



**Economic Analysis of Nanotechnology for Energy Applications**

## 1. Table of Contents

Table of Contents .....	2
Executive Summary.....	3
1. Methodology.....	5
1.1. Definition .....	5
1.2. Methodology for Preparing the Report .....	5
1.3. Methodology for Quantitative Assessment.....	5
2. General Market Description .....	6
2.1. Brief Market Description .....	6
2.2. Nanotechnology Impact .....	7
2.3. Drivers and Barriers to Innovation.....	9
2.4. Relevant Sector Segmentation and Applications .....	10
2.5. Possible Future Products and Time Range.....	10
3. Application Profiles.....	11
3.1. Solar Photovoltaics .....	11
3.1.1. Short application description .....	11
Functional requirements .....	15
3.1.2. Boundary conditions.....	15
3.1.3. Product examples.....	18
3.1.4. Economic Information and Analysis .....	19
3.1.5. Selected Key Companies Profiles.....	24
3.2. Batteries .....	27
3.2.1. Short application description .....	27
3.2.2. Functional requirements .....	28
3.2.3. Boundary conditions.....	29
3.2.4. Product examples.....	30
3.2.5. Economic information for present products .....	30
3.2.6. Selected Key Companies Profiles.....	31

## 2. Executive Summary

The energy market encompasses a vast range of economic activity, from the extraction of fossil fuels, generation of energy – by burning coal to generate electricity, for example; distribution, and consumption.

Nanotechnology has the potential for significant impact at all stages of the energy value chain. A number of oil companies are investigating ways in which nanotechnology can improve the effectiveness of oil drilling. One of the main applications for nanotechnology in energy generation is solar photovoltaics, with thin film solar technologies, using CIGS and CdTe, and dye-sensitized solar cells. Energy storage is also affected by nanotechnology. Novel electrode materials are already commercially available and are increasing the power density and stability of batteries.

The primary driver – and it is of immense importance – is the increasing awareness of the threat of climate change, and a policy climate which reflects that. Companies which are developing energy technologies that do not produce significant quantities of CO<sub>2</sub>; generating energy from the sun, the wind, water and vegetable matter; know that they will have access to a supportive policy environment and an investor community which is very focused on developing these technologies.

Currently two applications of nanotechnology for energy are considered; solar photovoltaics, and batteries.

Solar photovoltaic (PV) cells convert sunlight to electricity. As an indication of the market potential, some projections call for 12% of Europe's electricity needs to be satisfied by solar generation by 2020, a total of 420 terawatt hours (TWh). Solar PV applications can be divided into grid-connected, off-grid systems, and portable applications. A number of companies have commercial products and development activities focused on nanotechnology-based solar technologies.

The battery market is expected to grow substantially in the coming years. This is partially driven by growth in existing battery applications – particularly laptops, 'netbooks' and mobile devices. However, the primary driver will be new applications, particularly in the automotive industry.

Nanotechnology for batteries is a very active field of research and development. Nanotechnology can provide an improved solution to important functional requirements such as power density, charge/discharge efficiency, and self discharge rate, as well as making the batteries themselves less volatile.

## **3. Methodology**

### **3.1. Definition**

For the purposes of this report, nanotechnology is defined as “the study of phenomena and fine-tuning of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.”<sup>1</sup>

The specific focus of this report is on applications of nanotechnology for energy, including solar photovoltaics and batteries.

### **3.2. Methodology for Preparing the Report**

The development of this report has been a three stage process. Desk research using publicly available sources of information was used to produce a first version of this report. Input and feedback is then sought from experts, via questionnaires, interviews and discussions, and from the ObservatoryNano symposium which takes place in March 2009. A final report is then produced, which synthesises the desk research and external expert input.

### **3.3. Methodology for Quantitative Assessment**

Quantitative assessments of market size, growth rates, and the current market shares of nanotechnology enabled products are developed using external data sources such as market research providers, industry groups, and individual experts. Estimates and market size projections that are made by the authors of this report are clearly marked as such.

All forward looking estimates are necessarily a projection, and are therefore subject to error within the market models themselves, as well as to unforeseen external events. In particular, the current economic crisis has forced countries and companies to significantly adjust their growth forecasts – in most cases, this will not have been taken into account in projections which date from before 2008.

---

<sup>1</sup> Introduction to Nanotechnology, [http://ec.europa.eu/nanotechnology/index\\_en.html](http://ec.europa.eu/nanotechnology/index_en.html)

## 4. General Market Description

### 4.1. Brief Market Description

The energy market encompasses a vast range of economic activity, from the extraction of fossil fuels, generation of energy – by burning coal to generate electricity, for example; distribution, and consumption. A simple value chain is shown below:

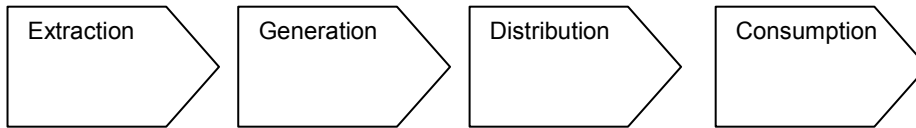
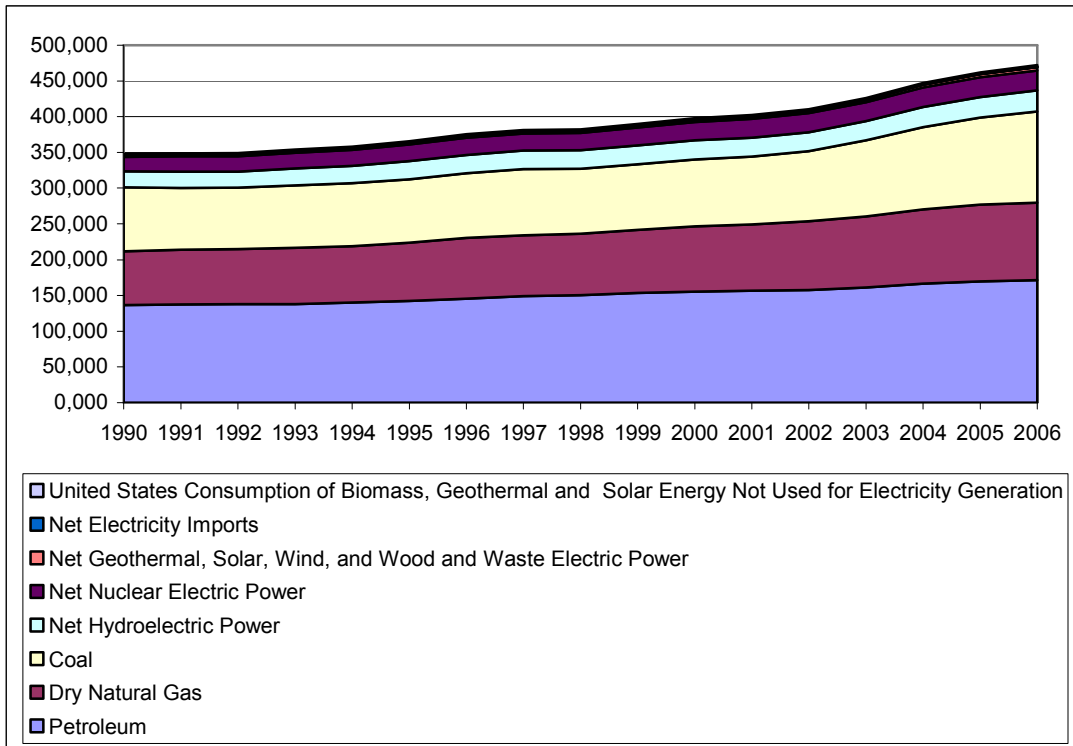


Figure demonstrates global energy consumption (measured in quadrillion Btu's) over the period 1990 – 2006. World energy consumption has increased at rates of between 1% and 5% over the period, for compound consumption growth of 36% in 16 years. Fossil fuels continue to account for the majority of energy consumed, representing a share of 86.2% in 2006. This proportion has remained basically consistent, having been 86.6% in 1990.



The threat of climate change (see for example the Stern Report<sup>2</sup>) has highlighted the environmental damage caused by a build up of carbon dioxide in the atmosphere. A substantial proportion of CO<sub>2</sub> is generated by activities in this energy value chain; burning fossil fuels in a power plant, a factory or a vehicle. Therefore, and with varying degrees of success, renewable energy sources are being introduced.

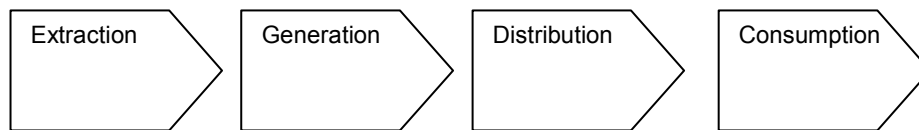
The macro-level consumption figures obscure growth in renewable energies, albeit from a fairly low base. For example, 2008 saw wind energy capacity grow by 28.8% to 120.8 GW, with 27 GW coming on stream during the year. The market value of the wind industry was € 36.5 billion, and it employs 400 000 people. A third of new capacity was installed in Asia, doubling China's capacity to 12.2 GW.<sup>3</sup>

The European Photovoltaics Industry Association estimated that installed solar PV capacity in 2007 was 2.25 GW, and that the amount installed per year would increase to 7.3 GW by 2012. Hydroelectric power generation accounts for energy consumption of 29,728 quadrillion BTUs. This is fractionally more than the amount of energy produced by nuclear generation.

Efforts to price in the effect of CO<sub>2</sub> emissions, including the EU Emission Trading Scheme, increase the costs of fossil fuel usage, further driving adoption of alternative technologies. There are also other pressures beyond climate change on the current energy economy. The world's oil resources are finite; as oil becomes more challenging to extract, prices will rise. Post-extraction, there is a global shortage in refining capacity to turn crude oil into usable petroleum products.<sup>4</sup>

## 4.2. Nanotechnology Impact

Nanotechnology has the potential for significant impact at all stages of the energy value chain:



---

<sup>2</sup> <http://www.occ.gov.uk/activities/stern.htm>

<sup>3</sup>

[http://www.gwec.net/index.php?id=30&no\\_cache=1&tx\\_ttnews\[pointer\]=1&tx\\_ttnews\[tt\\_news\]=177&tx\\_ttnews\[backPid\]=4&cHash=cc6f0e93a2](http://www.gwec.net/index.php?id=30&no_cache=1&tx_ttnews[pointer]=1&tx_ttnews[tt_news]=177&tx_ttnews[backPid]=4&cHash=cc6f0e93a2)

<sup>4</sup> <http://www.researchandmarkets.com/reports/451126>

## **Nanotechnology for Energy Extraction**

Technologies include sensors that can be injected into oil reservoirs in order to provide information about the location, consistency and presence of oil deposits.

Nanotechnology could also be used in the process of converting crude oil to petroleum; a filter which is composed of carbon nanotubes was found to filter large hydrocarbons from oil.<sup>5</sup>

## **Generation**

One of the main applications for nanotechnology in energy generation is solar photovoltaics. Thin film solar technologies, using CIGS and CdTe, now account for 10% new solar installations, and are a very active area of development; especially in production optimisation. Dye-sensitized solar cells are another promising technology area, and dye-solar has already given rise to commercial products, albeit in far smaller quantities than thin film approaches. Nanotechnology has the potential to generate step changes in the efficiency and production cost of solar.

Nanotechnology can also assist in other areas of energy generation. Mechanical methods; wind turbines, and gas turbines, can benefit from improved efficiency due to material innovation. CNT-composite material for wind turbine blades can prevent shearing and increase the lifetime of the turbine. Sensors on a turbine blade could detect build up of fouling and increase preventative maintenance.

## **Supply**

Energy storage is also affected by nanotechnology. Novel electrode materials are already commercially available and are increasing the power density and stability of batteries. Retrofitting nano-enabled batteries to hybrid Toyota Prius<sup>7</sup> is increasing their range (and therefore their attractiveness). More generally, improvements in battery technology will increase the speed with which electric vehicles and hybrid-electric vehicles can take over from conventional combustion engines.

Fuel cells are another area that will benefit from nanotechnology innovations. The use of carbon nanotubes in the catalyst support structure as a replacement for metal membranes allows for higher temperature operation.

---

<sup>5</sup> [http://findarticles.com/p/articles/mi\\_m1200/is\\_7\\_166/ai\\_n6212592/](http://findarticles.com/p/articles/mi_m1200/is_7_166/ai_n6212592/)

## **Consumption**

Finally and more indirectly, nanotechnology can also reduce energy consumption. Vehicles whose chassis is made from more lightweight materials will consume less energy; machinery which employs nanotechnology in low friction bearings or lubricants will be more energy efficient to operate. Solid state lighting as a replacement for incandescent lighting reduces energy consumption, and also provides a positive feedback loop in which lower power requirements can be satisfied with local renewable energy sources – such as a roof mounted solar cell.

### **4.3. Drivers and Barriers to Innovation**

#### **Drivers for Innovation**

The primary driver – and it is of immense importance – is the increasing awareness of the threat of climate change, and a policy climate which reflects that. Companies which are developing energy technologies that do not produce significant quantities of CO<sub>2</sub>; generating energy from the sun, the wind, water and vegetable matter; know that they will have access to a supportive policy environment and an investor community which is very focused on developing these technologies.

Subsidies decrease the cost of renewable energies; cap and trade schemes increase the price of energy produced with fossil fuels. However, there remains a price gap in which fossil fuels are substantially lower cost for important uses such as electricity generation. An important driver for the development of new technologies is therefore improvements in their cost-effectiveness; in the case of photovoltaics, this comes from reducing material costs, increasing production efficiency, , and increasing the efficiency of PV cells in use.

#### **Barriers to Innovation**

The largest energy companies are still those which extract and process fossil fuels. Whilst they may still invest in new technologies – and some are quite supportive of renewable energy – there is not as much substantial industrial investment in energy technology as there is in ICT, for example. However, this is offset by the large amounts of public funding that are being directed towards energy research.

#### 4.4. Relevant Sector Segmentation and Applications

The impact of nanotechnology on energy was described in section 2.2. A segmentation of these applications would be the following – applications in bold are those considered in this report, others will be addressed in later years:

Extraction:

- Oil Recovery
- Petroleum Processing

Generation

- **Solar Photovoltaic Generation**
- Applications in Wind and Hydroelectric Generation

Supply

- **Batteries**
- Supercapacitors
- Fuel Cells

Consumption

- Improving energy efficiency with low friction bearings and lubricants

#### 4.5. Possible Future Products and Time Range

Application	Commercially Available	1-3 years	3-5 years	5+ years
<b>Solar Photovoltaics</b>	Thin Film Solar, dye-solar for small scale generation	Large scale dye-solar	Quantum-dot, more exotic PV technologies	
<b>Batteries</b>	Nanotechnology-enhanced electrode material	Reserve batteries with separation membrane		

## 5. Application Profiles

### 5.1. Solar Photovoltaics

The dominant current technology for the production of solar PV is amorphous or single crystal silicon. This accounts for over 90% of current solar PV production. The technology sector report produced by CEA identifies several nanotechnology-based approaches to solar PV, which are differing stages of market readiness:

**Thin Film.** This technology area is often described as ‘second generation’ solar PV. Materials used include Amorphous Silicon (aSi), Copper Indium Gallium Selenide (CIGS), and Cadmium telluride (CdTe). Thin film solar PV is currently in production.

**Emerging Approaches.** The third generation of solar PV includes emerging approaches such as dye-sensitive solar cells (DSSC) and quantum dots. DSSC and conducting polymer PV cells are currently in production, though seemingly in much lower quantities than crystalline silicon and thin film – in fact they may currently account for no more than 0,1% of the total annual PV market<sup>6</sup>.

The impact of nanotechnology may be to lower the cost of solar PV by reducing material requirements or by introducing more efficient manufacturing methods. It may also enable novel applications of solar PV technology, such as integration with building materials or even clothing.

#### 5.1.1. Short application description

Solar photovoltaic (PV) cells convert sunlight to electricity. Applications range from very large grid-connected solar power plants to small solar cells for portable devices. A combination of factors, including government subsidies, cost reductions, and the increasing cost of alternatives contributes to substantial growth in the solar PV market. As an indication of the market potential, some projections call for 12% of Europe’s electricity needs to be satisfied by solar generation by 2020, a total of 420 terawatt hours (TWh).

---

<sup>6</sup> Photon International, referenced by EPIA Solar Generation V report

Solar PV applications can be divided into grid-connected, off-grid systems, and portable applications.

### **Grid-Connected Solar PV**

The application category includes solar PV installations that are connected to the electricity grid. These range from solar power plants which are capable of generating sufficient electricity to power thousands of homes, to installations in industrial facilities, retail spaces and private homes. A number of companies have invested in the production of solar power plants. Grid-connected solar replaces other sources of electricity generation; typically coal or gas-fired power stations.

Industrial and home installations may be used to satisfy local electricity demand, and to supply additional power at times of peak demand; the classic example being their use to power air conditioning units on hot, sunny summer days. Grid connectivity also enables excess local electricity production to be supplied to the power grid, although this also requires billing and metering mechanisms and a device to convert the current.

Grid-connected solar PV has been the engine of solar growth over the last decade, and accounts for a very high proportion of all solar cells sold. The quantities involved render this a large-scale, manufacturing intensive business. Many of the larger companies in this space, such as Sharp or Kyocera, have experience in mass production of glass or displays, and have applied this experience to the production of crystalline silicon PV.

### **Off-grid systems**

Although this category includes a range of applications, off-grid systems are generally smaller scale than grid-connected PV. Off-grid solar PV may be used to provide power in places which are not connected to the electricity grid, in developing countries or in rural areas of developed countries. Electrifying rural areas is not only an economic opportunity, and also has wider societal benefits.

A significant application is the use of off-grid solar to power utilities, such as cell towers for mobile telephone networks. A combination of the power requirement of telecom base stations, and their location on high ground, make off-grid solar PV an attractive power source. Similarly, solar PV cells may be used to power street lighting, traffic lights, and signage. This application area reduces the cost and complexity of connecting these utilities to the electricity grid.

## Portable Devices

The most ubiquitous application of solar PV is their use to replace batteries as a power source for portable devices such as calculators and watches. This application area currently accounts for a very small proportion of the total global PV market. Despite their ubiquity, these are a small, commoditised component of a low cost device, and therefore the value is low.

Category	Existing Application Examples
Grid-Connected	Solar power plants. Industrial, retail and domestic applications
Off-Grid	Rural electrification. Utilities; lighting, signage and telecoms.
Portable	Devices; watches, calculators

## **Nanotechnology Enabled Novel Applications**

The current dominant technology, silicon, limits the form factor of solar PV to inflexible, fragile flat panels. Whilst this is adequate for most current applications, especially large-scale grid connected solar; there are novel applications that would be enabled by new form factors.

**Integration with Building Materials.** A potential application of DSSC is their use as windows, given that their structure may render them partially translucent (and that the coloured dye used could even have a decorative effect)<sup>7</sup>.

More flexible manufacturing methods, essentially enabling the application of PV coatings in the same way that corrosion-resistant coating are applied, could be integration into the production and finishing process of items like structural steel. DyeSol, an Australian DSSC producer, has a research partnership with steel producer Corus to integrate its technology with roofing materials. This is anticipated to result in commercial products by 2010<sup>8</sup>.

A closer to market application would be the construction of PV cells with curved surfaces, enabling their use on roof tiles or supporting columns.

**Use on Flexible Substrates.** Konarka has investigated applying its organic polymer-based solar cells to clothing, such as outerwear or bags. Whilst the amount of power generated would not be huge - how much time is spent standing in direct sunlight with a jacket on – it may be sufficient to power a portable device, such as a cell phone<sup>9</sup>.

---

<sup>7</sup> Window Power, Technology Review, 1<sup>st</sup> November 2006

<sup>8</sup> Dyesol and Corus Accelerate Building Integrated Solar Cell Commercialisation, DyeSol Press Release, 16<sup>th</sup> December 2008

<sup>9</sup> Konarka Corporate Website, [http://www.konarka.com/index.php/site/tech\\_power\\_plastic/](http://www.konarka.com/index.php/site/tech_power_plastic/), Accessed 30<sup>th</sup> Jan 2009

## Functional requirements

Regardless of the technology used, solar PV has the following functional requirements:

**Effectiveness.** Simply put, the PV cell must provide enough electrical energy to offset the costs of its production, installation and use.

**Durable.** The industry standard is that the PV cells should be able to withstand the elements and maintain a certain level of performance for at least 20 years.

**Lightweight.** When considering whether or not put a solar installation on a roof, it is important that the installation be structurally stable. The lighter the PV cell, the more locations in which they can be installed (in addition to being easier to transport).

**Disposable.** Given that solar PV is sold as an environmentally-friendly product, it is important that cells can be disposed of safely at the end of their useful life. This mitigates against the use of polluting heavy metals, or at least places a burden on the manufacturer to ensure that safe disposal methods exist.

**Easy to Installation.** PV Cells are typically installed by system providers, but it may also be that installation is performed by maintenance workers, homeowners, and others who cannot be expected to possess specific technical skills. This means that ease of installation is important, and fragile or complicated designs are less likely to win market acceptance.

### 5.1.2. Boundary conditions

For nanotechnology-based approaches to supplant crystalline silicon for large-scale installations, the following boundary conditions will have to be satisfied:

#### Improved Cost Effectiveness

The key price metric for solar PV is cost per kilowatt hour (cost per watt is sometimes also used). This is a factor of materials and manufacturing costs, efficiency in use, and installed lifetime.

## **Reduced Material Costs**

Until recently, limited supply and commensurate high cost of silicon has been a major factor in increasing the cost of crystalline silicon PV. There is some evidence that this pressure will ease in coming years, though it may also be the case that the bottleneck simply shifts down the value chain to wafer production. Whilst this factor will not alter if one costly element (silicon) is replaced with another (indium), several new approaches either employ less rare materials or reduce the quantities needed.

## **Lower-cost Manufacturing**

There are two elements at work here. Production of crystalline silicon is being scaled up, with major manufacturers opening larger and larger facilities; SolarWorld has expanded its main German facility to production capacity of 1GW. This should result in manufacturing economies of scale.

Meanwhile, production processes for thin film solar are being improved. Nanosolar, which builds thin film CIGS cells, claims that it has optimised several different elements of the production process including applying CIGS as a printable ink using a roll to roll process. The key question is to what extent rapid, incremental reductions in the cost of manufacturing crystalline silicon cells are outweighed by the inherent efficiencies in print-like production.

## **Improved Efficiency**

The efficiency of a PV cells is a measure of how well it converts absorbed light into electrical energy, and is typically expressed as a percentage. Whilst this is an important measure amongst the research community, it is just one element of the key metric, cost per kilowatt hour.

Currently the highest efficiencies are obtained by concentrator PV (CPV) cells, which are capable of generating conversion efficiencies of around 40% (a European record of 39,7% was achieved by Fraunhofer ISE in 2008)<sup>10</sup>. Efficiencies achieved by other technology approaches are shown in Table 1.

---

<sup>10</sup> Fraunhofer beats European record with 39.7-percent cell, Photon International, October 2008

Table 2: Comparison of Efficiency Levels Achieved by Solar PV Technologies<sup>11</sup>

Technology	Highest Recorded Efficiency
Concentrator PV	40%
Crystalline Silicon	24%
Thin Film – CIGS	19%
Thin Film - CdTe	16%
Thin Film - aSi	12%
Organic PV	5%

The conversion efficiency of the specific technology used is just one element of the overall system efficiency, it being further affected by the packaging and other elements of the photovoltaic system.

### **20 year + Installed Lifetime**

Clearly one of the most important factors in calculating the life-cycle cost of PV cells is how its efficiency will change over time (and how long it takes until it simply fails to operate). The target lifetime for a PV cell is at least 20 years, in a temperature range of -40C to 85C<sup>12</sup>, and many manufactures issue warranties to this effect. Durability is a particular issue with organic approaches; degradation of conducting polymers is a well-studied phenomenon.

---

<sup>11</sup> Various Source, including Best Research Cell Efficiencies, NREL,

<sup>12</sup> PVNet Roadmap for PV, Version 12/2002

### 5.1.3. Product examples

#### **Konarka flexible solar cells**

Branded as Power Plastic, this solar cell design uses an organic polymer material and is mainly intended for portable devices.

Note that the product specifications describe a flex radius of 2 inches, so it may not be quite as flexible as the picture suggests.



Figure 1: Konarka's Power Plastic® material<sup>13</sup>

#### **Nanosolar foil solar cells**

Nanosolar produced thin film CIGS solar cell using a roll to roll manufacturing process. The flexibility of this project- it is essential a foil – makes it suitable for architectural use. This product is currently available.

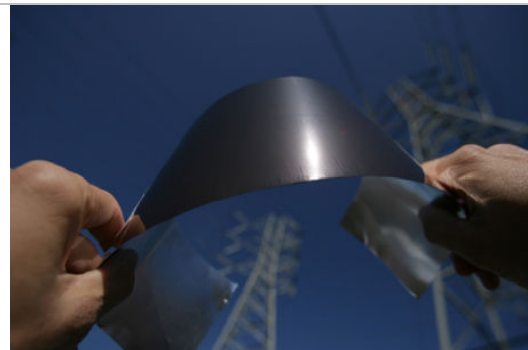


Figure 2: SolarPly™ by Nanosolar

#### **Flexible solar panel for use in charging cellphones**

G24 Innovations has licensed DSCC technology and is manufacturing light, flexible fabric covered cells, mainly intended to power portable devices.



Figure 3: 'Gcell Flex', manufactured by G24 Innovations<sup>14</sup>

<sup>13</sup> Konarka Corporate Website, [http://www.konarka.com/index.php/site/tech\\_power\\_plastic/](http://www.konarka.com/index.php/site/tech_power_plastic/)

<sup>14</sup> G24 Innovations, <http://www.g24i.com/pages.products-flex-series.40.html>

#### 5.1.4. Economic Information and Analysis

This chapter considers the current market for solar PV, and assesses the proportion which is currently accounted for by nanotechnology. The drives that will affect the future share of nanotechnology-enabled products are also analysed.

##### Total Market Size of Solar PV

The European Photovoltaics Industry Association projects that the global market for solar PV will be 7282 MW in 2012, up from 2249 MW in 2007. Figure 4 illustrates this growth in installed PV capacity.

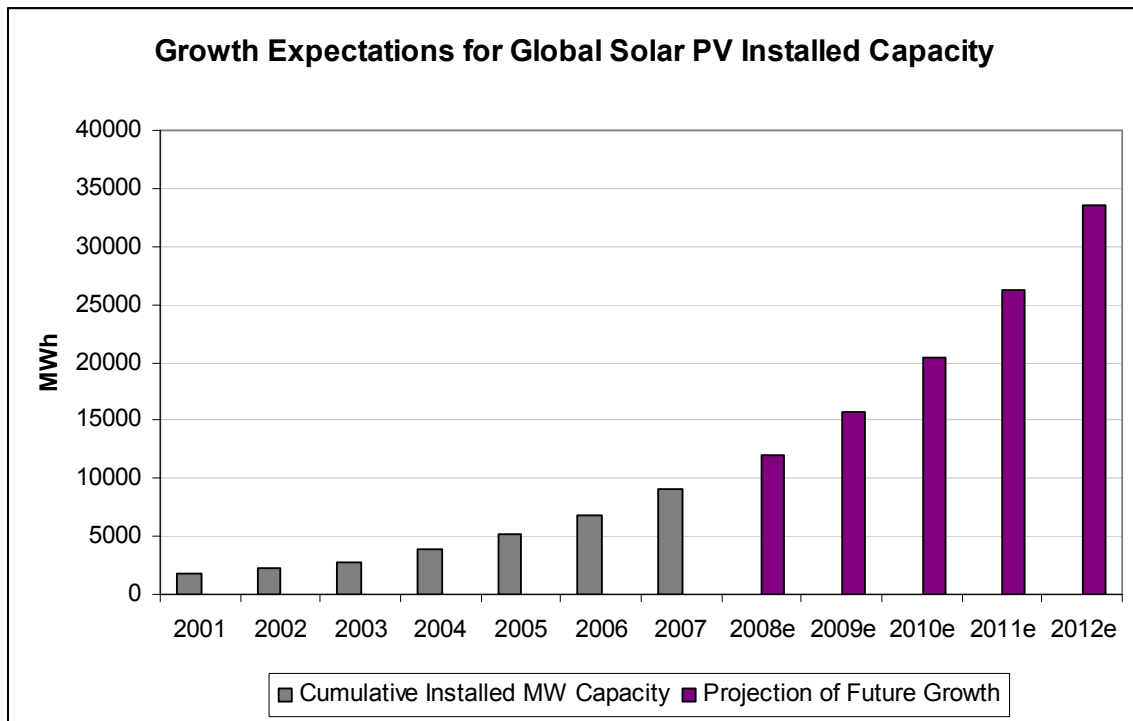


Figure 5: Global Solar PV Installed Capacity<sup>15</sup>

<sup>15</sup> Solar Generation V – 2008, EPIA

## Share of Nanotechnology-Enabled Products

Market share of nanotechnology-enabled solar PV was estimated in 2007 to be almost exactly 10%. Table 3 illustrates the dominance of mono- and multi-crystalline silicon in the PV market.

Table 4: Market Shares of Various Solar PV Technologies (2007)<sup>16</sup>

	Technology	Market Share
Thin Film	a-Si	5,2 %
	CdTe	4,7 %
	CIS	0,5 %
Crystalline Silicon	multi c-Si	45,2 %
	mono c-Si	42,2 %
	ribbon c-Si	2,2 %
DSSC?	Others	0,1 %

The EPIA currently projects that thin film solar PV will have a production capacity of 4GW by 2010, accounting for 20% of the global total<sup>17</sup> (figure 6). Assuming that market share and production capacity are directly linked, and that the increase in market share will be linear, this implies that the market share of nanotechnology-enabled approaches are growing by 25% pa. (table 5).

Table 6: Nanotechnology-enabled approaches market share

	2007	2008	2009	2010
Market Share of nanotechnology-enabled approaches	10,0 %	12,6 %	15,9 %	20,0 %

<sup>16</sup> Photon International, referenced by EPIA Solar Generation V report

<sup>17</sup> Global Market Outlook for Photovoltaics until 2012, EPIA.

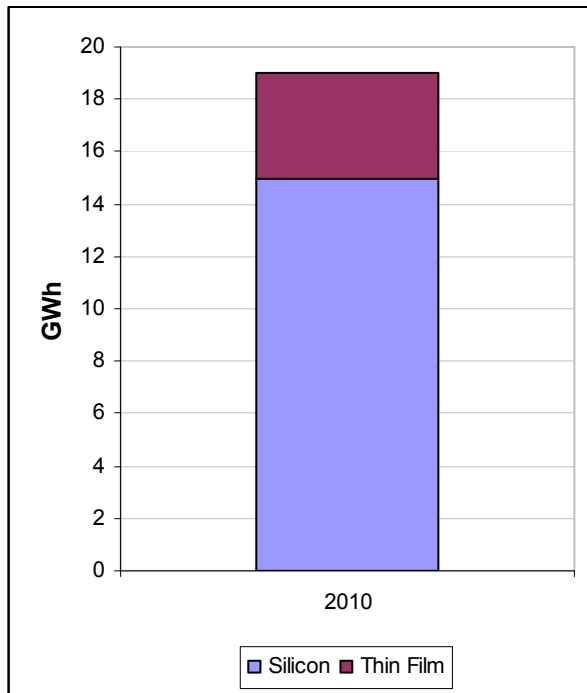


Figure 7: Production Capacity of Solar PV Technologies in 2010

### **Drivers for Market Size Increase of Solar PV**

The growth of solar PV has been driven by the factors; reduced costs (via subsidy), and an increase in the cost of alternatives due to rising fuel costs and emission pricing.

**Importance of Subsidies.** At least 11 EU member states offer subsidies for solar power, with instruments ranging from feed in tariffs, to investment grants and subsidies, tax credits, and beneficial credit terms. This support is available to utilities, companies and individual households.<sup>18</sup> A cautionary note, in the past months some solar manufacturers have complained that subsidies which offer tax rebates are no longer effective, as companies are not making a profit on which to pay tax in the first place.

---

<sup>18</sup> Overview of European PV support schemes, EPIA, 16<sup>th</sup> December 2009

**Pricing Emissions.** Initiatives which aim to ‘price in’ the true cost of carbon dioxide emissions, (such as the EU’s Emission Trading Scheme) reduce the cost-effectiveness of fossil-fuel based power generation.

**Increasing Fuel Costs.** A combination of static or declining supply and increasing demand has, until recently, caused an increase in the cost of fuels used for power generation; typically coal and natural gas.

An underlying assumption is that demand for energy will continue to rise. Whilst this will likely hold true, the current financial crisis and its dramatic effect on economic growth may render some growth forecasts excessively optimistic.

## Drivers Affecting Market Share of Nanotechnology-enabled Solar PV

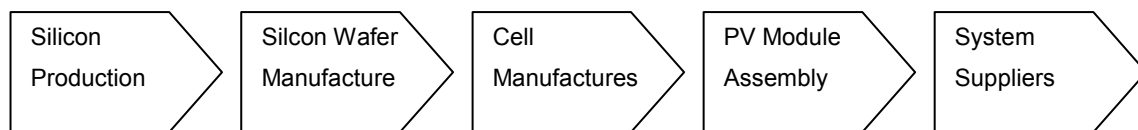
Two factors will impact the extent to which nanotechnology-based approaches become price competitive with crystalline silicon; cost of materials, and cost of production.

**Silicon shortage in 2008 may give way to oversupply by 2012.** Renewable Energy Corporation, an integrated producer of silicon, wafers, cells and modules, projects that polysilicon production capacity will increase from under 50 000 MT in 2008 to 125-160 000 MT in 2012. This would exceed their projection of demand for polysilicon in 2012, potentially leading to a price drop<sup>19</sup>. This is in part because the solar industry currently competes with the semiconductor industry for high grade silicon, but in future 'solar grade' silicon will emerge with a distinct supply chain<sup>20</sup>.

**Restrictions on capital expenditure will drive low cost manufacturing.** Manufacturing expenses account for a small proportion of total solar PV cost on an ongoing basis (materials are the largest cost item). However, the costs of building a manufacturing plant are substantial, and during a period where capital will be difficult to access, lower cost manufacturing methods could gain market share.

## Effect of Nanotechnology-Enabled Products on the Solar PV Value Chain

The current value chain for crystalline silicon solar PV is as follows:



**Thin film solar PV will reduce the importance of silicon production and wafer manufacture,** given the flexibility to apply onto a number of substrates. However approaches which continue to use rare metals (such as CIGS) could simply replace the silicon supply bottleneck with an Indium shortage.

---

<sup>19</sup> Corporate Presentation, Renewable Energies Corporation, 18<sup>th</sup> January 2008

<sup>20</sup> Silicon Rally, The Economist, 28th August 2008

**Dye-sensitized solar cells do provide an opportunity for bulk chemical manufacturers to enter the PV market,** supplying titanium dioxide and the dye itself. It is unlikely that they would be able to appropriate much value from this, and the titanium dioxide market is somewhat commoditized.

**PV coatings would change the role of the cell manufacturer.** In the case the value is likely to be in the coating machinery, which would then be installed in existing steel plants, for example. In the case the value chain is likely to consist of the chemical supplier, the equipment manufacturer and the material manufacturer, who could offer PV-integrated materials as a differentiated product.

**Cell Manufacturers sell directly to device manufacturers for portable applications.** This would replace module assembly as a step in the value chain – instead the PV cell would be like a batteries, display, or other component which is just integrated into the manufacturing process of an electronic device (such a mobile phone).

### 5.1.5. Selected Key Companies Profiles

This is a listing of some of the companies presenting using thin film, dye-sensitised solar, and other nanotechnology-based approaches to PV.

Name:	Konarka
URL:	<a href="http://www.konarka.com/">http://www.konarka.com/</a>
Technology Used:	Conducting polymers. Production capacity of 1GW.
Investment:	The company held a 45MUSD funding round in 2007.
Description:	Konarka was established in 2001, and has a technology portfolio which incorporates the work of Nobel Laureate Alan Heeger on conducting polymers, and Sukant Tripathy’s work on photovoltaics.

Name:	Nanosolar
-------	-----------

URL:	<a href="http://www.nanosolar.com/">http://www.nanosolar.com/</a>
Technology Used:	CIGS thin film
Investment:	Nanosolar has raised almost 500 MUSD since founding. Investors include AES Corporation, EDF and the Carlyle Group.
Description:	Nanosolar is the most high-profile thin film solar producer, and claims to have optimised roll to roll production of CIGS cells to such an extent that cost per watt is said to be 30 US cents. The company is currently shipping products and has established production facilities in California and Germany.

Name:	Solaronix
URL:	<a href="http://www.solaronix.ch/">http://www.solaronix.ch/</a>
Technology Used:	Dye-sensitized solar cells (DSSC)
Investment:	
Description:	Solaronix sells components for DSSC manufacture in addition to developing the cells themselves.

Name:	G24 Innovations
URL:	<a href="http://www.g24i.com">http://www.g24i.com</a>
Technology Used:	Dye-sensitized solar cells (DSSC)
Investment:	The company has received 100 million USD in venture funding, with investors including Morgan Stanley and Renewable Capital.
Description:	G24i licenced technology from Michael Gratzel, enabling it to produce DSSCs. The company has a production facility in Wales, and is targeting developing country users of it's products.

Name:	FirstSolar
URL:	<a href="http://www.firstsolar.com">http://www.firstsolar.com</a>
Technology Used:	Thin Film CdTe
Investment:	FirstSolar is NASDAQ listing as FSLR
Description:	FirstSolar is the largest thin film solar manufacturer, with a production capacity of almost 1200 MW (including an 800MW facility in Malaysia).

	Cost per watt is stated to be \$1,08, with pricing at around \$2,53. The company projected 2008 annual revenues to be in the range 1,22 – 1,24 bn USD.
--	--

Name:	CSG Solar
URL:	<a href="http://www.csgsolar.com">http://www.csgsolar.com</a>
Technology Used:	Thin film manufacture using silane gas
Investment:	€24M investment from Apax Partners Funds and Good Energies in January 2005
Description:	CSG solar has a production capacity of 13 MWp, having entered mass production in 2007. The company produces PV modules for large applications.

Name:	Flexcell
URL:	<a href="http://www.flexcell.ch">http://www.flexcell.ch</a>
Technology Used:	Thin film deposition of amorphous silicon
Investment:	Q-Cells invested €7M in 2007
Description:	Flexcell was established in 2000 to commercialise work carried out at the Ecole d'Ingénieurs du Canton de Neuchâtel. The company is now a subsidiary of Q-Cells

## 5.2.

## 5.3. Batteries

### 5.3.1. Short application description

The battery market is divided into three types; primary batteries, which are non-rechargeable; secondary batteries, which are able to be recharged; and reserve batteries, which are intended to be used when a primary power source fails. The chapter mainly considers secondary or rechargeable batteries. These account for two thirds of the global battery market, a share valued at around USD 38 billion by Freedonia Group<sup>21</sup>.

The battery market is expected to grow substantially in the coming years. This is partially driven by growth in existing battery applications – particularly laptops, ‘netbooks’ and mobile devices. However, the primary driver will be new applications, particularly in the automotive industry. The number of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEV - which utilise a combustion engine and a battery pack as dual power sources) is set to increase. A number of car manufacturers are following the lead of Toyota and Honda to develop EVs or HEVs; these range from new manufactures producing high-end sports cars; such as Tesla Motors; and major existing firms; including General Motors, with its Chevy Volt.

There are currently four main technology approaches to rechargeable batteries; lead acid; nickel cadmium; nickel metal hydride; and lithium ion batteries. The latter two technologies are increasing their share of the overall rechargeable market, primarily because their energy density – measured in Watt hours per kilogram (Wh/kg) is substantially higher. Lithium ion batteries have particularly gained market share in this decade, increasing their use in mobile devices and laptops.

Lithium-ion batteries use a positive electrode which is typically Lithium Cobalt Oxide (LiCoO<sub>2</sub>) and a graphite negative electrode. These are typically formed as two sheets, kept apart by a plastic separator. The electrodes are held within a liquid electrolyte (which can release oxygen when punctured or overcharged, causing an explosion). The electrodes are pressed together by a metal case.

The energy density advantage of Lithium-ion batteries is substantial; an average value would be 150 Wh/kg, a six-fold increase on the performance of lead acid batteries (at 25 Wh/kg). Another advantage of Lithium-ion technology is that there is significantly less power leakage than with other technologies, at just 5% per month. However, Lithium ion batteries also have drawbacks; if

---

<sup>21</sup> [http://www.kth.se/polopoly\\_fs/1.25005!Battery.pdf](http://www.kth.se/polopoly_fs/1.25005!Battery.pdf)

the positive and negative electrodes come into contact, the battery itself can explode. Exploding laptop batteries has forced manufactures to issue extensive, expensive product recalls. Other issues with Lithium ion batteries include a risk that they become ruined if they are completely discharged, and their heat sensitivity.

More recently, Lithium-ion polymer batteries have been developed. These hold a lithium salt electrolyte within a polymer composite. These can be lower cost, because they no longer need a welded case to hold the electrodes in place – the case can even be flexible. These are also more robust, in that the electrolyte is less prone to explode.

### **Impact of Nanotechnology**

Nanotechnology for batteries is a very active field of research and development. A development by Yet-Ming Chiang at MIT used an iron phosphate material as a replacement for the Lithium Cobalt electrode. Later reductions of the iron phosphate size to less than 100nm further improved performance. This technology is less prone to explode, is smaller (because higher energy densities mean that a battery cell with given power can be smaller) and have a lower cost of materials. This technology was licensed to a number of firms, including A123 Systems.<sup>22</sup>

Another MIT group, led by Gerbrand Ceder has also developed a lithium ion phosphate cathode material, which is capable of discharging its entire energy capacity within 10 seconds (compared to 90 seconds for a conventional Lithium-ion battery. This makes it more like a supercapacitor, used to deliver a high charge in a short burst.<sup>23</sup>

### **5.3.2. Functional requirements**

#### **Power Density**

The primary functional requirement for batteries is their power density, expressed as Wh/l or Wh/kg. Li-ion batteries currently have power densities in the range 100-200Wh/kg, with NiMH approaching 100 Wh/kg. New Li-ion batteries are predicted to deliver power densities in excess of 300 Wh/kg.<sup>24</sup>

---

<sup>22</sup> <http://www.technologyreview.com/blog/editors/22186/>

<sup>23</sup> <http://www.technologyreview.com/energy/22280/?a=f>

<sup>24</sup> [http://www.kth.se/polopoly\\_fs/1.25005!Battery.pdf](http://www.kth.se/polopoly_fs/1.25005!Battery.pdf)

### **Charge/Discharge Efficiency**

The charge/discharge efficiency of a battery describes how rapidly it can delivery charge and be recharged. The battery work by Gerbrand Ceder at MIT found a discharge speed of 10 seconds, which is substantially quicker than existing solutions. Note here the distinction between batteries, in which other attributes are also important, and supercapacitors, for which the primary intention is to deliver as high a charge in as short a time as possible.

### **Self Discharge Rate**

Most batteries gradually lose their charge, even whilst a current is not being drawn. This is particularly a challenge for reserve batteries, which would need to retain a charge even after a long period (years) of inactivity.

### **Cycle Durability**

Cycle durability is another measure of the lifetime of a battery, indicating the number of times it can go through a charge/recharge cycle. This was typically in the range 300-500 cycles, but LiFePO<sub>4</sub> batteries, for example, have been found to last for 2000-3000 cycles<sup>25</sup>.

## **5.3.3. Boundary conditions**

### **Stability**

For automotive applications, the risk of explosion is felt to a barrier to adoption of Li-ion batteries; the consequences would be more severe with larger battery packs, or if an explosion were to occur when the vehicle was being used. Companies like A123 Systems are therefore at pains to point out that the consequences of their batteries being punctured are far less severe than with conventional Li-ion batteries.

### **Operating Temperature Range**

For most battery applications, an operating temperature range of  $-40^{\circ}\text{C}$  to  $80^{\circ}\text{C}$  is necessary, and performance should not be substantially degraded at the extremes of this temperature range.

---

<sup>25</sup> <http://zeva.com.au/tech/LiFePO4.php>

### 5.3.4. Product examples

#### Smart NanoBattery

mPhase's smart NanoBattery uses a silicon based, superhydrophobic membrane to keep the electrolyte separate from the electrodes, maintaining the battery in an 'off' state which drains no power. When an electric field is applied to the membrane, an electrowetting effect allows the electrolyte to flow through the membrane barrier, activating the battery.<sup>26</sup>

#### ZPower Silver-Zinc Battery

ZPower's batteries have an element of nanotechnology, in that they employ a silver cathode which is coated with unspecified nanoparticles, presumably increasing surface area. The batteries also have a composite polymer zinc anode, and a layered separator which is designed to reduce dendrite growth<sup>27</sup>. The battery is advertised as having *40% more running time* and as being *90% recyclable*. The technology is protected by an extensive patent portfolio, with 25 patents granted and 36 pending.

#### 26650 Series Cell, A123 Systems

A123 systems 26650 cell was originally intended for use in power tools, and claimed a tenfold increase in power capacity over conventional lithium ion batteries, as well as rapid charging – to high capacity in five minutes.<sup>28</sup>

### 5.3.5. Economic information for present products

Growth in the Lithium-ion battery market comes from a number of sources, including portable devices, power tools, and electric vehicles. The Li-ion market for automotive applications is projected to increase from US\$ 337 million in 2012 to US\$ 1.6 billion in 2015.<sup>29</sup> A report by

---

<sup>26</sup> <http://electronicdesign.com/Articles/Print.cfm?ArticleID=20734>

<sup>27</sup> <http://www.zmp.com/technology/index.htm>

<sup>28</sup> <http://www.a123systems.com/products>

<sup>29</sup> <http://factclipper.com/en/news/2008-05-13/forecast-lithium-ion-automotive-market-could-reach-16b-by-2015-strong-hevs-to-domina>

iRAP assessed the value of the nano-enabled battery market at USD 169 million at present, increasing to US\$ 1.133 billion in 2013; a 46.3% annual growth rate. Within this, the market share of ‘large format modules’; battery packs for electric vehicles, increases from US\$ 64 million (38%) to US\$ 960 million (85%).<sup>30</sup>

### **5.3.6. Selected Key Companies Profiles**

#### **Nanoexa**

Nanoexa (<http://www.nanoexa.com>) is a manufacturer of high power lithium batteries, and is based in California. The company develops manganese-rich electrode structures, which enable higher (up to double) the power storage of Lithium cobalt oxide.

#### **mPhase**

mPhase’s (<http://www.mphasetech.com>) subsidiary, AlwaysReady has developed the Smart NanoBattery. This is designed to provide back-up power and utilises a triggerable porous membrane which keeps the electrolyte separate from the electrodes. This means that in its off / dormant state the battery suffers no power loss.

#### **A123 Systems**

A123 Systems (<http://www.a123systems.com>) has a case for being one of the most successful ‘nanotech’ companies, now having 1800 employees. The company produces batteries which employ a doped nanophosphate material as an electrode; technology which A123 has licensed from MIT. The company’s first product was high power rechargeable battery for power tools, and it has also developed a battery pack for use with hybrid vehicles. This is designed to supplement the factory battery of the Toyota Prius, offering greater energy storage capacity. A123 signalled its intention to float in August 2008, though the economic crisis may now have delayed this plan.

---

<sup>30</sup> <http://www.azonano.com/news.asp?newsID=10496>

**Seeo**

Seeo (<http://www.seeo.com/>) develops Li-ion batteries which have a solid polymer electrolyte. To overcome the conductivity challenge (liquid electrolytes are more conductive than polymers) a block co-polymer is used; this has the advantage of making the battery more stable. The company does not disclose revenue or headcount, but received an investment of US\$ 1 million from Khosla Ventures in 2008.

## 6. References

Renewables Made in Germany – Photovoltaics, German Energy Agency (DENA),  
<http://www.renewables-made-in-germany.com/en/photovoltaik/>

Overview of European PV support schemes, EPIA, 16<sup>th</sup> December 2008,  
[http://www.epia.org/fileadmin/EPIA\\_docs/documents/20081215\\_EPIA\\_EU\\_support\\_schemes\\_overview-PUBLIC.pdf](http://www.epia.org/fileadmin/EPIA_docs/documents/20081215_EPIA_EU_support_schemes_overview-PUBLIC.pdf)

Solar Generation V – 2008, EPIA,  
[http://www.epia.org/fileadmin/EPIA\\_docs/documents/EPIA\\_SG\\_V\\_ENGLISH\\_FULL\\_Sept2008.pdf](http://www.epia.org/fileadmin/EPIA_docs/documents/EPIA_SG_V_ENGLISH_FULL_Sept2008.pdf)

Global Market Outlook for Photovoltaics until 2012, EPIA,  
[http://www.epia.org/fileadmin/EPIA\\_docs/publications/epia/EPIA\\_MarketPublication\\_18feb.pdf](http://www.epia.org/fileadmin/EPIA_docs/publications/epia/EPIA_MarketPublication_18feb.pdf)

Renewable Energy Corporation, 20<sup>th</sup> February 2008,  
<http://hugin.info/136555/R/1193521/241443.pdf>

PVNet Roadmap for PV, Version 12/2002,  
[http://paris.fe.unilj.si/PVnet/files/PVNET\\_Roadmap\\_Dec2002.pdf](http://paris.fe.unilj.si/PVnet/files/PVNET_Roadmap_Dec2002.pdf)

Dyesol and Corus Accelerate Building Integrated Solar Cell Commercialisation, 16<sup>th</sup> December 2008.  
<http://www.dyesol.com/index.php?page=NewsArticles&archiveitemid=5&archiveitemdatetime=2008-12-16%2011:36:42&archiveitemstart=1&archiveitemtotal=69&archiveitemlimit=3> ,

Best Research Cell Efficiencies, National Renewable Energy Laboratory,  
[http://www.nrel.gov/pv/thin\\_film/docs/kaz\\_best\\_research\\_cells.ppt](http://www.nrel.gov/pv/thin_film/docs/kaz_best_research_cells.ppt)

Silicon Rally, The Economist, 28th August 2008,  
[http://www.economist.com/business/displaystory.cfm?story\\_id=12010071](http://www.economist.com/business/displaystory.cfm?story_id=12010071)

[http://www.mckinsey.com/mgi/reports/pdfs/next\\_energy\\_crisis/MGI\\_next\\_energy\\_crisis\\_full\\_report.pdf](http://www.mckinsey.com/mgi/reports/pdfs/next_energy_crisis/MGI_next_energy_crisis_full_report.pdf)

<http://www.renewableenergyworld.com/rea/news/article/2009/03/getting-serious-about-clean-energy-stimulus>

[http://www.nanowerk.com/spotlight/spotid=7424\\_1.php](http://www.nanowerk.com/spotlight/spotid=7424_1.php)

<http://www.nanowerk.com/spotlight/spotid=7424.php>

## **7. Appendix 1: Expert Engagement**

ObservatoryNano symposium attendees included:

Dr. Erik Ahlswede (Zentrum für Sonnenenergie- und Wasserstoff Forschung)

Dr. Tony Byrne (Ulster University)

Dr. Gilles Goer (PV Alliance)

Dr. Eric Laborde (PV Alliance)

Dr. Philippe Pantigny (INES)

Dr. Nicolas Tetreault (EPFL)