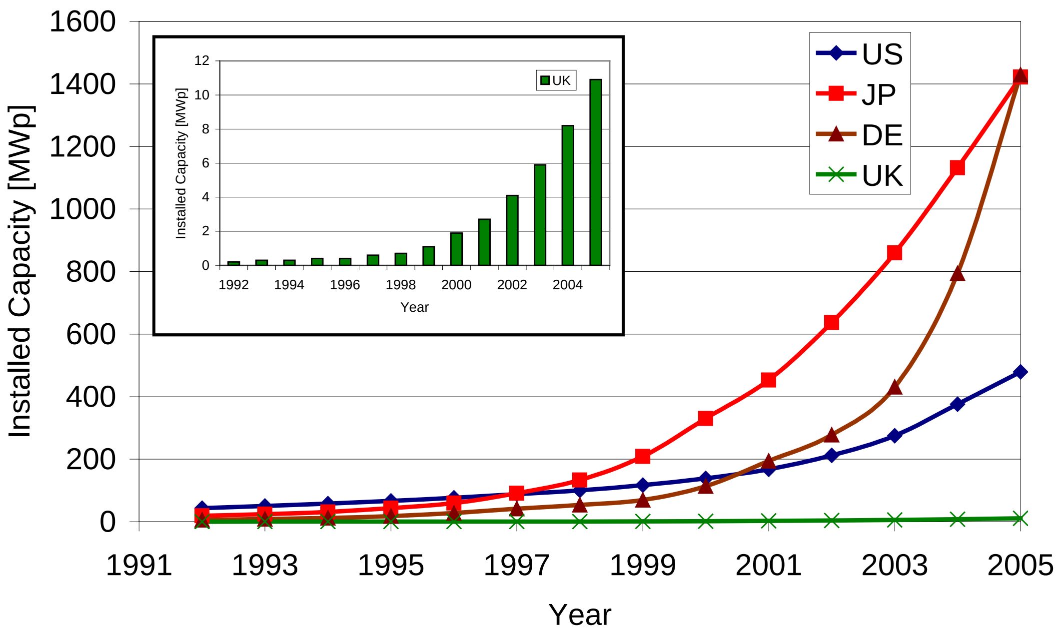

Figure 1: PV domestic market growth rates in the USA, Japan, Germany and the UK, the insert allows the low UK installation rate to be visible.

The successful development and implementation of an R&D strategy requires the determination of what that strategy should achieve and what targets or aspirations

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[1] Various industry experts estimate the 2005 module shipments at around this figure. See for example, the report from Solarbuzz on http://www.solarbuzz.com/Marketbuzz2006-intro.htm.
[2] Digest of United Kingdom Energy Statistics 2006, URN No: 06/87, Department of Trade and Industry, Chapter 7
[3] See, for example, the article in Renewable Energy World at the following web address: http://www.earthscan.co.uk/news/printablearticle.asp?sp=&v=3&UAN=350.

should be set in order to measure those achievements. In regard to the UK roadmap for research in photovoltaics (PV), the main aspects of such a vision are:

- The role that photovoltaics should play in the UK energy supply mix, now and in the future;
- To highlight the wider benefits to the UK, beyond green energy generation;
- To encourage UK industry to supply and implement photovoltaic technology in the UK and overseas, including in countries where feed-in tariffs have already resulted in a significant market offering export opportunities.

Since PV is a global industry with applications worldwide, the UK roadmap should be consistent with the PV R&D roadmaps developed by other countries and regions. So as to ensure the competitiveness of our industry, UK research should be complementary to that ongoing in other countries and our goals should be compatible with those of other countries. Given the importance of both the European market, and the well structured and supported European Research Area, the most important roadmap to consider is that of the European Union.

In 2005, the European Commission published “A Vision for Photovoltaic Technology”, a report produced by a group of European experts forming the Photovoltaic Technology Research Advisory Council.[4] The projections and targets discussed here are compatible with the vision presented in that document, which is now being used to develop a strategic European R&D agenda under the auspices of the European Photovoltaic Technology Platform.[5] The European vision incorporates an assumed reduction in module and system prices as shown in Table 1 and these goals are taken to apply to the UK situation as well. Assuming different cost targets would be ill advised and will not assist UK industry in becoming competitive in the longer term.

Table 1 – Target prices up to 2030 reproduced from “A Vision for Photovoltaic Technology” (reference details in footnote 3)

Deadline	Module target price (€/W)	System target price (€/W)
2010	2	3
2020	≤ 1	2
2030	≤ 0.5	1

Target prices are expressed in €/W; these translate into energy prices based on the system output at a given location, itself dependent on the solar energy input at the site in question. As a northern European country, the expected electricity output in the UK will be lower than for southern Europe and hence the prices for a generated kWh will be higher for the same system price. Nevertheless, it can be shown that, if the targets are achieved, PV generated electricity will become fully competitive with conventionally generated electricity in the UK well before 2030, even allowing for only

[4] “A Vision for Photovoltaic Technology”, European Commission, 2005, Office for the Official Publications of the European Commission, ISBN 92-894-8001-1 (also available for download from http://www.eupvplatform.org/fileadmin/Documents/vision-report-final.pdf)

[5] The European Photovoltaic Technology Platform is an initiative to mobilise all the actors necessary to realise the long-term vision for photovoltaics in Europe. More information on the Platform and its activities can be found at http://www.eupvplatform.org/

a very modest rise in conventional electricity prices (1% per annum).[6] This does not take into account the economic benefits that can be obtained from building integration of PV systems or any financial benefit due to selling green electricity to the grid, or assume that a carbon tax or similar legislation is adopted.

In recent years, results from Government sponsored field trials and demonstration projects, coupled with the experience of individual investors in PV systems, has shown that a well designed and implemented system can produce around 800-820 kWh/kWp per year in the UK (where kWp relates to the rating of the installed system).[7] With technology advances, this may be increased, but the targets discussed below do not assume this. Rather it is assumed that further experience and component development will allow this level of production to be met by the average system.

The European vision document suggests that PV can generate 4% of world electrical energy production by 2030, with a rapidly growing role thereafter. Clearly, the percentage will vary from country to country. The Netherlands has a similar latitude and climate to central and southern England and for this reason a comparable target has been adopted to that published in the Dutch roadmap[8]. Table 2 summarises their vision for PV installations and the contribution to energy supply up to 2050.

Table 2 – Summary of goals for Netherlands PV Roadmap developed by Holland Solar (reference details in footnote 8)

	2015	**2030**	**2050**
PV electricity price (€/kWh)	0.25	0.10	<0.06
PV capacity installed (GW)	0.5	6	75
Electricity contribution	100,000 households	3%	25%

If we assume that the UK, like the Netherlands, wishes to provide 3% of its electricity requirement from PV systems by 2030, what would this mean in terms of installed systems? According to the Digest of UK Energy Statistics, the total electricity consumption in 2005 was 346 TWh.[9] The long-term trend shows an average increase of 1.7% per year in consumption since 1986. However, examination of recent data suggests a slow down in the rate of growth to around 0.9% per year on average since 2000. If we assume that a combination of energy prices, environmental awareness and energy efficiency limits the growth in this way up to 2030, we arrive at a prediction of a 25% overall growth on 2005 figures to around 430 TWh, as illustrated in Figure 2. It is not the purpose of this document to provide a rigorous prediction of

[6] W. Sinke, WG3 leader, presentation to European Photovoltaic Technology Platform General Assembly, 19th May 2006 (available from the Platform web site, http://www.eupvplatform.org/)
[7] See, for example, the results from the UK Photovoltaic Domestic Field Trial (PV Domestic Field Trial, Final Technical Report, BRE, 2006, to be published on http://www.berr.gov.uk/files/file36660.pdf)
[8] "Transitiepad zonnestroom", Holland Solar, May 2005 (in Dutch). Holland Solar is an organisation for the promotion of solar energy in the Netherlands. The roadmap was produced by a group of experts from industrial and research organisations.
[9] Digest of United Kingdom Energy Statistics 2006, URN No: 06/87, Department of Trade and Industry, Table 5.1.2, p.333

energy consumption and this figure is only taken as indicative of electricity demand for the purpose of estimating of the PV capacity required to meet the target contribution.

The PV target for 2030 is set somewhat conservatively at 3% of 430 TWh or around 13 TWh of generated electricity per year. Assuming the yield figure of 800 kWh/kWp quoted earlier, this corresponds to approximately 16 GWp of installed PV systems. To put this in perspective the Japanese governmental organisation NEDO is predicting that Japan will have 100 GWp of installed PV capacity by 2030[10]. It is also relevant that an extrapolation of the UK installed capacity, assuming an expansion rate which is the average of that achieved in Germany over the last five years, will reach 16 GWp before 2021[11]. Germany, with a not too dissimilar solar resource to the UK's, will have 16 GWp of installed PV before 2013 if their present rate of installation continues. It can be concluded that if the right market stimulation policies are adopted there should be no difficulty in meeting the projected growth rate for the UK. Indeed, Germany and Japan have already demonstrated that near exponential growth is possible up to the 1.4 GWp level[12]. Figure 2 shows the growth in the PV contribution to UK electricity supply following the above assumptions.

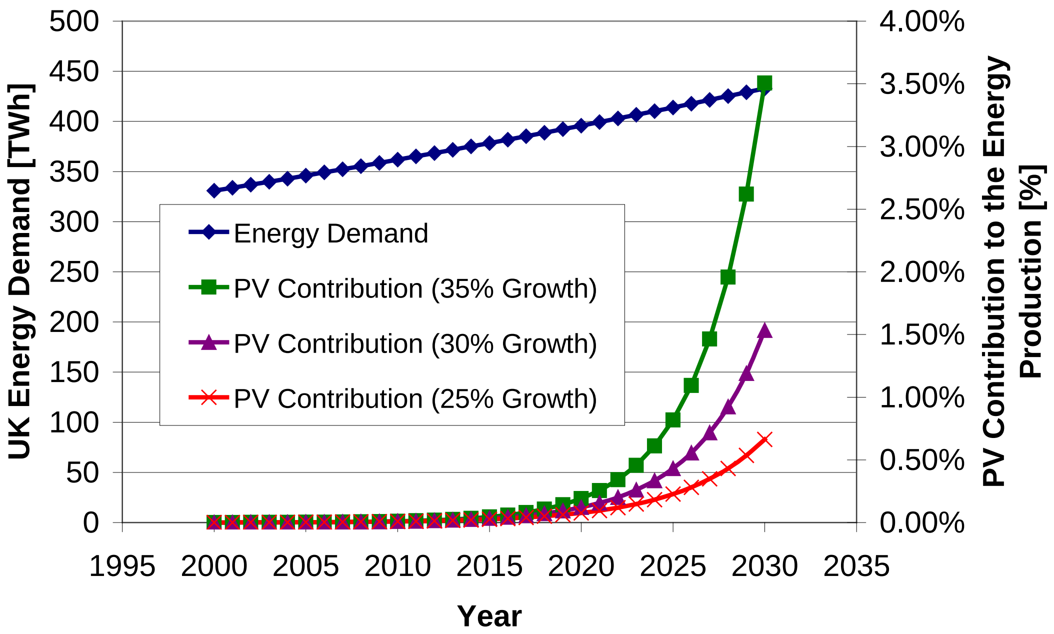

Figure 2: Projected growth of UK PV system electricity generation

The average domestic system size within the UK Photovoltaic Domestic Field Trial, due to be completed in 2006, is 1.6 kWp, but this is not the maximum size of system that could be accommodated on a normal domestic roof, even using today's technology. If we assume that as a result of technology advances and cost reductions that make PV competitive with other forms of generation and so encourage larger system sizes, future domestic systems may well average around 3 kWp in capacity.

[10] Progress in Photovoltaics, Research and Applications, Special Edition, 461, (2005)
[11] Barnham and Mazzer, New Statesman Supplement, xi, 15th May 2006
[12] PV Power, International Energy Agency, 24, 3 (2006)

If we further assume that 75% of the installed capacity relates to domestic systems, then this implies just over 4 million such systems installed by 2030.

The Department for Communities and Local Government estimates that England and Wales reached about 23 million households in 2006, with a further 2.3 million in Scotland.[13] This correlates well with the housing stock, numbering 26 million in 2004. It is projected that the households in England and Wales will grow to around 25 million by 2021. If we assume limited growth thereafter, we could estimate a total of around 30 million UK households by 2030, 1 in 7 of which would have a PV system installed. The balance of capacity would be made up of larger systems, installed on public and commercial buildings. Examples within Europe range from systems of a few tens of kilowatts on office buildings to systems of up to 5 MW on factory and warehouse roofs. The target would require 4 to 5 GWp to be installed on these types of buildings, that is around 45,000 buildings at an average of 100 kWp per building.

One reason why the industry in the UK is not benefiting as much from the international developments as it could is the conspicuous lack of funding for PV in general and the extremely low funding of R&D in particular. The UK is the fourth largest economy in the world, but the R&D investments in PV are negligible in relation to those of the other larger economies (see Figure 3). In this context, it is important to note that around half the main PV manufacturers worldwide grew out of research institutes or universities or were led by people who had built up their expertise over many years of research in such organisations. Admittedly, the other half of the production is driven by a combination of major electronic manufactures and oil companies. A stronger UK PV research base will undeniably lead to a stronger commercial sector, with a larger added value for the UK. A strong research community could also encourage further inward investment.

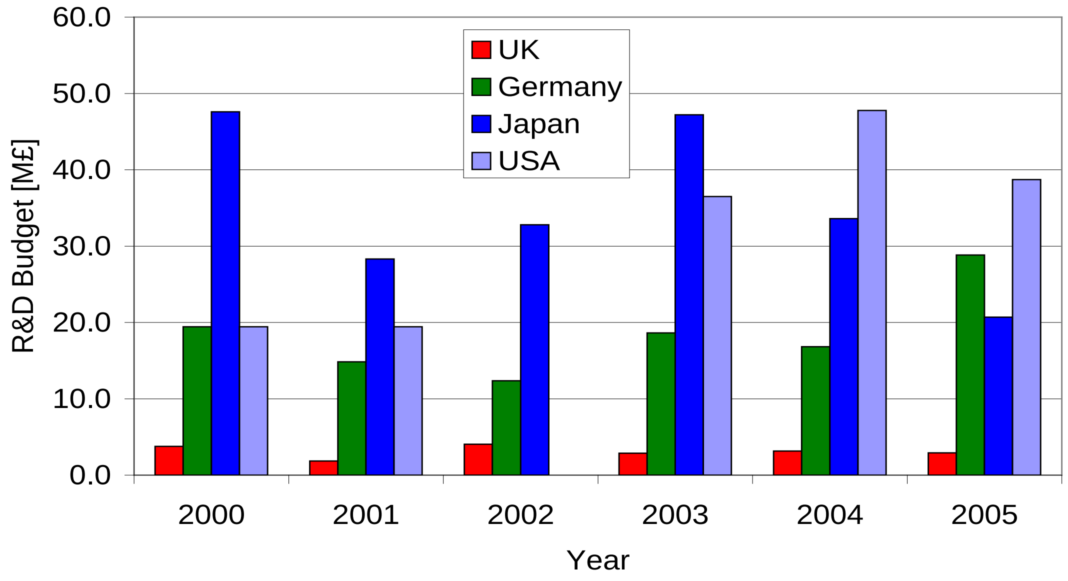

Figure 3: Annual PV Research Budgets of the world's four largest economies[14].

[13] Table 401, Household estimates and projections, Great Britain, 1961-2021, Department of Communities and Local Government
[14] Source: IEA PVPS programme (www.iea-pvps.org, taken from the annual reports 2000-2006 for publicly funded research), assuming $/£ = 1.8.

The successful development of such a market would provide large commercial opportunities in the supply of components, the design and installation of systems and in all associated industries, coupled with a substantial growth in jobs. The European Vision Report predicts up to 400,000 new jobs to be created in Europe by 2030, based on a projected 40 GWp market. These include jobs in both manufacturing and implementation and thus represent an opportunity for all European countries to benefit. A strong UK PV industry would result from an expanding local demand if a feed-in tariff policy similar to those in Japan, Germany, Spain and a growing number of other countries were to be implemented. Moreover, this would provide a base from which UK companies could provide goods and services to other countries both within Europe and beyond where such policies have already implemented.

The R&D roadmap concentrates on activities with the potential for the development of new components or in areas relating to implementation of systems under UK conditions. It builds on existing strengths within the UK PV research community, but also targets essential areas where the UK should build capacity to allow full participation in this rapidly advancing field.

Photovoltaic systems are expected to provide a significant part of the world's future energy supply and can make a substantial contribution to meeting the electricity needs of the UK in the post-2020 timeframe. To allow this potential to be realised, a robust R&D programme must be implemented to promote UK expertise within the worldwide PV market.

UKERC's recently published PV Research Landscape for the UK[15] states that the "overall aim of research in PV has to be to reduce PV generated electricity costs to be competitive with bulk electricity generation from conventional sources and the leading alternative renewable sources." It goes on to say that "some improvement in conversion efficiency is required, particularly for the thin films, but this must be coupled to dramatically reduced production costs" and that "increased research emphasis on the manufacturing process is required." Materials research aimed at improved PV devices must constantly bear in mind the manufacturability of provided device architectures. Although most of the research challenge lies with PV module design and manufacture, some systems are presently let down by underperforming balance of system components and in particular the inverter. Moreover, presently available performance prediction tools are inadequate and as a result potential customers can be misled. This Research Road Map will examine these issues in some detail.

1.1 Existing UK research community

UKERC's Landscape document describes in some detail UK PV research and its funding sources. What is immediately apparent from this record is the fragmented nature of the UK's PV research community. The community is small compared to that in the leading countries of Japan, USA, and Germany and we lag behind many other

[15] UKERC PV research landscape: http://ukerc.rl.ac.uk/ERL0301.html

European countries, Korea, Australia and many others. Why this should be the case is not completely clear. The UK has a strong materials science base and also is well known in the field of innovative manufacturing research, but this has not been harnessed to its potential to grow a specific PV research community. The lack of an aggressive market support programme in the UK is perhaps part of the answer, and also perhaps the UK's continuing wider failure to translate strong basic science research into technology. The UK also lacks the central laboratory infrastructure that other European countries and the USA and Japan have used very effectively to drive forward their PV research. Despite these handicaps, there is world leading PV research going on in the UK, details of which can be found in the Landscape document.

BP Solar established a leading laboratory for PV research in the UK; following the closure of this facility in 2004, the core of the expertise they developed moved to NaREC where a PV Technology Centre has recently been established[16]. For this and other reasons, the UK research community tends to be fragmented with over 20 Universities having some sort of activity. Often only one full-time academic is involved; few groups could genuinely claim to have reached critical mass. On a positive note, the diversity of skills and interest within the university sector, despite lack of a strong market or indeed a consistent research policy, is a potential that can be developed. The recent Supergen programmes from EPSRC are sound attempts to structure the community and achieve critical mass. Both Supergen programmes: PV Materials for the 21st Century, and the Excitonic Solar Cells Consortium are fairly broad but they do highlight the UK's strength in polymer and dye cells and the competences relating to silicon and thin film hetero-junctions. In addition, certain leading groups have particular strengths in systems related research.

Applied research in the PV area is limited in the UK and in the main is funded by the DTI. UK industry to date has not been particularly active in the PV sector. For many years ICP at Bridgend was the only manufacturer of PV modules in the UK. It is now pleasing to see that both Sharp and Romag are currently assembling modules and that Sharp, who currently assemble over 100 MW of capacity per annum, has ambitious plans for cell manufacture. Also, on a positive note regarding the materials supply chain, Crystalox based in Wantage has become one of the world's major suppliers of silicon to the PV industry, and a number of equipment manufacturers relevant to PV production such as Plasma Quest and SVS are based in the UK. In general RDAs have been slow to spot the potential for PV to strengthen the regional economy but some initiatives are now visible. Perhaps the most important was the support of One North East, the local RDA, for the PV Technology Centre at NaREC. This is the UK's only dedicated PV research facility and was formally opened in October 2006, and it focuses primarily on silicon wafer research and development. Another important regional development is the recent announcement that G24i is investing £60M to bring large scale Gratzel cell manufacture on stream in Cardiff.

[16] Appendix 2 lists the UK central facilities relevant to PV, including NaREC's.

2 Technology Assessment Framework

For assessment purposes the research area has been broken down into 4 categories: crystalline wafer silicon PV; thin film PV[17]; advanced PV concepts (including concentrator systems); and balance of systems issues to include all other relevant aspects including building integration. During the 2 day workshop each of these topics was represented by separate break out groups. Membership of these groups is indicated in Appendix 1. A common assessment and presentation methodology was agreed.

Because the nature of the UK PV research community, and because publicly provided research funding in this area is limited, it was important to identify how strong and relevant existing research capability in the UK was by sub-topic. This is not to say that we should only play to existing strengths; indeed the category of opportunities was included in the reporting format to capture new areas of research highly deserving of attention in the UK context. It was also agreed to categorise research challenges according to the timescales to bring specific research topics to a conclusion. Three categories were adopted: immediate research priority; capacity building over the medium term (5-10 years); background level research over the longer term (probably with lower level of resourcing but topics for which it was considered important to maintain ongoing research). The resulting 3x3 matrix for research topic assessment is shown below, and in the report sections below tables having this structure are presented. Sometimes the 4 research areas identified above have been broken down into designated research topics to add clarity.

Note that if no pressing research is identified for a given element in the matrix, then that box will remain empty. For example in the Tables 4 and 6 below, the element for immediate priority weaknesses is empty; this should not be interpreted to mean that there are no areas of weakness, but rather that there is no plan to address these.

It is also worth pointing out that four categories considered are not all at the same stage of development. Crystalline Silicon and a number of thin film technologies are already well developed and commercially available and as a result much of the immediate research is concerned with issues relevant to manufacturing. In contrast, for the advanced devices such polymer cells, the immediate priorities are for research to provide stable and efficient cells.

	immediate priority	capacity building	background research
Strengths			
Weaknesses			
Opportunities			

Footnotes have been used extensively to provide background and explanation to table entries.

[17] Strictly, existing thin film PV.

3 Crystalline Silicon

Two principles were adopted that guided the identification and categorisation of research topics under this heading: the need to reduce significantly the cost of crystalline silicon modules and to make the process of production and use more sustainable. Two avenues to silicon cost reduction can be distinguished: reduced silicon consumption per Watt peak (Wp) and reduced silicon cost per kg. Of course these approaches can be combined. Possible approaches to cost reduction include:

a. low-cost solar grade silicon feedstock
b. high-quality, low-cost crystallization
c. low-loss cutting of very thin wafers
d. thin-film wafer equivalents

This would also have the desirable effect of shortening the energy pay-back time for crystalline silicon modules.

Other approaches to reducing the cost per Wp include high-throughput, high-efficiency cell processing and low-cost module manufacturing:

a. high-efficiency cell design concepts and processes
b. in-line processing
c. rear contact schemes for thin wafers and easy module manufacturing
d. new encapsulation materials

Enhanced sustainability would include the replacement of critical materials (such as Ag, Pb, etc) and design for recycling.

The prioritization of research is summarized in Table 3 below, and the accompanying footnotes.

Table 3 – Research topics for Crystalline Silicon

	Immediate priority	capacity building	background research
S	• Processes for improved crystal growth[18]	• Low defect silicon[19]	• Defect characterisation & control[20]
W	• Improved techniques for thin wafering & kerf loss reduction[21]	• Cell & module manufacturing for thin wafers[22] • New wafering methods[23] • Design for recycle[24]	

[18] The UK has a good base on which to build silicon wafer research, of note is Crystalox who produce 15% of the PV global cast silicon that is of world-class quality; developing crystal growth technology and capability is seen as a high priority activity.

[19] High yield wafering of cast silicon and high efficiency cell fabrication require low-defect silicon (inclusions, carbon, oxygen, etc). Building on this capability in UK is essential to the longer-term sustainability of the technology.

[20] An essential background support to low defect silicon production is the capability for defect characterisation. UK expertise in this area should be utilised and enhanced.

[21] The reduction (minimisation) of silicon feedstock consumption in silicon wafers is key to lowering the module cost. This can be achieved with (i) thinner wafers – reducing from today's 200-250 mm thickness to 100-150 mm, (ii) reducing the kerf loss in the wafer sawing activity – from today's 200 mm to values below 150 mm and (iii) optimising the recycling of the silicon (including recovery and recycle of the kerf). At the present time there is no UK capability in this area and this is seen as a strategic requirement for future silicon wafer growth in UK.

[22] Cell and module fabrication is a cornerstone of PV manufacture and a key area for realising cost reduction. The UK has expertise in PV cell manufacturing tools (lasers, furnaces, plasma process tools – see appendix) and in device materials (metallisation pastes and plating products). It also has cell R&D and pilot demonstration facilities for cell fabrication at NaREC and within the universities. Building on this capability and developing new processes for thin wafers (e.g. ink jet printing) is seen as a priority area.

[23] Today's silicon wafering is based on wire sawing using SiC grit in a mineral oil or glycol cutting fluid. The importance of improving this process by reducing kerf loss (wire diameter) has been discussed in (4). Whilst the UK is weak in this field, further developments of this technology (thinner wires, new cutting fluids, etc.) and/or new wafering technologies is an area for potential investment in applied R&D, perhaps supported by the DTI.

[24] In the high volume deployment of PV that is expected at or before 2020 it will be important to design modules with a view to re-cycling. The UK has limited current capability in this area, so essential for future sustainability. Nevertheless, it has strong materials research and a number of companies supplying materials in this area.

O	• Design concepts & processes for high efficiency cells[25]	• Reusable crucibles[26] • Pilot demonstration of high efficiency /high throughput cell fabrication[27] • New materials & processes for low-cost High throughput module assembly[28]	• New materials & processes for non-Ag contacts[29] • New Si feedstock process[30] • Defect control in Si [31] • New encapsulants [32] • New high speed processes [33] • New device concepts for very high efficiency [34] • Epitaxial Si films on low-cost wafers [35]

[25] High efficiency cells/modules enable low-cost module and system cost (per Wp). There is an opportunity in wafer silicon PV technology for UK to build immediate R&D capability in this area building on expertise at NaREC and in the universities.

[26] The crucible is a high cost item in the current casting process. If fused silica is used the crucible must fracture on cooling. Alternative ceramics such as silicon nitride need to be used which can give multiple casts. Although the initial crucible cost will rise the crucible cost per cast must be demonstrated to fall significantly.

[27] New cell designs at the laboratory level will be accomplished in (8). A further phase is then necessary to move these concepts into an industrial environment. This requires a pilot line to demonstrate that the new concepts can produce high efficiencies when processed at high throughput in industrial scale equipment. Cells will probably be of larger area than in the laboratory.

[28] Module assembly accounts for 37% of final module costs. The topic has been under-researched. New concepts are needed which eliminate the slow batch-based vacuum lamination process. In-line processing for solar cells, which are likely to be thinner than 200 microns, will be required. Possible methods include roll-to-roll processing with new types of UV-stable adhesive encapsulants or spray-on polymer techniques. New materials as well as processing equipment will be required. The UK has skilled companies in this area.

[29] The development of new solar cell structures may require novel metallisations and new processes, which will give rise to reduced area contacts with lower recombination at the contact thus increasing efficiency. Metals other than silver may be more appropriate to achieve this end. Projected future demand also indicates that, without substitution, a high fraction of the world silver supply will be required and so alternative metals, particularly non-precious ones, should be sought. The replacement of silver should further drive cost reduction. The UK has enabling skills in this area through paste manufacturers such as Dupont Thick Film Materials and a number of specialist metals companies e.g. Johnson Matthey.

[30] Silicon feedstocks currently come from high energy content polysilicon produced by reduction of chlorosilanes. Alternative routes such as refined metallurgical grade silicon or electro-reduction of quartz should be assessed to produce new feedstocks. These should be of lower cost, be sustainable in the long-term and have a lower embedded energy content than the present supply. The UK has limited strengths in this area but Crystalox is leading on supply.

[31] It is envisaged in (3) that the defects limiting efficiency will be largely identified. Further research is then required to modify the casting process to minimise or eliminate harmful defects which cannot be otherwise passivated.

[32] Assembly and encapsulation forms 37% of final module cost. New encapsulants and foils are needed which are of lower cost and permit more rapid module assembly and encapsulation such as roll-to-roll as in (11). DuPont and other UK companies are active in this field.

[33] Cell cost process reduction will come from highly automated processes giving low labour cost and high throughput per work station to give low capital cost per processed wafer. New cell processes such as rapid thermal processing, in-line diffusion, etc need to be developed for this and be consistent with the achievement of high efficiency.

[34] The route to 20% efficiency is well understood if not yet implemented. New design concepts will be needed to move into the 20-25% efficiency range. This will involve new emitter structures and novel metallisation concepts as well as improved surface passivation and high quality wafers.

[35] The current routes to low cost have risk in achieving high efficiency on very thin wafers. A lower cost alternative is the use of silicon films of 5 to 50 mm on non-silicon or very low cost silicon substrates. UK universities are well placed to undertake this work.

4 Thin Film Technologies

The driver for all thin film technologies is their potential to achieve large scale and high throughput PV module production at low manufacturing costs. The ultimate success in achieving such a goal lies in the capability to understand the basic material and device properties, fabricate, evaluate and optimize solar cells in the laboratory, and subsequently design and develop the required processes for large-scale production.

The different thin film technologies are at different stages of development and pose different, albeit often related, research challenges. This section first sets out some of the common research themes to be addressed and then provides some additional detail on specific research areas for the three main material types: cadmium telluride (CdTe); copper indium gallium diselenide (CIGS); and thin film silicon (embracing amorphous silicon and more recent developments in micro and nano-crystalline silicon).

4.1 Common thin film PV research issues

The common themes relate mainly to the provision of higher quality component layers rather than the cell structure itself. These include TCOs, contacts and insulating layers, the development of production equipment including in-line diagnostics, enhanced production processes in terms of quality, yield and reproducibility and development of suitable encapsulation processes for both rigid and flexible modules. There is a general need for more in-depth understanding of the roles of the layers and their properties in the cell operation.

Table 4 – Common thin film research areas

	Immediate priority	capacity building	background research
S	• Use of alternative lasers for production processing[36] • Improved connections and bonding[37] • Understanding of layer properties, interfaces and defects[38]	• Improved non-conductive coatings[39] • Alternative lower cost encapsulants[40] • Development of in-line diagnostics[41]	
W		• Develop recycling processes	• Close the recycling loop for modules / waste material from large scale production
O	• Improved laser scribing[42] • Improved scribing configurations[43] • Alternative TCOs (including p-type materials, light trapping)[44]	• Improved module interconnections and sealing[45] • Fast high quality TCO /substrate preparation	• Large area module production equipment, designed for low energy, low materials usage • Roll to roll processing

[36] Lasers are a high capital cost element of the production process. Typically these are yag and double-yag systems, which can be complex and expensive. To help reduce the cost other laser types and connections systems need to be investigated and developed.
[37] Connection to the photovoltaic material can often be an area of failure. Further investigation of the materials, the interaction between materials and bonding methodologies such as conductive adhesives, soldering, ultrasonic bonding and laser bonding techniques, should be explored and investigated. For example using laser technology it may be possible to make all the final connection; post lamination automatically, this would both reduce cost and improve reliability.
[38] There is a general requirement to obtain a better understanding of the factors that affect layer, interface, defect and stability issues. Specific requirements for individual cell types are discussed in the text and tables in the following sections.
[39] For conductive materials such as foils or steel cladding materials, there will be a need for non-conductive coatings to be developed that are compatible with the subsequent deposition of the contact layers, solar cell and laser scribing processes.
[40] In order to effect a substantial cost reduction we will need to find alternatives to EVA type lamination processes. For example; the weather protection afforded by paint and the subsequent lacquer process for steel clad buildings is extremely high.
[41] For a large scale continuous in-line process to be successful, an advanced in-line diagnostics capability is essential for continuous monitoring and feedback in order to produce high quality products with high yields. In some cases the similarities among the various thin film technologies will offer opportunities to collaboratively develop the necessary diagnostics, while in other instances it will be necessary for each technology to address its own specific needs, depending on the methods of deposition, device configuration, and other process characteristics, such as the deposition environment.
[42] Laser scribing or mechanically scribing monolithically interconnected modules can often cause micro-shorts or fusing of the materials. Therefore better analytical methods need to be investigated and developed to understand where and how this occurs.
[43] As substrates get larger and inline processing, such as roll to roll become the norm, the use of a flat bed laser processing system is no longer suitable or cost effective. Research should be undertaken to look at different architecture, such as vertical and inline systems, with a small magnetic drive floating over the glass, steering the laser beam, removing the need for expensive tables and drive systems.
[44] Transparent conducting oxides are utilized by all thin film technologies. The choice of TCO material and the required opto-electronic properties depend solely on the characteristics of the specific thin film technology. Therefore there exists a need for the undertaking of a comprehensive study to investigate this class of materials and tailor their properties (structural, electrical, optical, conductivity type etc.) to meet the need of each technology.
[45] Making connections and how we interconnect modules will need to be developed along side the new high speed process techniques This should include the idea of imbedded connections, inline moulding, new

	• Cell structure for light trapping/harvesting, including optimisation for large areas • Cell concepts for flexible substrates	• High throughput, low cost packaging processes and equipment for highest module lifetimes • Industry and manufacturing aspects (pilot line studies)[46]	for flexible substrates

materials and configuration. Investigations should therefore be undertaken to look at providing a sealing layer that can be applied inline, sealing the solar cell.

[46] For all technologies, there is a need to consider the transfer of laboratory based procedures to the production process, maintaining device quality whilst addressing issues such as throughput, yield and quality control.

4.2 CadmiumTelluride solar cells

In order to achieve large scale production of efficient, high power CdTe modules, two issues are critical:

- improved understanding of the material properties (absorber, window, front and back contact layers and their interfaces)
- development of advanced deposition technologies with reduced materials and energy input.

Improvements in deposition methods are required to overcome limitations of the processes in regard to grain boundaries, pinholes, impurities and defects and their effect on layer properties such as minority carrier lifetimes, inhomogeneities, doping control, nucleation and film morphology (particularly for thinner films). Understanding of the effect of interdiffusion at interfaces is key to the engineering of new device structures. In the longer term, it is also desirable to address these issues for CdTe alloys and hybrid concepts, in the context of future generation solar cells.

In research on production techniques, emphasis should be placed on high growth rates and low temperature processes that can be applied to low cost substrates. Device structures for roll-to-roll manufacturing would be a challenge but offer high value if successful. Advanced deposition technologies for the in-line continuous production of large area modules are also a critical area of research. In addition to the deposition processes for the semiconductors (window and absorber layers), other key processing steps include post-deposition chlorine heat treatments, and dry surface treatment techniques. There is a critical need for a pilot production line to demonstrate the potential for these new deposition and process technologies.

Table 5 – Specific research topics for Cadmium Telluride solar cells

	Immediate priority	capacity building	background research
S	• Control of nucleation and film morphology during deposition • Understanding and control of interface interdiffusion • Improved doping processes • Understanding of inhomogeneities and grain boundary effects	• Reduction of thickness of active layers	
W	• Recycling schemes to create a sustainable product.	• Improvement of ohmic back-contacts • Advanced control of homogeneous deposition	

O	• Identification and elimination of pinholes and weak diodes	• Advanced activation suited to in-line production • Alternative window layers	• Modified device structures (inverted film sequence, pin cells) • Tandem/triple cell concepts • Structures to allow efficiencies to approach single junction limit (full spectrum utilisation) • Hybrid dye/II-VI cells, CdTe alloy cells

4.3 Copper Indium Gallium Diselenide (CIGS) solar cells

Despite the record high efficiencies of the CIGS technology, the need for improved understanding of the materials properties (e.g. composition, point defects, impurities) and how these correlate to the particular deposition technologies is critical in improving the potential of this material for the production of large area modules. As with CdTe cells, key issues include include the role of defects, impurities, buffer layers, and specific processes on device performance and the observed metastability effects.

The potential of established large area techniques such as sputtering and electrodeposition should be explored in regard to the high throughput manufacture of CIGS cells and modules. The potential for roll to roll processing also needs to be investigated. The long term stability of these modules needs to be assured and, in addition to the fundamental materials properties, the packaging of the modules must also be considered.

Table 6 – Specific research topics for CIGS[47]

	Immediate priority	capacity building	background research
S	• Monitor CIGS modules in outdoor operation • Understanding of the role of deposition parameters for layer quality (absorbers / other functional layers)		
W		• Quantitative ageing models and understanding of long term instabilities	• Processes for large area CIGS modules at efficiencies up to 17% • Cell concepts for >18% efficiency[48]
O	• Understanding of defects, impurities, metastabilities	• Processes for high speed deposition of functional layers • Alternative 'low cost' deposition methods for CIGS absorber • Alternative buffer	• Develop concepts for the use of CIGS nanoparticles as absorbers in organic cell structures • CIGS modules for space applications • Replacement of

[47] Note that it is possible to vary the In:Ga ratio within the material to modify the properties. For simplicity of presentation, the term CIGS is used here as a generic name to include all reasonable In:Ga combinations, including CIS (i.e. where there is no Ga in the material).

[48] Concepts for full spectrum utilisation such as up/down conversion and quantum dot structures can be envisaged, in addition to various multijunction structures with modified chalcopyrite materials, silicon or dye materials as cell components.

		layers • Understanding of electronic band structure with respect to buffer layer chemistry and increased cell efficiency	scarce or expensive raw materials (e.g. In, Ga) in the cell design • Control of bandgap by the use of new materials

4.4 Thin film Silicon

Thin film silicon (TFSi) is expected to play a major role in the future of PV. Nanocrystalline Si (nc-Si) (more commonly referred to as microcrystalline Si) and large-grained polycrystalline Si (pc-Si) have the potential of significantly advancing solar cell performance beyond the present a-Si technology through development of a detailed understanding of the properties of TFSi layers, coupled with high efficiency cell designs.

Device performance is primarily influenced by defects and interfaces and additionally, in crystalline TFSi, by grain boundaries and intra-grain defects. Therefore, it is important to understand the factors that control and limit the electronic properties (e.g. carrier lifetime and mobility) of layers and interfaces. Grain boundary, interface and defect passivation treatments need to be fully understood and more effective treatments developed for higher efficiencies. Research on better understanding and optimization of light trapping schemes is a key requirement for higher efficiencies.

Tandem, hetero-junction and hybrid structures combining TFSi with other types of absorbers are also key areas in need of further research and development. Nanostructured device concepts could lead to significant gains in efficiency in the long term and should be investigated. These include concepts such as spectrum conversion using quantum dots and plasmonic structures, hot carrier devices, etc. P-type TCOs could also provide opportunities for novel devices in the longer term.

Thin film Si (TFSi) is the most mature technology in the thin film arena. However, the growth, both in terms of performance and market share has been comparatively slow compared to the silicon wafer industry. This is because it requires bespoke equipment for its manufacture, whereas crystalline wafer technology was accelerated by using processes developed for the semiconductor industry. The TFSi industry will start to benefit from equipment manufacture for the flat panel display industry, which is moving into the TFSi arena. This can be illustrated by the fact that over 200MW in production capacity has been announced in the last 12 months (2006) along with 8% -10% efficiency, eclipsing previous capacity growth and performance.

Table 7 – Specific research topics for thin film Silicon

	Immediate priority	capacity building	background research
S	• Production PECVD systems for deposition of microcrystalline-Si • Development of improved device layers (e.g. µc-Si, nc-diamond) • Development of thin film polycrystalline Si[49]		
W			
O	• Large area processes for amorphous, microcrystalline and polycrystalline Si • Plasma process control[50] • Quantitative understanding of electronic properties of layers and interfaces in devices • Quantitative understanding of light	• Demonstration of next generation equipment with lower material use, higher throughput and higher efficiency[51] • Alternative techniques for absorber deposition • New techniques for high-rate deposition	• Design and development of ultra –high throughput lines/reactors[52] • Incorporation of quantum dots or spectrum-converting effects in thin film Si • Combination of thin film Si with other absorbers/PV technology merging

[49] Processes to produce large-grained poly-Si layers (grain size » film thickness) in adequate thickness need to be developed and optimized, and scaled to large areas. These include the approach of low temperature epitaxial thickening of large-grained seed layers produced by various processes. For pc-Si, research is needed on low cost substrates, substrate/film interactions, crystal growth, grain size enhancement and controlling grain orientation. Low temperature growth on flexible substrates is also an important area of study.

[50] For plasma CVD, deposition parameters such as plasma density, gas chemistry, process speed, substrate temperature, etc have a significant impact on material structural and electronic properties and uniformity over large areas. These inter-dependencies need to be fully understood and higher deposition rate processes developed. Deposition process control and in-line diagnostics need to be fully developed.

[51] For the medium and long term the focus needs to be even more on cost, which means that we really need to think on a different scale. To illustrate this you need to look at comparative industries such as the architectural glass industry and steel cladding industry, who both operate and coat their products at a truly mass production level.

It is when we achieve this level of operation that PV will play the major role in energy provision. And because silicon, in a crystalline form, is stable and it does not contain any rare earth materials, it is probably still the best candidate for 'super production scale' manufacture; where long life will be a major driver. However this will require the development of non-vacuum based technologies, producing thin film poly or micro silicon films at high volume. Consideration must also be given to the architecture of mass production equipment. For example the APCVD systems deployed at the end of a glass line, to produce the architectural glass coatings, utilize the fact that the glass is already at a high temperature, thus avoiding the need to add further energy cost to the product. The UK leads both the development of large volume glass and glass coating production as it does in the steel industry, which the solar industry needs to take advantage from. To take these principles forward, we first need to take a fundamental research approach, to open up new thinking, looking at all the likely technologies and proving concepts. Once this has been completed, we then need to move to the next phase, which will be to build small pilot systems, so the methodology and concepts can be developed and evaluated.

[52] New techniques and deposition reactor concepts for very high rate deposition over large areas are an important requirement. Methods such as microwave CVD and hot-wire CVD could have a role to play here and need to be investigated further with extension to higher pressure regimes. Solution processing of TFSi could be a future disruptive technology.

	trapping	• Use of plasmon effects, photonic crystals, diffraction effects, effective medium approaches, etc.	

Thin film Silicon footnotes continued

5 Advanced PV devices

This section covers novel excitonic devices (both dye cells and polymer cells), quantum wells and quantum dots for improved photon capture and conversion and concentrator systems.

5.1 Excitonic devices

Table 8 – Research topics for Excitonic devices

		Immediate priority	capacity building	background research
Dye Solar Cells	S	• Develop and extend device optimisation and materials base in oxides, electrolytes, dyes[53] • Develop cost-effective module manufacturability[54]		
	W	• Improve device lifetimes[55] • Higher efficiencies[56]		
	O	• Establish and embed UK-located commercial base[57]		
Organic Solar Cells	S		• Develop and extend device	

[53] The UK possesses world-leading University groups with research linked through a Supergen network. Organic optoelectronics R&D and production in the UK is of a very high quality.
[54] The best lab devices are batch prepared on glass substrates. There is a need to develop continuous manufacture on flexible substrates to take advantage of the potential for very low costs.
[55] Current device lifetimes are too short to be competitive for mass power generation within the built environment and initial commercial ventures are directed more towards consumer and specialty goods. Development of materials and processing should enhance lifetimes.
[56] Development in module design could allow mass-produced modules to better approach the efficiencies achieved in lab devices of up to 11% for example through improved fill factor. Better materials could allow for example better spectral matching, light-harvesting or charge collection.
[57] While world-leading commercialisation is underway (G24 Innovations is to manufacture in the UK through a licensing deal with Konarka and EPFL Lausanne) we should take the opportunity to rapidly establish the critical mass needed to secure the UK competitive position in this field. The academic community and new commercialisation developments should build mutually-beneficial interactions upon a sustainably funded academic base to continue the expansion of the commercial sector. The capital investments required to scale up production are comparatively small and this could allow rapid growth of this technology if manufacturing can be embedded.

			optimisation and semiconductor materials base[53]	
	W		• Achieve better device lifetimes and higher efficiencies[58]	
	O		• Establish UK critical mass[59]	

[58] Currently these are too low for commercial development with the best lab devices around 5%, which is approximately half of that achieved with dye solar cells. Improvements in recent years have been rapid however and this technology is viewed as a possible follow-on, with commercialisation of dye solar cells coming first.
[59] The strong UK academic base in organic optoelectronics could allow the UK to take a leading position in this area if this can also build on complementary developments and commercialisation in the dye solar cell area. Recent support via the Carbon Trust's PV Accelerator programme is in the process bringing together researchers and industry to create commercial opportunities which may transform the activity in the UK.

5.2 Quantum wells and dots

Table 9 – Quantum wells and dots and thermal photovoltaics

		Immediate priority	capacity building	background research
III-V Solar Cells (exp. Quantum Well Solar Cells) [60]	S	• Aim for 40% 3-junction cells within 2 years		
	W	• Improve device fabrication facilities		
	O			
(N) Colloidal Semiconductor Quantum Dots [61]	S			
	W		• More facilities for material preparation needed	
	O		• Focus research on the application to concentrator systems • Two UK companies are operating in this sector[62] and research should be directed in support of their technologies	

[60] Commercialisation is under way for which world leading wafer growth is available in the UK, but for which a national device fabrication facility is urgently needed to avoid a manufacturing bottleneck and provide secure UK device manufacturing. Possible candidates are CST Glasgow, CIP Ipswich, Caswell Bookham, Optic Technium Wales, New fab/incubator facility at Sheffield University, etc.
[61] The UK is among the world leaders in this field with a novel approach which requires further R&D to improve quantum efficiencies at longer wavelengths. If successfully developed this would have a strong impact on solar concentrators and on up/down converters.
[62] Trackdale and Nanoco.

(N) Up/Down Conversion, Plasmonic effects etc. [63]	S			• Need to capitalise on UK expertise in this area through demonstration of Up/Down converters
	W			
	O			
(E) Thermo-Photovoltaics [64]	S			• Expertise and test facilities developed during the last few years should be made use of
	W			
	O			• Hybrid (solar+TPV) systems merit further development

[63] Basic R&D required which should benefit from the strong UK optoelectronic research activity. The result of these activities could also impact on section IV through improved quantum efficiencies at longer wavelengths.
[64] Hybrid solar+TPV (round-the-clock) microgeneration systems should be considered and investigated taking advantage of the existing UK expertise on cells, solar concentrators and refractory materials. The UK effort needs to focus on system development.

5.3 Concentrator PV systems

Table 10 – Research topics for Concentrator system

		Immediate priority	capacity building	background research
Concentrator Systems [65]	S	• Design expertise, R&D in optics and testing facilities should be applied to the challenge of improving concentrator system designs • Potential application of UK designs to the development of PV curtain wall structures		
	W	1. Manufacturing facilities needed to move technology to demonstration phase		
	O	2. Potential to assist UK companies improve concentrator system designs		

[65] There are two UK companies, Whitfield Solar and Solarstructure, close (less than 2 years) to commercialisation with novel technological approaches. Whilst the world-leading concentrator-cell designs and materials are available in the UK, the national (device fabrication) facility discussed under III-V Solar Cells would boost the commercialisation of these systems. Cross fertilisation with UK optical and optoelectronic industries would also benefit this sector. Whitfield Solar's products are standalone concentrators (mainly for foreign markets) while Solarstructure's BIPV concentrators are also appropriate for installation in the UK

6 Balance of Systems Components and Other Systems Issues

Major cost factors, often overlooked, are the contributions beyond the semiconductor itself. Making the semiconductor into a useable device can contribute as much as 50% to the overall module cost and these account for roughly 50% of the installed PV system cost. Thus 75% of the costs are non-device related. Despite this, they attract only a limited amount of interest; which might account the level of failures seen in the field.

A large number of components contributes to an overall system and the energy generation is determined by the whole ensemble and unfortunately the quality of different components is not additive. In the contrary, if the best inverter is imperfectly matched to the best module, the overall system will under perform and thus the cost of energy will be disproportionately high. Unfortunate examples in the UK field trials have demonstrated that some systems produce as little as ¼ of the energy yield expected, quadrupling the energy generation costs.

Table 11 – Research topics for BOS and other systems aspects

	Immediate priority	capacity building	background research
S	• Low cost support structures (including PV roof tiles), connectors, cables etc[66] • Minimisation of system losses[67] • PV as a building element, improved functionality [68] • Assessment of value of PV within the micro-generation context[69] • Advanced diagnostic tools [70] • Energy rating etc [71] • LCA [72]	• New concepts for stability and control of electrical grids at high PV system penetration levels[73]	
W		• Inverter development: improvements in performance including MPPT/ cost/ reliability/ lifetime (W2)[74]	• Development of new storage technologies (W3? S2)[75] • New battery technology and management

[66] There is a pressing need to reduce system costs. Installation costs are affected by the detailing of the technology. There is a reasonable commercial strength that should be nurtured to address these issues, it is of immediate need as it addresses installed system cost in the short and medium term. Research in this area would consider the development of components and techniques that are widely applicable whilst providing the flexibility needed for the variety of UK applications.

[67] Low PRs have been recorded in the UK for some systems. Useful steps can be taken to improve this, in particular module designs for high energy yield in the UK: shading tolerant; low angle of incidence tolerant; spectral design for improved yield; thermal and electrical mismatch tolerant. This may be cross linked with the module development associated with individual technologies.

[68] thermal properties, maybe heat production, self cleaning, consistency with construction techniques

[69] Financial rewards to PV generators will be influenced by an understanding of the value of this form of micro-generation to the electricity supply system. These in turn will critically determine the market growth. It is important to assess the value of PV generation in the context of other micro-generation sources and the operational aspects, both technical and economic, of the UK electricity supply system.

[70] Systems often under perform in ways that are difficult to identify. Low-cost diagnostics could reduce the cost of energy generation significantly. This might include system specific approaches as well as inclusion into smart building controls and other advanced communication strategies. Work will have a long term focus to allow for emerging technologies.

[71] It is urgently required to give reliable energy estimations for PV systems to underpin market development. This needs to be done for existing technologies immediately and in the longer term for the currently emerging technologies as appropriate. Research into the performance of systems under UK climatic conditions informs this need, along with an understanding of how current system output estimation tools should be adapted for UK situations.

[72] There is a lack of awareness of energy payback periods, specifically in the UK context. Establishing the real numbers is crucial to maintain public acceptance and should be established in the short term (S1). Further capacity building is required to enable a European consensus (S2). There is an existing strength in energy analysis at Northumbria University.

[73] DNOs need to be assured that PV will not disrupt their operations. In planning for the future the DNOs need to understand the technical impact and agree steps to ameliorate this. Network design and inverter operation to accommodate very high levels of PV penetration is thus an important topic. DNOs as well as inverter manufacturers should be engaged in this process.

[74] There is considerable UK strength in power electronics (design and manufacture as well as university research), but currently not directed at PV. As PV system sales increase there will be significant market opportunities for inverter manufacturers. To capitalise on these markets, UK companies need to work with

			systems (W3? S3)[76]
O	1. Reliable lifetime estimation of key components [77] 2. In line production control[78]	3. Prefabrication [79]	4. Design for recycling [80]

researchers to develop new improved products. There will be knock on benefits to the PV community in terms of increased energy yield and reduced per unit electricity costs.

[75] There is an emerging UK strength in Flowcell technology. This may well not be applicable to PV in the UK. However, because of the wider implications of storage in electricity network this research may be attractive.

[76] The UK has a lead in innovative high temperature batteries which are not yet applied to PV. Engaging them with PV will create significant market opportunities. Specifically the battery characteristics and management systems may require adaptation to the behaviour of PV.

[77] Energy costs rely on the design lifetime of the system components and reliable techniques are required for estimation and assurance of lifetime. This work is probably best done in collaboration with other countries in Europe, but with UK requirements and conditions represented.

[78] There is a large capability of process control within the UK, which could be developed into PV specific applications. This potentially would allow a very significant reduction in production costs by increasing yield and quality. Some approaches will be generic and apply to all PV technologies, but most will probably be technology specific.

[79] There is an opportunity for significant cost reduction through prefabricated units for building installation which currently is not exploited specifically by the UK's building industry.

[80] As modules and components develop design for recycling should be introduced as a integral part of the R&D process, specific research projects might be defined where a need is identified. New chemical extraction processes could reduce the cost of recycling of current and emerging technologies. The UK has a strong chemical industry which should able to carry out such activities.

7 Research Support and Research Infrastructure in the UK

As already mentioned, the backbone of current UK PV research is formed by the two EPSRC Supergen consortia: PV Materials for the 21st Century, and the Excitonic Solar Cells Consortium. In addition, the UK is participating in projects supported within the EU FP6 Programme. Compared to Germany, Japan, USA, Switzerland and Korea, to mention just a few, the UK research programme is small. In addition, as documented by UKERC, the research community is rather fragmented, and most notably it lacks the kind of dedicated central facilities or national laboratories that can be found in most other PV active countries. These countries have each used such facilities very effectively to drive forward their PV development programmes, enabling the gap between research (both basic and applied) and pilot scale production to be bridged.

Some general central facilities of relevance do exist such as the III/V facility in Sheffield and, specific to terrestrial photovoltaics, there are important but limited facilities at Northumbria and Southampton. In the field of wafer silicon cells, the NaREC facility is arguably the only true UK central facility dedicated to cell production. All these are described in some detail in Appendix 2. Both the long-term maintenance of equipment and the retention of specialist staff beyond the lifetime of individual projects are difficult in the purely academic environment. Central facilities can play an important role in providing well supported experimental capability and also provide stable career path development for key specialist PV researchers. Such central facilities could be operated along similar lines to the III/V Facility at Sheffield and the Ion Beam Facility at Surrey. They would build a pool of knowledge and experience to be made use of by researchers to improve the quality of their activity.

Good models for the operation and support of such facilities can be found overseas. In the main funding is from central or regional government with strong involvement of both academia and industry. For instance, in Germany, the Fraunhofer ISE and in the USA, NREL, provide a flexible manufacturing facility enabling different combinations of manufacturing and characterisation to be assessed. The “Process Development and Integration Laboratory” (PDIL) within the new “Science and Technology Facility” at NREL will be aimed at integrating prototype processes in a flexible manner for thin film technologies. In Japan much of the research is co-ordinated by manufacturers with governmental support from NEDO to establish pilot production, and a major central facility is provided at AIST.

Consultation carried out within the UK indicates clearly that establishing appropriate central facilities for PV is considered essential. Specifically there was strong support for a central facility for thin film PV. It was appreciated that the facility and its development would need to be flexible so as to address the wide range of promising PV materials, and that possible cross-contamination issues due to the diversity of thin-film materials would need to be addressed. In device engineering there is a common interest in solutions that have been identified by other groups or industries around the world; special facilities and expertise are required to implement these approaches. In academia, failure to produce well-engineered devices can mask valuable research results. Poor device performance may simply be the result of poorly optimised designs and overcoming this requires a mixture of expertise and equipment resources. There are several issues of common concern to thin film PV researchers. These include transparent conducting oxides (TCOs) with the appropriate combination of electrical, optical, structural properties; interconnects between cells; laser scribing; packaging of modules; in situ diagnostics for the thin-film deposition to provide monitoring for feedback control; continuous roll production; standardised testing and characterisation. A suitable central facility would help in bringing the expertise together to work on these problems. Two centres based in the North East of England may be able to contribute to a future thin film facility: the Centre of Excellence in Nanotechnology, Micro and Photonic Systems (CENAMPS)[81] looking at thin flexible displays & PV; and the Centre for Process Innovation (CPI)[82] integrating developmental technologies on a pilot scale. Moreover, at St Asaph in North Wales there is the Technium OpTIC (Opto-electronics Technology and Incubation Centre) that showcases 1000 m^2 of thin film CIGS on its façade[83]. This facility hosts some major UK projects involving universities from across the UK, and being located in Wales, can access European regional grants. In addition there may be cross fertilisation between thin film PV and the glass and optics manufacturing knowledge in the area. Light-trapping and cell/module packaging are important aspects of thin film PV design that may gain from solutions taken from glass research.

Another facility might be directed specifically at bridging the gap between basic and applied research on the one hand, and industrial scale production on the other. Such a laboratory would need to have PV cell production facilities that represent the most attractive production technologies, i.e. in-line and roll to roll processing. However, at this early stage it is far from clear how wide a range of technologies such a centre should deal with. It may be that very specialized processes such as quantum well formation would be best provided by a different facility. And again, polymer cells involve rather different science, technology and production processes so might be better supported by a dedicated facility.

Historically the UK has a poor record in overcoming the transition from basic research through pilot production to full-scale manufacturing. Scaling-up of processes must be considered even before all technical problems have been solved at the research laboratory scale. Taking PV from research laboratory to commercial production requires one or more central facilities of the type outlined above. For successful implementation, key issues such as long-term funding, technical strategy, location and how to incorporate various stakeholders will have to be resolved. There is a risk that if the development of suitable central facilities is delayed, the gap between what the UK can achieve now and what other countries have already achieved will become much more difficult to cross.

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[81] http://www.cenamps.com
[82] http://www.uk-cpi.com
[83] http://www.technium.co.uk/index.cfm/optic_technium/en5956

What is needed now, and urgently, is to start the debate with the funding agencies around central facility provision so as to not drift further behind the main players through inaction. The proposed Energy Technologies Institute could provide an ideal platform for these developments. Alongside the strengthening of research, there needs to be a growing commercial activity responding to the demands of a growing UK market for PV. Indeed to hit the targets set in Section 1, the UK requires significantly improved market stimulation measures.

Appendix 1 Participants in Edinburgh PV road mapping exercise

Barnham, Keith	Imperial College London
Bonnet, Dieter	SOLARPACT
Bruton, Timothy	NaREC
Ferekides, Chris	University of South Florida
Gottschalg, Ralph	CREST, Loughborough University
Infield, David	UKERC and Loughborough University
Irvine, Stuart	University of Wales Bangor
Jansen, Spencer	Jantec Solar
Mason, Nigel	BP Solar
Mazzer, Massimo	Imperial College London
Pearsall, Nicola	Northumbria University
Reehal, Hari	London South Bank University
Robertson, Neil	University of Edinburgh
Scott, Mike	IQE plc
Sinke, Wim	Energy Research Centre of the Netherlands
Skea, Jim	UKERC
Wilson, John	Heriot-Watt University

The professional facilitator was Penny Walker of the Environment Council, Jane Palmer of the UKERC Meeting Place organised the event and Aurelie Mejean took notes during the event. Jim Skea of UKERC outlined the nature of organisation and David Infield described the road mapping exercise.

Break out group membership:

- Existing thin films (SJ, CF, DB, SI, HR, JW)
- Crystalline Wafer Silicon (WS, NM, TB)
- Advanced concepts (NR, MM, KB, MS)
- BOS systems, horizontal, SSE (RG, NP, DI)

Appendix 2 UK Central Facilities Relevant to PV

Four central facilities of relevance to the PV community have been identified: the III-V facility at Sheffield University, NaREC's PV Technology centre, the University of Northumbria's PV testing facility, and Southampton University's PV systems test facility[84]. Details of the capabilities of these facilities are provided below.

EPSRC National Centre for III-V Technologies

This centre is based within the Department of Electronic and Electrical Engineering at Sheffield University. III-V technologies are used for high performance solar cells. Although these are mainly used for space applications, there is an interest in their use in concentrator cells as made clear in the research road map. Researchers from Imperial College have made use of the facility to investigate the MQW strain balanced pin solar cell (SBMQW). This extends the absorption edge of the central cell to ~950nm from the GaAs value of 870nm, providing better current matching to the upper p/n GaInP and lower GaAs/Ge junctions. Work at the Centre has shown that depositing $GaAs_{0.91}P_{0.09}$ at a temperature of 600C provides well defined MQW interfaces, but increasing the growth temperature results in a partial relaxation of the structure in the form of interfacial texture. The highest performing single junction MQW pin cells on GaAs have now exceeded the efficiency of conventional p/n GaAs devices when measured under AM1.5 radiation.

Deposition Facilities

a) A VG V80H single 2 inch wafer MBE reactor with up to ten source ports.

   It is equipped with an arsenic cracker, one gallium, two indium, one aluminium, one silicon, one beryllium solid source knudsen cells, one nitrogen plasma cell, and one antimony cracker. This configuration gives it the flexibility to grow several different III-V compounds on GaAs and InAs substrates. This MBE can be used to grow quantum dot structures and p-i-n diodes.

b) A VG V90 4 inch, 3 inch or 3 X 2 inch wafer MBE reactor with up to twelve source ports.

   It is equipped with an arsenic cracker, a phosphorus cracker, two indium, two gallium, two aluminium, one silicon and one beryllium solid source knudsen cells and one nitrogen plasma source. A Laytec EpiR optical monitoring system provides in-situ spectral reflectivity and temperature measurement. The system is dedicated to the growth of optoelectronic device materials, mainly focussed on InGaAs growth on GaAs and InP substrates.

c) A MR350 provides one or two 2 inch wafer capacity growth for the alloys matched to InP as well as (Al)GaInP deposited on GaAs.

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[84] Southampton University's silicon processing facility is no longer operational.

Thomas Swan robot loading 7x2" flip-top showerhead reactor

This multi-wafer growth (7x2" or 3x3") reactor includes novel switching and in-situ reagent purification technology developed within the National Centre. Future development with this reactor will include the growth of Quantum Cascade Lasers for the 5 to 10 micron wavelength range and strain balanced MQW pin solar cells. Both these devices place tight demands on multiple thin layer MOVPE growth.

Nitride MOCVD using Thomas Swan Reactor

The susceptor is capable of growth on three 2" wafers at one time. A three-zone resistive heater gives uniform heating, to temperatures in excess of 1100°C. The reactor is capable of being operated over a wide range of growth pressures.

Device Fabrication

a) Electron Beam Lithography - a Raith 150 electron-beam lithography (EBL) system is capable of producing nanostructures with dimensions of the order of 20nm. Since its commissioning in November 2001, this facility has played a major role in a number of nanotechnology research projects, and will continue to do so in the years ahead.
b) Dry Etching
c) Plasma Therm 790 Series PECVD for deposition of SiN_x and SiO_2
d) Mattson RTP for annealing samples for intermixing, and formation of metal contacts.

Metrology

Philips FEGSEM, Dektak profilometers, and ellipsometer, for inspecting critical dimensions and layer refractive index and thickness.

Characterization

a) The assessment facility provides the growers with rapid, detailed information about the structures grown and helps identify problems when they arise. The work also involves electrical measurements on final device structures manufactured within the device fabrication laboratories. A large fraction of our customers now request that the wafers and devices come supplied with characterisation information, where possible, and we now routinely satisfy this requirement.

b) Photoluminescence (PL) measurements can be undertaken using wavelength dispersive measurement systems.
The PL of GaAs and InP based materials is usually measured using a dedicated long wavelength (up to 1700nm) PL system with a cooled Ge detector. The excitation is provided by laser emission at wavelength of 532nm. With another laser emitting at 1064nm wavelength and a cooled InSb detector, this same setup is also used for PL measurements with wavelengths longer than

1700nm. Electroluminescence measurements are also carried out routinely using this setup. For the wider bandgap GaN-based materials, another short wavelength PL system with a cooled Si CCD array detector is used with the excitation provided by either a 325nm laser or an Argon-ion frequency-doubled laser (wavelength of 244nm).

Both PL setups described above are equipped with cryostats and temperature controllers to allow measurements of PL at temperature from 12K to 300K. In addition to these setups, there is an the Accent RPM2000 PL setup allowing automatic mapping of the PL of the wafer under test at room temperature, using 633nm and 543nm excitation sources. Using tungsten halogen or xenon mercury light sources and monochromators, there are also separate facilities for measuring photocurrent and reflectivity at wavelengths ranging from UV to near IR.

c) Electrical characterisation (Current-Voltage and Capacitance-Voltage characteristics) is often used to characterise devices fabricated in the Centre. The device can be cooled down to 12K for low temperature measurements of Current-Voltage characteristics. Reverse breakdown characteristics can be measured more accurately using separate photomultiplication measurement setups equipped with lasers emitting at different wavelengths.

   There is a separate facility for on-wafer laser diode characterisation. An ILX laser diode driver and a HP optical spectrum analyser are used to assess the laser emission from the visible to the near IR.

d) Structural characterisation is undertaken by XRD measurements. Simple lattice mismatch are routinely measured using a QC2A and a BEDE Model 200. For more complicated measurements, there is a Bede D1 system with higher x-ray intensity and wider range of diffraction conditions, compared to the other two x-ray systems.

NaREC PV Technology Centre

The centre offers a well equipped solar cell process line and characterisation laboratory operated by an internationally recognised research and development group with over 60 man-years experience.

The facility is managed and operated by the New and Renewable Energy Centre - a Centre of Excellence created in the North East of England to provide enablement, testing and development services to the energy sector. Key features of the centre include:

- Full process capability for small scale production of high efficiency Laser Grooved Buried Contact (LGBC) solar cells
- Solar cell interconnection and lamination
- Silicon wafer and solar cell characterisation
- Solar module test facilities including solar simulator, environmental chamber and light soak

Other facilities available are:

Wafer Processing

a) Wet chemical etching
b) Phosphorous diffusion
c) LPCVD silicon nitride
d) Laser patterning & cutting
e) Plasma etching
f) Wet/dry silicon dioxide growth
g) Metallisation (sputter-deposition and electroless plating)
h) Controlled atmosphere sintering

Cell Characterisation

a) Light & dark I-V measurement
b) Spectral response
c) Dielectric layer thickness
d) Reflectance
e) Metallisation analysis and thickness

Wafer Characterisation

a) Minority carrier lifetime
b) FTIR impurity analysis
c) Wafer thickness (non-contact)
d) Bulk & sheet resistivity (4 point probe)

University of Northumbria's PV testing facility

Northumbria University has two Class A solar simulator systems, purchased under a DTI grant, for the measurement of solar cells. The larger simulator is capable of measuring samples up to around 300 mm in diameter at the required uniformity and is coupled with a spectral response measurement unit capable of measuring samples up to 100 mm in diameter, with white light bias. The close match simulator accommodates smaller samples (up to around 35mm in diameter) but has the capability for manipulation of the spectrum due to its multiple lamp system. This is useful for measuring novel and advanced cell designs, including multijunctions or quantum well devices.
With this simulator, we can get a five-fold improvement in matching of the spectrum to the AM1.5 standard when compared to the Class A specification.

Southampton University's PV systems test and reference STaR facility

The Southampton STaR facility was constructed in 1994 with support from the DTI New and Renewable Energy Programme to assist a successful development and integration of photovoltaics in the UK. The Facility provides:

- A reference photovoltaic system on which apparatus and ideas may be tested and evaluated
- A training centre in all aspects of photovoltaics
- Advice and consultancy in photovoltaics and utility integration issues

Facility is situated on the roof of the Engineering Faculty Lanchester building, and comprises a photovoltaic generator connected via a power conditioning subsystem to the public electricity supply. An extensive monitoring scheme with automatic data acquisition provides detailed information about the system operation. Solar radiation data and other environmental parameters are provided by a dedicated weather station in the University's Chilworth Science Park, as well as by a number of sensors at the Lanchester site.

The Facility is constructed using state-of-the-art components which include:

Two 1.7kWp Photovoltaic Arrays using 40 high-efficiency BP Solar Saturn modules based on the laser-grooved crystalline silicon technology.

An experimental PV facade comprising 660Wp single crystal Solec cells, 540Wp multicrystalline Eurosolare cells, and a 400Wp Intersolar amorphous silicon array. It was the first PV facade constructed on the south coast of Britain, and - in addition to research - it serves as demonstration of photovoltaics in buildings.

All arrays can be configured to supply power at the required voltage for the inverters.

Power Conditioning A number of inverters are being tested at the facility. Up to 12 inverters - ranging in power from 100VA to several kVA - can be tested in parallel. The Facility specialises in islanding tests with single and multiple PV inverters as well as using PV inverters in combination with conventional rotating generators.

Weather station at Chilworth records global solar radiation on a horizontal plane using a WMO Class 1 thermopile Kip & Zonen pyranometer. Wind speed, wind direction and ambient temperature in the shade are also recorded. A dedicated data logger is linked to the Lanchester site by a telephone line, allowing data retrieval and real-time comparison with the operation of the PV system. The sensors at Lanchester site measure the in-plane solar irradiance, the ambient temperature and the operating temperature of the solar cells.

System operation is monitored by an automatic data acquisition system which allows a comprehensive waveform characterisation and transient analysis of the AC output in addition to a detailed characterisation of the DC output of each string. Both DC and AC bus bars can be reconfigured in a number of ways, including the incorporation of impedance loads to monitor the interaction between several PV generators embedded in the utility distribution system.

The Facility offers the following services:

Testing and performance monitoring Inverters and utility interfacing equipment can be tested in a variety of conditions and configurations

Research, development and consultancy The Facility provides consultancy and carries out research in a number of areas in photovoltaics, specialising in the integration of photovoltaic systems into utility supply networks. The current research programme contributes to the experimental Task 5 Programme of the International Energy Agency, the UK Photovoltaic Power Systems Agreement, and includes work funded by the Engineering and Physical Sciences Research Council and the Royal Academy of Engineering. The Facility participates in the development of new standards for PV integration, and a full service is expected to be available from autumn 1998.

Education and training Courses and seminars on all aspects of photovoltaics are organised at the Facility, and specific courses can be arranged on request. Click here for examples of teaching materials and a recent UNESCO/British Council Seminar.