ObservatoryNANO

Nanotechnology and Photovoltaic

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Executive summary

Solar photovoltaic (PV) technology may be used in several types of applications: grid-connected and off-grid systems as well as consumer electronics. Grid-connected solutions have been the engine for solar PV growth over the last decade, and it accounts for biggest share of the market. Growing interest for building integrated PV (BIPV) is also recognised and nanotechnology is a key, when producing flexible thin film products for buildings.

While single junction silicon devices still dominate the market, very active R&D activities have been observed in other PVs technologies, in particular CIGS-CIS and CdTe thin films, DSSC, and third generation solar cells. Thin film technologies could take advantage of those new nanotechnology-based concepts that aim at increasing the photon absorption rate, their main weakness. Those various strategies involving nanotechnologies to improve absorption efficiency are among plasmonics, photonic crystals, transparent electrodes and reflection layers.

Dye-sensitized solar cells could also benefit from nanotechnologies developments, such as the realisation of TiO_2 nanostructures on which dye molecule are deposited. The aim of these developments consists in photons diffusion improvement in order to increase the rate of light absorption.

Third generation solar cells are the most promising applications field for nanotechnology, as it covers the most innovative concepts, like radial junction cells on nanowires. These PV technologies are at an early-stage development level with several barriers slowing the technology's transition to market. Cost competitiveness, system integration to existing infrastructure and other renewable energy sources, supply chain, market deployment and policy framework with feed-in tariffs are important factors affecting the commercialisation of PV systems. Effects of nanotechnology can be seen on solar photovoltaic's prices and shorter value chain of thin film produced PV. At the application level the functional requirements for solar photovoltaics are efficiency, durability, ease of installation, lightweight and disposable.

The global solar photovoltaic installations increased in 2009 to reach 6 GW. Market share for nanotechnology enabled thin film technology increased sharply, but is still slightly under 20% in 2009 while market was still dominated by crystalline silicon wafer based technology. Most of the European companies already producing or about to produce solar cells and modules utilizing nanotechnology seems to focus on *a*-Si:H. In addition copper indium selenide ($CuInSe_2$, CIS), copper indium gallium selenide ($CuIn_xGa_{(x-1)}Se_2$, CIGS) or dye-sensitized solar cells (DSSC) PV technologies seems to be the focus of several European companies based on internet research by ObservatoryNano-project. From the total number of European companies studied about 60 to 75% were small or medium sized and 90% were focused only on solar photovoltaic. Most of the companies were based in Germany.

Chapter 1 Introduction

1.1 Definition

A solar cell or photovoltaic cell is a device that converts solar energy into electricity thanks to the photovoltaic effect. The base reference for photovoltaic material, crystalline silicon, performs this conversion relatively efficiently, but silicon cells are expensive to manufacture. Cells based on other semiconductors, which can be deposited as thin films, have also reached market, but although they're cheaper, their efficiency has yet to reach that of silicon. Therefore, other technologies such as multi-junction cells have been developed.

Solar cells technologies can be divided into three generations. At present there is concurrent research into all three generations with first generation technologies being the most highly represented in commercial production.

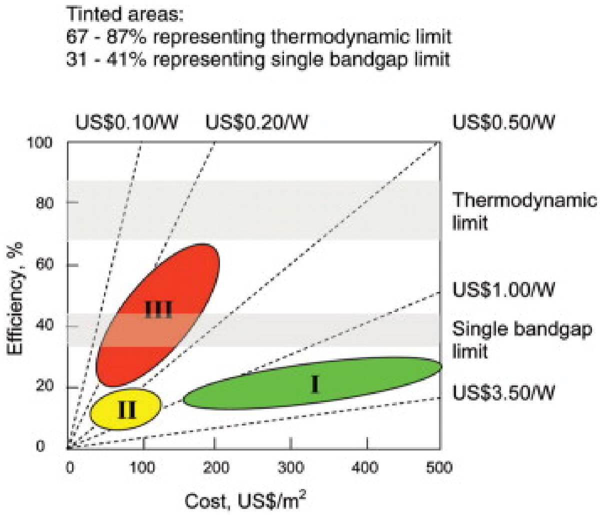

Figure 1: Efficiency vs. cost for the 3 solar cells generations[1 2]

1.1.1 First Generation

First generation cells consist of large-area, high quality single crystalline silicon junction devices. Those technologies involve high energy and labour costs that prevent any significant reduction of production costs. Single junction silicon devices are approaching the theoretical limiting efficiency of 33% (25% have been experimentally reached[3]). The energy payback (the timescale necessary of a PV system to operate to recover the energy—and associated generation of pollution and CO2—that went into making the system in the first place) is estimated to be between 2 to 4 years.

1.1.2 Second Generation

Second generation materials have been developed to address energy requirements and production costs of solar cells, while using thin film technologies. As of now, the most successful second generation materials have been cadmium telluride (CdTe), copper indium gallium selenide (CIGS), hydrogenated amorphous silicon (*a*-Si:H) and micromorphous silicon (PIN/PIN tandem cell: one cell is made of *a*-Si:H and the other is made of μc-Si:H). These technologies do hold promise for higher conversion efficiencies, particularly CIGS-CIS. Dye Sensitized Solar Cells (DSSCs) and CdTe offers significantly cheaper production costs. There is certainly a commercialization trend towards second generation technologies but full production has yet to be demonstrated.

1.1.3 Third Generation

Third generation technologies aim to enhance poor electrical performance of the second generation thin film technologies while maintaining very low production costs. This should be possible through the development of highly efficient polymer semiconductor thin films that would be compatible with roll-to-roll production. This solar cell generation is still at a laboratory stage but current research is targeting conversion efficiencies of 30-60% while retaining low cost materials and manufacturing techniques.

1.2 Short description

Photovoltaic devices are based on semiconductors, working on the following principle: the direct or indirect absorption by a semiconductor or a sensitizer of a photon with energy greater than the semiconductor bandgap promotes an electron into the conduction band, leaving behind a vacancy, or "hole" which acts like a positive charge in the valence band. If this electron-hole pair or exciton is formed in the vicinity of a space charge, such as at a p-n junction, charge separation takes place due to the electric field. With the proper provisions for collecting the opposite charges, this generates a potential that can drive an electric circuit.

Most of the following type of solar cell can be used solely or combined in tandem solar cells. This last type is generally based on monolithic solar cells connected in series. A triple-junction cell, for example, may consist of the semiconductors: GaAs, Ge, and $GaInP_2$. Each type of semiconductor will have a characteristic band gap energy which, loosely speaking, causes it to absorb light most efficiently at a certain colour, or more precisely, to absorb electromagnetic radiation over a wider portion of the solar spectrum. Specific organic or inorganic semiconductors are chosen for their wide absorption spectrum and good charge separation and transport properties thus ensuring a high electricity generation rate from a broad absorption and efficient charge collection.

High-efficiency multijunction cells were originally developed for special applications such as satellites and space exploration, but through intense research and development, their use in terrestrial concentrators might represent an important alternative for low cost generation in terms of $/kWh and $/W.

1.2.1 Bulk silicon based solar cell

The bulk silicon technologies are often referred to as wafer-based manufacturing. Silicon, used to make some of the earliest photovoltaic (PV) devices, is still the most popular material for solar cells. One major advantage is that silicon is the second-most abundant element in the Earth's crust. However, to be useful as a bulk semiconductor material in solar cells, silicon must be refined to a high purity close 100%.

Two major types of silicon solar cell materials appear:

- Single-Crystal Silicon
- Multicrystalline Silicon

In single-crystal silicon, the atomic structure is uniform, because the entire structure is grown from the same single crystal. This uniformity is ideal for efficient charge transport through the material. To make an effective PV cell, however, silicon has to be doped to create the p-n junction.

Multicrystalline silicon, in contrast, consists of several smaller crystals or grains, which introduce boundaries. These boundaries impede the flow of electrons and encourage them to recombine with holes to reduce the power output of the solar cell. However, multicrystalline silicon is much less expensive to produce than single-crystalline silicon. So researchers are working on other ways to minimize the effects of grain boundaries and residual impurities.

1.2.2 Thin film solar cell

The materials used in polycrystalline thin-film cells have properties that are different from those of silicon, mostly while using direct band gap materials. Generally two different semiconductor materials are used for the junction formation, inducing a hetero-junction interface.

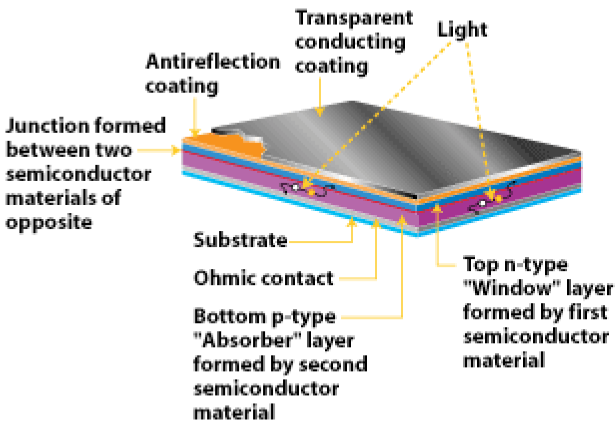

Figure 2: Thin film solar cell description

The various thin-film technologies currently being developed reduce the amount (or mass) of light absorbing material required in creating a solar cell. Their usual thickness is in the order of magnitude of the micron. This can lead to reduced processing costs but also tends to reduce energy conversion efficiency, although many multi-layer thin films have efficiencies above those of bulk silicon wafers.

CIS/CIGS is the first type of thin film material. CdTe and hydrogenated amorphous silicon are other prominent polycrystalline thin-film materials.

Hydrogenated amorphous silicon is the cheapest form of silicon-based solar cell to produce. Although its charge transport is not impeded by grain boundaries per se it still has very poor transport properties. However, it offers the best absorption characteristics and, thus, can be made thin enough that charges are efficiently collected. Its stability is still to be demonstrated since it has a tendency to loose hydrogen under illumination, which ultimately decreases its overall energy conversion efficiency.

One of the materials used in single crystalline thin film solar cell, GaAs, possesses characteristics suitable for single or multi-junctions solar cells. Its bandgap of 1.43 eV is nearly ideal; the absorptivity is so high that the thin film can still offer significant light harvesting; the cells are relatively insensitive to heat and radiation; a great number of GaAs alloys can be combined to improve flexibility without reducing the performance of the cell.

One of the greatest advantages of gallium arsenide and its alloys as PV cell materials is that it is amenable to a wide range of designs. A cell with a GaAs base can have several layers of slightly different compositions; this allows a cell designer to precisely control the generation and collection of electrons and holes pushing for efficiencies close to theoretical levels.

1.2.3 Polymer solar cells

Organic solar cells also called polymer solar cells are built from thin films (typically 100 nm) of organic semiconductors such as polymers and small-molecule compounds. These cells could be beneficial for some applications where mechanical flexibility and affordable roll-to-roll production are important.

These devices differ from inorganic semiconductor solar cells in that they do not rely on the large built in electric field of a p-n junction to separate the electrons and holes created when photons are absorbed. The active region of an organic device consists of two materials, one that acts as an electron donor and the other as an acceptor. When a photon is converted into an electron-hole pair, typically in the donor material, the charges tend to remain bound in the form of an exciton, and are separated when the exciton diffuses to the donor-acceptor interface. The short exciton diffusion lengths of most polymer systems tend to limit the efficiency of such devices.

1.2.4 Dye-Sensitised Solar Cells (DSSC)

Dye-sensitized solar cells separate the two functions provided by silicon in a traditional cell design. In the DSSC, the nano textured layer of the semiconductor is used solely for charge transport, the photoelectrons are provided from a separate photosensitive dye adsorbed on the high-surface area semiconductor. Charge separation occurs at the semiconductor-dye-electrolyte interface. Those cells use typically titan dioxide nano-textured surfaces functionalized dye molecules.

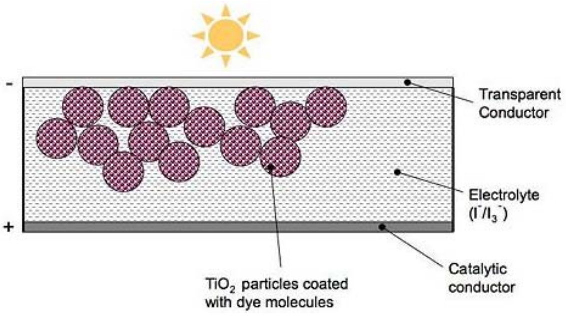

Figure 3: Dye-sensitized solar cell description

During operation, sunlight enters the cell through the transparent top contact, striking the dye on the surface of the nanoparticles. Photons with energy on the order of the semiconductor bandgap energy are absorbed in the dye. The excited electron is quickly injected in the semiconductor before slowly diffusing to the anode on top. Meanwhile, the oxidised dye molecule is quickly reduced by the liquid (volatile or not) or solid state electrolyte. The oxidized electrolyte is then reduced at the counter electrode to close the external circuit.

Advantages of dye solar cells are cheap manufacturing processes through screen printing or roll-to-roll manufacturing, high efficiency in direct or diffuse incidence of light (e.g. for in-house or window application) as well as the transparency and colour design possibilities of the cells, which open up interesting architectural application perspectives. Its disadvantage is rather low conversion efficiency and the need of an electrolyte, which is actually liquid and tends to evaporate under real state use. Reproducible prototypes have been implemented and fabrication processes have been well described.[4]

1.3 Keywords

Photovoltaic, solar cell, thin film, dye sensitised, silicon

2.1 State of R&D – Additional demand for research[5,6,7]

2.1.1 Efficiency

Most of the technologies described previously can be used either as single junction or tandem cells. Efficiencies for the relevant solar cell technologies are given in Figure 1.

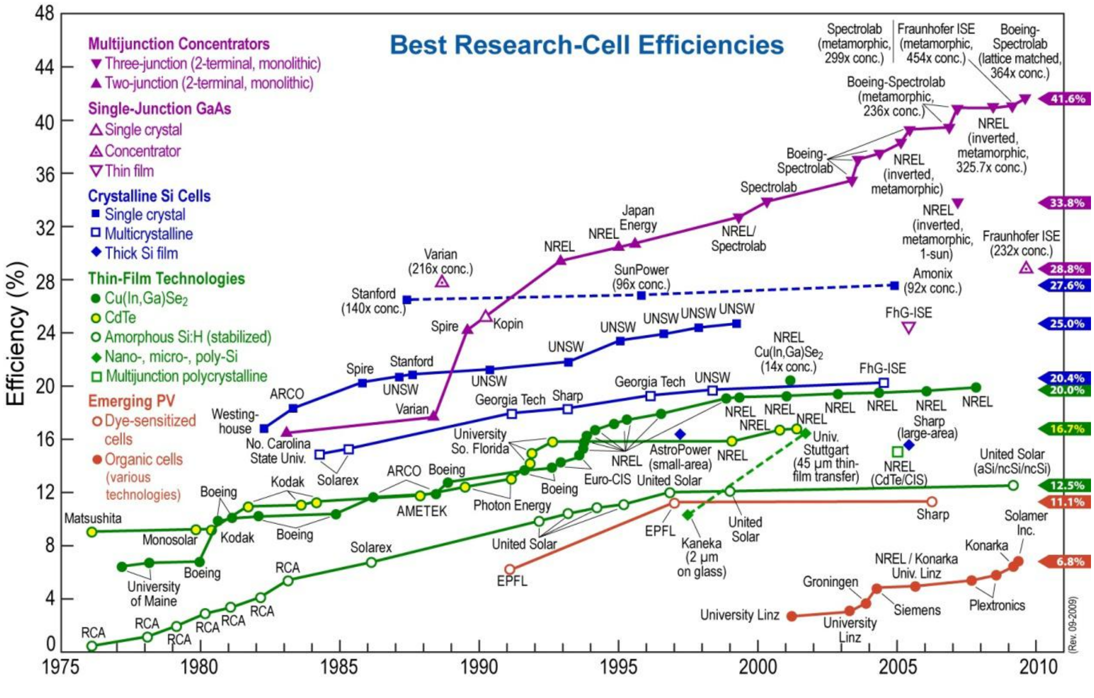

Figure 4: Efficiencies of different types of solar cells

The most efficient solar cells devices developed to date are those based on high cost, small area semiconductor multijunctions. Crystalline Si cells are now approaching the theoretical limit. Organic solar cell technology is still maturing so it is still difficult to properly assess their future. Nevertheless, with certified efficiency around 7-8% and increasing stability they do represent an interesting emerging technology. As for DSSC, the performances have been tied to the development or new, highly absorbing organic or ruthenium-based dyes. However, further research on nanostructured cells promises to push maximum efficiencies ever closer to that of the more expensive thin-film and crystalline technologies.

New records have been recently settled:

- Under 1 sun illumination:
  - an efficiency of 20,1% has been recorded on CIGS thin films …
  - an efficiency of 13.4% for Copper-Indium-Gallium-Diselenide solar cells (CIGS) on a polyimide substrate produced on an industrial roll-to-roll system had been recorded by Solarion AG from Leipzig, Germany
  - an efficiency of 11.1% for a DSSC using state of the art ruthenium-based dyes and highly scattering layers (Han, Japan & Grätzel, Switzerland)
  - an efficiency of 7.9% for organic PV has been demonstrated on small area

cells (Solarmer, US)

- Under concentration:
  - an efficiency of 28.3% for a multiple quantum well solar cell under 500 suns had been recorded by QuantaSol and confirmed by Fraunhofer-ISE
  - an efficiency of 41.6% for a triple junction GaInP/GaInAs/Ge under 364 suns had been recorded by Spectrolab and confirmed by the NREL (National Renewable Energy Laboratory)

The improvement of the efficiency of solar cells will mostly depend on the technology considered. It is here proposed to divide the global efficiency into absorption efficiency defined as the quantity of photons that are absorbed, the photon conversion defined as the quantity of photons that are converted into electrons and the quantity of electrons that are then collected and the electron collection defined as the final quantity of really available electrons for an outside electric circuit. Some technological solutions developed could improve on several of these efficiencies at the same time.

2.1.2 Photon absorption

Crystalline silicon cells have the advantage of being abundant and of well studied thanks to advances in microelectronics. But as a thin solar cell, silicon does have a few drawbacks. For example, it has poor light absorption coefficient which means that you typically need a very thick substrate (300 µm) to absorb light. This has a significant impact on the overall cost of the solar cell. However, if the optical absorption can be improved, by coupling it to microcrystalline or amorphous Si, then more electrons can be produced with less materials increasing overall efficiency and reducing costs. For example, researchers are exploring photonic crystals structures that reflect and “focus” light within the Si thin film to increase its light harvesting and produce more electrical current.[8] Photonic crystal can be realised by structuring the absorbing layer itself, in order to induce very slow light diffusion modes, including a light path length enhancement. Numerous simulation studies tend to show that absorption would then be improved and as a consequence the converted solar energy as well. Experimental results tend to confirm them. This effect could be applied in organic thin film cells[9], crystalline Si cells[10], or even Dye sensitized solar cells[11].

Metallic nanoparticles can be used to assist sunlight absorption in thin film photovoltaics with surface plasmon resonance. The nanoparticles are deposited at the interface between the absorbing layer and the air (or the superficial layer) and induce light diffusion at specific wavelengths. The absorption will then increase at characteristic wavelength of Plasmon resonance. First results (simulation and experiments) on thin films show that the global efficiency can bee slightly increased[12,13]. This principle can be applied for quantum dot thin film solar[14] cells or in polymer solar cells. In polymer solar cells the use of silver nanoparticles has proven a 12% relative increase of the efficiency.[15] The small silver particles help the polymer capture a wider range of wavelengths of sunlight than would normally be possible. Practically, silver particles are encased in an ultra-thin polymer layer (different than the light-absorbing polymer), which is deposited below the light-absorbing layer. Silver and gold nanoparticles have been shown to induce plasmonic resonances at their surface that tend to localize the solar energy in the active materials and improve its light harvesting to increase efficiency.[16]

In liquid electrolyte dye-sensitised solar cells, the quantum efficiency is already close to unity in the absorbing light range. This is not the case yet of solvent-free and solid state electrolyte DSSC so that new approaches are being developed to improve the latters' quantum efficiency. Nanotechnology provides various ways to diversify the shape of TiO_2 structure, in order to increase the surface and the light absorption coefficient. Aggregate of nanoparticles, nanorods, nanospheres have been proposed. One of the alternative ways uses ZnO nanowires or nanoparticles to replace the TiO_2 nanoparticles. Single crystal nanowire arrays have indeed excellent electron transport property and provide therefore an enhanced carrier extraction which increases the carrier collection efficiency[17,18]. ZnO nanoparticles aggregates offer the advantage to retro-diffuse the light which is not absorbed. The highest efficiency reached with ZnO nanoparticles is 6,58%, obtained in a cell formed by two layers of nanoparticles (diameter 20 nm and 600 nm)[19].

A relatively low-cost method of increasing energy yields of solar cells and solar collectors is the application of antireflection layers. These layers can enhance solar cell performance by increasing light coupling. Marketable developments on antireflection layers for flat glass based on a nanoporous coating of silicon dioxide have been demonstrated. The graded porosity allows the adjustment of the effective refractive index between glass and ambient air, which helps reducing reflection losses of glass panes of usually 8% to 2%. Some others research direction lies in the development of antireflection layers based on ZnO nanostructures for Si solar cells. The proposed solution achieves a weighted global reflectance of 6.6%, which is inferior to that of an optimized SiN single layer anti-reflection coating.[20]

2.1.3 Photon conversion

The improvement in the quantity of photons absorbed can be obtained by increasing the absorption coefficient of the materials used or increasing the wavelength range harvested by these materials, or both. A few different strategies are employed to achieve these complementary goals. One common idea is to stack several solar cells with different bandgaps in order to widen the absorption region. This can be achieved for example by using complementary polymers, semiconductors, nanoparticles or dyes. For example, silicon solar cells can use a mixture of crystalline, microcrystalline and amorphous Si or even quantum dots to produce various bandgaps for enhanced absorption and carrier generation.[21] Composite solar cell combining polymers and CdSe nanostructures have also been proposed[22]. The additional advantage of these cells lies in the capacity of both components to absorb light in a complementary way, unlike polymer/fullerene composite cells, where fullerene contributes very little to the spectral response.

Nanoparticle synthesis and characterisation (new core/shell systems and functionalising materials), is a very active research field. The aims of these studies are quantum efficiency improvement, absorption and emission tuning, blinking and whitening suppression, particle coupling improvement. These properties are interesting for photovoltaic applications, even if most studies remain very fundamental works, which could also serve other applications (imaging, lightning…)[23,24,25].

Some laboratories are working on new nanoparticles which could replace standard materials used for thin film solar cells (like CIGS or CdTe). Low cost production processes, non toxicity and high availability of the materials are the main advantages of this kind of compounds. For example Cu_2ZnSnS_4 (CZTS) is a promising quaternary compound. Progresses in synthesis of CZTS nanoparticles (10 to 25 nm) have been recently reported, and preliminary results show still modest efficiency results[26,27]. Multi-crystalline CZTS thin films have also been synthesised[28].

2.1.4 Electrons collection

In polymer solar cells the use of fullerene derivates like PCBM as electron acceptors has now become standard in high efficiency cells because it allows fast charge transfer and transport to take place at the sub 10-nanometer scale, on the order of the diffusion length of an exciton generated from organic semiconductors.

In dye sensitized solar cells, new architectures including a series of semi-conductor nanotubes allowing concentric extraction of the charges produced by the dye[29]. This new concept opens novel ways to research on use of nanostructures in all types of photovoltaic cells.

The absorption efficiency can be increased by improving light management through the front electrode. Several different options are in development to achieve this goal. The first one consists in the use of carbon nanotubes. Compared to existing transparent conductor technologies such as Indium Tin Oxide (ITO), CNT films have a number of potential advantages. These include the use of an abundant material (carbon), high film flexibility, and solution processibility.[30] It is also possible to use ultra thin graphene films which possibly exhibit a high conductivity and a transparency of more than 70% over 1000-3000 nm.[31] The use of nanostructured ZnO[32] and Ag nanowires are also an alternative.

Nanotexturized transparent conductive oxide layers are also analyzed as front electrodes. It shall help optimize light dispersion in the substrate and minimize reflection losses.

2.1.5 Process improvement

Semiconducting nanoparticles can be used as constituent in inks and deposited thanks to low cost processes on rigid or flexible substrate. Thanks to roll-to-roll printing process, the company Nanosolar deposits an ink containing 20 nm nanoparticles. The Nanosolar thin solar cells have reached a NREL certified efficiency of 15.3% in 2009[33], which could allow them competing with First Solar, the current leader in CdTe thin film solar cells.

DSSC technology has made enormous progresses in the last decade. Though the stability increased significantly, it still does not meet the guaranty standards of other solar modules (longer than 20 years for temperatures down to -40°C and up to 85°C). The liquid electrolyte, sealing and phase changes make it technologically very hard to achieve. Therefore studies on solvent-free ionic liquid and solid state electrolyte DSSC are being developed as an alternative to the liquid electrolyte version. Efficiencies for the ionic liquid cells are fast approaching those of the high efficiency liquid cells (9-10% vs 11%) but the solid state DSSCs are still trailing behind at this point (about 5-6% efficiency). Rapid development on nanostructured DSSCs should, however, bring higher efficiencies for all types of electrolytes.

DSSC have one of the shortest energy payback time of all solar cell technologies. Indeed, payback time of 0.6-0.9 year haS been forecasted. (ECN, 2007)

2.2 New concepts

In silicon solar cells some new researches are conducted to replace the layer of bulk silicon by a layer of silicon nanowires. The purpose is to replace the planar p-n junction by a high surface area radial p-n junction. Then the absorption of light is made along the axis of the nanowires and the electron collection is made along the radius of the nanowires.[34] Recent theoretical[35] and experimental[36][Perraud] results seem to show that this technology could provide 15% efficiency solar cells on different kinds of substrates, including flexible ones. Limitations of this technology have also been identified: bulk contamination of the nanowires and surface recombination of the electron-hole pair could be the main issues to be solved.

Publication of nanowire-based solar cells concepts is greatly expanding. New solar cells based on GaAs nanowires have been proposed in 2009. Efficiencies of 4.5% with a high form factor, dependent on internal cell resistivities, of 0.65 has already been obtained[37]. The main problem remains scaling to macroscopic panels.

Tandem organic solar cells structured in the PIN configuration (P-type / P and N-type interpenetrated / N-type) have been demonstrated by Heliatek, a start-up from Dresden University. This company announced in June 2009 an energy conversion rate of 5.9% on a surface of 2 cm^2, demonstrating the possible availability of organic photovoltaic devices in the next few years. [38]

Also, CdSe nanoclusters have been pined in TiO_2 nanotubes through a novel photo-enabled electrodeposition method. The vertically aligned nanotubes thus constitute a dye sensitized-like solar cell and, even if the conversion rate remains low (<3%), the low cost elaboration method seems interesting in order to increase the efficiency of such nanostructures.

2.3 Applications and perspectives

The applications and therefore the markets greatly depend on the kind of solar cells considered. Three main fields of applications with their own market scale seem probable.

First, portable and stand-alone applications can be cited. Flexible technologies such as thin films, organic or amorphous silicon solar cells seem very appropriate. Current requirements are low, while the need in voltage is specific to the used electronics. The weight also needs be reduced to a minimum. As an example, backpacks covered with a cheap, lightweight, and flexible dye-sensitised solar cell, for on-the-go recharging of portable electronics, were unveiled at the Hong Kong Electronics Fair last October. The solar cells were made by the Cardiff, U.K.-based G24 Innovations Company. The modules demonstrated could by sewn on clothing, tents, and awnings. Additionnaly, Konarka polymer solar cells also show great promise for incorporation by the textile industry.[39]

Second, building applications have to be mentioned. Here Si, thin film and dye-sensitised solar cells seem appropriate. We already know of the hug potential for rooftop installations but it is worth noting that dye-sensitised solar cells are a promising technology for use as windows.

Third, farm applications connected to grids can be cited. These applications should produce electricity as a price comparable to that of production by conventional power plants. They can be used in places where the sun is abundant and other sources of energy (water, coal …) are limited. In these cases, high efficiency solar cells are the most appropriate. These can also integrate sun tracking machinery and solar concentrator to improve yield and decrease costs. Mostly Si-based solar cells as well as efficient thin films and tandem cells seem most appropriate.

2.4 Current situation within the EU

Europe has the great advantage of possessing an active European Technology Platform dedicated to photovoltaic. In 2007, it has indeed published a very important document: a Strategic Research Agenda (SRA)[40], which aims at describing which R&D activities the EU and its Member States should fund to make PV a widely used technology generating significant returns for Europe. In 2009, a sequel to this SRA was published: the Implementation Plan[41], which aims at describing how to realise the SRA's findings and recommendations.

Europe also benefits from large PV research infrastructures. Among those, the following facilities have been flagged by the European PV Technology Platform:

- PV-TEC (PV Technology Evaluation Center) used by about 40 companies and run by the Fraunhofer-ISE
- ECN's line available to company through joint research projects on new processes, manufacturing equipments and cell and modules concepts
- CEA-INES's platform RESTAURE used by about 8 companies but mostly CEA researchers
- PVcomB (Competence Centre Thin-Film and Nanotechnology for Photovoltaics Berlin) whose goal is to support thin-film PV technologies and products
- IMEC's solar cell facilities which develops c-Si and organic solar cells thanks to an expertise in microelectronics and organic electronics

Several Technology Platforms on various fields contribute also to the development of the PV sector:

- EuMat (Advanced Engineering Materials and Technologies):
- EPoSS (European Platform on Smart Systems)
- Photonics21
- ESA (European Space Agency)
- ENIAC (European Technology Platform on Nanoelectronics)
- e2b-ei (Energy-efficient Buildings Public-Private Partnership)

Recent economic announcements point to the fact that European activity in solar energy is progressing. For example, two major energy companies Total and GDF SUEZ and their common solar cells manufacturing subsidiary Photovoltech have joined the IMEC industrial affiliation program (IIAP) to develop the next generation of crystalline silicon solar cells. Their multi-partner R&D program concentrates on sharply reducing the amount of silicon used, whilst at the same time increasing the efficiency of solar cells. This would substantially lower the fabrication cost for this technology. Total has also signed a partnership with LPICM a French laboratory from the CNRS-Ecole Polytechnique joint research unit in order to develop a joint-team on thin-film Si solar cells as well as on Si nanowires.[42]

On dye-sensitised solar cell, the European expertise has been recognised since G24 Innovations (G24i), the global pioneer of DSSC, has signed a formal agreement with three of China's most prestigious institutes to accelerate industrial development of the technology, just three weeks after they successfully launched the world's first commercial application of DSSC.

3.1 Short application description

Solar PV technologies can be used in several types of applications: grid-connected systems, off-grid systems, and consumer goods.

3.1.1 Grid-connected

Electricity grid connected solar power plants are capable of generating electricity from several hundred kilowatts to several megawatts. Industrial and home installations may be used to satisfy local electricity demand, and to supply additional power at times of peak demand. 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. 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.[43]

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 panels 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.

3.1.2 Off-grid systems [Add a summary of commercial rooftop PV here]

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 an electricity grid, in developing countries or in rural areas of developed countries. Electrifying rural areas does not only represent an economic opportunity, but also presents wider societal benefits. One significant application of off-grid solar power would be for powering important local 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. For this application, local electricity production through the use of PV would represent significant advances for developing societies in terms of cost, maintenance, and coverage.[43]

3.1.3 Consumer goods

The most ubiquitous application of solar PV up to now was their use as replacement for 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 represent a small, commoditised component of a low cost device, and therefore the value is low.[43]

3.2 Drivers and barriers

PV is still an early-stage technology so there are several barriers which slow the technology's transition to market. The high price seems to be most prominent factor. PV plants have a higher investment cost than competing technologies, but lower operating cost and no fuel price risk. Other barriers are the market power of incumbent energy firm and valuation methods that favour large-scale power plants. The cost disadvantage is influenced by subsidies. The Swiss University of St. Gallen´s Institute for Economy and the Environment reported in 2009 that duration of administrative process was the most important attribute encouraging PV project developers. Almost as important was also the level of Feed-In Tariffs, as seen from the Figure 5.[44]

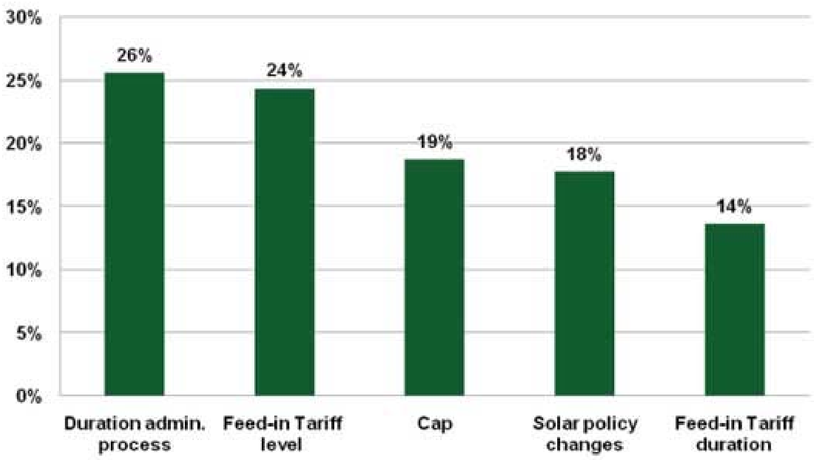

Figure 5. Relative importance of policy attributes by Swiss University of St. Gallen´s Institute for Economy and the Environment research [44].

According to the EPIA report "Set For 2020 - Solar Photovoltaic Electricity", the potential of PV deployment depends on six independent framework conditions. These framework conditions are: system integration, cost competitiveness, market deployment, policy framework, interaction with other renewable energy sources and the supply chain.[45]

3.2.1 System integration

Daily and seasonal variation affects the generation of solar energy and thus requires flexibility of grid management. That is achieved by better coordinated long-term planning of investments in new generation capacities across the European electricity market. However, system integration to the infrastructure and evolution of the generation mix will limit market penetration of new energy technologies.[45]

3.2.2 Cost competitiveness

Increased market penetration of PV will reduce the price level and make investments competitive in Europe. This enables market-driven growth in the near to mid-term without Feed-in Tariffs. The first step is technology development to enable price reduction at system level. Extensive R&D investment and continued support of PV market development is required for price reduction.[45]

3.2.3 Market deployment

The development of innovative products to meet diverse customers' needs, certification for safety, and reliability as well as availability of appropriate financing solutions is key to enable successful PV deployment. [45]

3.2.4 Policy framework

Feed-In Tariffs are the best support, especially when they are sustainable, not unduly generous and develop with the growing market share of PV.[45] At least 11 EU member states offer subsidies for solar power including instruments such as feed in tariffs, investment grants and subsidies, tax credits, and beneficial credit terms. These supports are available to utilities, companies and individual households[46]. A cautionary note, in 2009 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.

3.2.5 Integration with other renewable energy sources

PV is essential component of the EU´s 20/20/20 objective. PV and wind with grid connection has a common interest.[45]

3.2.6 Supply chain

The PV supply chain is expected to maintain a global multi-gigawatt production capacity in the coming years. Key challenges for the chain are: the availability of polysilicon and commodity materials, cell and module capacities, and the availability of professionals. Therefore education is an important to maintain a leading PV industry position in Europe.[45]

3.3 Functional requirements and impacts of nanotechnology

Nanotechnology-based solutions may be used to improve the functional requirements of solar photovoltaics and to speed competitive PV-applications market entry. 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 increase the efficiency of semiconductor materials and enable novel applications of solar PV technology, such as integration with building materials or even clothing. Regardless of the technology used, solar PV has the following functional requirements[47]:

3.3.1 Effectiveness

PV cell must provide enough electrical energy to offset the costs of its production, installation and use. Currently the highest efficiencies are obtained by concentrator PV cells, which are capable of generating conversion efficiencies of around 40% (a European record of 39,7% was achieved by Fraunhofer ISE in 2008)[48]. Efficiencies achieved by other technology approaches are shown in Table 1.

Technology	Highest Recorded Efficiency
Concentrator PV	40%
Crystalline Silicon	24%
Thin Film – CIGS	19%
Thin Film - CdTe	16%
Thin Film - aSi	12%
Dye sensitized	11%
Organic PV	5%

Table 1. Comparison of Efficiency Levels Achieved by Solar PV Technologies[49], [50]

For example carbon nanotubes might be used in photovoltaic cells to make more efficient next-generation solar cells[51]. Using roll to roll nanoimprint lithography the solar cells could also be produced cheaply[52]. Use of nanocrystals may also give a potentially high efficiency[47].

3.3.2 Durability & 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 what is lifetime. The target lifetime for a PV cell is at least 20 years, in a temperature range of -40 °C to 85 °C[53] and many manufactures issue warrantees to this effect. Durability is a particular issue with organic approaches; degradation of conducting polymers is a well-studied phenomenon.

3.3.3 Easy installation & lightweight

The easier the installation is more potentially the PV application win market acceptance. The lighter the PV cell is, the more locations in which they can be installed. A potential application of DSSC is their use as windows, given that their structure may render them partially translucent[54]. PV coatings may be also applied for example to the surface of roof material in the same way that corrosion-resistant coating.[55]

3.3.4 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.[56]

3.4 Nanotechnology impacts on value chain

Silicon supply has been the PV industry bottleneck since 2005 and that has enabled the PV Thin Film industry to grow[74]. However, silicon supply is no longer the bottleneck as the price has fallen closer to spot price, so silicon solar panel producers are able to sell their products below $2 per watt. The price of silicon panels was narrowing to the price of cadmium-telluride panels in 2009.[57]

Competitive price levels and production with low manufacturing cost per kWh are the targets in the PV market. This target is being reached by investing in larger manufacturing processes and equipment and materials suppliers' partnerships. As seen from Figure 7 and Figure 8, crystalline silicon technology has many steps in the value chain and several players are typically needed, whereas one producer can handle the whole value chain in one factory using thin film technology. Innovation of thin film production equipment and materials are the key parameters when moving towards thin film PV production, according to the Yole Dévelopment Photovoltaic Report.[58]

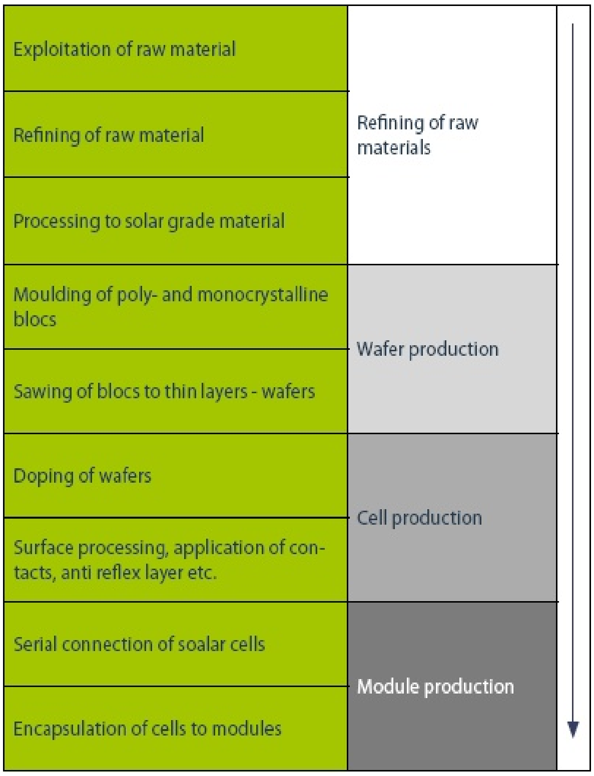

Figure 6. Value chain for crystalline silicon solar cells [59]

Exploitation of raw material	Refining of raw material
Refining of raw material	
Coating of active material on suitable substrate	Module production
Serial connection of solar cells	
Encapsulation of cells to modules	

Figure 7. Value chain for thin film cells59

Several factors will impact the extent to which nanotechnology-based approaches become price competitive with crystalline silicon; cost of materials cost of production, and efficiency.[60] 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, as 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 of thin film PV the value chain is likely to consist of the chemical supplier, the equipment manufacturer and the material manufacturer, who could offer PV-integrated materials for the differentiated product.

3.5 Product and company examples

This is a listing of some innovative companies using thin film and other nanotechnology-based approaches to PV production or products. The adoption potential and market penetration of PV technologies was evaluated by questionnaire and interviews and those are therefore company specific.

Amorphous silicon is mentioned to be the best developed thin film technology. It is potentially cheaper than crystalline silicon or other thin film technologies, although it´s less efficient (4% - 8% stabilized module efficiency). It’s advantage is based on the lower material cost and cheaper and more scalable manufacturing processes.[61]

VHT-Technologies (Flexcell) is a good example of the thin film Amorphous silicon PV products market penetration. The first PV consumer products were launched in 2003 and the product range was enlarged in 2008 with flexible building integrated solutions. Alexandre Closset, CEO of VHT-Technologies argued that, “Convincing a customer with a new technology and its advantages was a major barrier, when coming to the market with new products. Competition from China is increasing and it brings tight price competition.” Closset also described the advantages of amorphous silicon technology; “Flexible building integrated solutions utilizing a-si *thin film technology benefits from lighter weight and improved temperature performance compared with crystalline silicon. PV modules with a-si technology produce more power in hot surroundings, whereas it is opposite for products with crystalline silicon technology."*

Name:	**VHF-Technologies SA (Flexcell)**
URL:	http://www.flexcell.com
Used technology:	Thin film Amorphous silicon deposition to flexible plastic substrate instead
Investment:	25 MW production line
Description:	Flexcell was established in 2000 to commercialise work carried out at the Institute of Micro Technology in Neuchâtel. The company is now a subsidiary of Q-Cells

Flexible building integrated solutions

Flexcell makes flexible PV modules an integral part of the various sized and shaped building component. Applications are lightweight and easy to install. Efficiency is 5%.

BIPV solution from Flexcell

CIS, copper indium selenide, achieved greater than 14% efficiency. However, manufacturing costs of CIS solar cells are high, when compared with amorphous silicon solar cells.[62]

Bernhard Dimmler, CEO of Würth Elektronik Research GmbH, pointed out that "market adoption of our CIS modules is good, but we are selling the module together with a complete, grid connected PV system. The potential efficiency is for sure the biggest advantage of CIS technology. The current average efficiency will be increased in the near future, with efficiencies already reached at laboratory scale. The biggest opportunities for CIS modules compared to conventional c-Si are a lower temperature coefficient, higher low light behaviour, much higher flexibility in module design, and a favourable cost structure with higher production volumes, especially in the future." Dimmler continued: "Surely there are still barriers to overcome especially with further designs for BIPV (building integrated PV), in addition to existing varieties we are already offering. An additional barrier is set by the proposal to change the German feed-in tariff, as well as our scaling velocity and innovation potential, which are not rapid enough to compete easily in the market. The major barriers when coming to the market with CIS modules are new materials, new products, and a shortage of references. It was necessary to build a good sales *channel."*

Dimmler emphasized the importance of nanotechnology: "I think it could become a very important technology for thin films".

Name:	**Würth Solar**
URL:	www.wuerth-solar.de
Used technology:	Thin film CIS
Investment:	In 2008 expansion to 30MW production capacity
Description:	Würth Solar was the first company worldwide to begin large-scale production of GeneCIS solar modules in its specially-built CISfab solar factory in Schwäbisch Hall in autumn 2006 – setting new benchmarks in the industry.

GeneCIS modules

GeneCIS modules generate relatively high yields even in high temperatures that can occur in European latitudes in early summer or in scattered light.

GeneCIS modules area efficiency is at the moment max. 14%

GeneCIS modules by Wûrth Solar

CIGS are currently the most efficient thin film technology. Efficiency is not however as good as crystalline silicon solar cells, but they are substantially cheaper than crystalline due to potentially lower production and material costs. CIGS has also very strong light absorption and therefore thinner layer of material is needed than to achieve the same absorption as crystalline silicon PV. In addition, smaller amounts of toxic cadmium are used in CIGS than in CdTe cells.[63]

Name:	**Q-Cells SE (Solibro)**
URL:	http://cigs.q-cells-moduls.com
Used technology:	Thin Film CIGS
Investment:	Q-Cells shares from thin film subsidiaries Solibro (100%), Calyxo

	93%, Sunfilm 50%, Flexcell 58,11% (Year 2009 figures)
Description:	CiGS modules produced in Q-Cells´s subsidiary Solibro´s factory are the world's highest efficiency (12%) thin-film solar modules. Good performance in low and oblique light and positive power sorting result in excellent energy yields. First CIGS modules were manufactured in 2008 and the production capacity was expanded in 2009.

CIGS modules Q-Cells' CIGS modules are distinguished by the world's highest efficiency (12%) for thin-film solar modules. Their long-term stability is also proven in quality tests. Glass-glass composite SL1 PV module is self-cleaning and cost-efficient without frame.	 *SL1 modules by Q-Cells*

CdTe potential emissions of cadmium have concerned the communities. It has been shown that Cd compounds cannot be emitted during normal use of PV modules. Environmental emissions to environment would occur only after decommissioning, if modules ended up in municipal waste-incinerators. Recycling completely resolves these problems.[64] CdTe semiconductors, like a-si, are less susceptible to cell temperature variations than traditional crystalline semiconductors and therefore the modules produce more electricity in hot areas.

GaAs, gallium arsenide is also known as single crystalline thin film. It is a high cost and high efficiency (>32%) solar cell. These solar cells have taken over from silicon as the cell type most commonly used in satellite applications. Many solar cars also utilize GaAs. Gallium arsenide's toxic and carcinogenic properties are drawbacks of the technology. [65]

Morten Schaldemose, CEO from SunFlake A/S described, that successful results have been published from GaAs technology and first products will be on the market after a few year. Advantages of the technology are based on among other things to high efficiency and beneficial band gap when comparing to silicon and other thin film technologies. Uniform structure growth for crystalline is one of the biggest barriers to overcome with the technology. Concentrating solar power (CPV) in high irradiance areas and other applications where space is limited are maybe the most significant threats for GaAs applications. Nanotechnology can be seen as a enabler of CPV and other new applications.

Name:	**SunFlake A/S**
URL:	http://www.sunflake.dk
Used	GaAs

technology:	
Description:	SunFlake is among the very first companies to use nanostructures as the only active element in a solar cell. The prospect of achieving record high conversion efficiencies combined with a reduction in fabrication cost gives advantage on the market. Households in rural areas around the world with no stable energy supply, as well as future high-tech mobile phones can benefit from this technology.

Dye-sensitized cells (DSSC) are cheaper to manufacture than other thin film technologies and they can be printed quickly on flexible surfaces. Special benefits over other thin-film solar technologies are that dye-based cells work well at wide angles, are longer lasting and they work more efficiently in indoor light.[66] These solar cells may have a small niche in the market right now. Professor Michael McGehee, at Stanford University said on Technology Review (11/2009), that "in the future we may see this technology compete with the more traditional thin-film solar technologies based on amorphous silicon, cadmium telluride, and cadmium indium gallium arsenide if the combination of efficiency, cost, and durability improves."

"Solaronix´s current DSSC technology is ready for indoor and some outdoors industrial usages and ongoing qualifications are in progress for building applications as well. In the next 2 years, efficiencies will be increased to ca. 8 – 9 %, while we estimate that the production costs will be less than 0.5 € /Wp, thanks to the fully automatic "all printed" concept we pursue", told Toby Meyer, CEO from Solaronix SA.

Name:	**SOLARONIX SA**
URL:	http://www.solaronix.com
Used technology:	Dye-sensitized solar cell modules (DSSC)
Investment:	New facilities with 30 cm wide "all printed" module production test line, chemicals production up scaling for industrial supplies.
Description:	Solaronix, located in Aubonne Switzerland, was established end 1993, and is the leading provider for all the specialty products related to the DSSC field, such as sensitizers (with ruthenium and pure organic), nano-titania pastes for all printing methods, ionic liquid electrolytes, etc.

The DSSC MIM's The DSSC MIM's are manufactured from a few cm^2 up to 30 x 30 cm with the actual equipments. The current efficiency is 6 to 7 %. The monolithically integrated modules	

(MIM) are made by screen printing of all the active layers. The modules contain 34 cells, delivering ca 250 mA and 18 V when lit at one sun.	 *Monolithically integrated module (MIM) by Solaronix SA*

Organic solar cells' optical absorption coefficient is high, but the main disadvantages associated with then are low efficiency, low stability and low strength compared to inorganic photovoltaic cells.[67]

One company indicated that they had a prototype already available and high adoption potential for the products is seen.

Name:	**Solar Press**
URL:	http://www.solar-press.com/home
Used technology:	Organic
Description:	A newly formed company for the commercialisation of Organic Photovoltaics (OPV). An international and multidisciplinary partnership of scientific pioneers in plastic electronics and materials processing is collaborating with Solar Press in accelerating OPV technology innovation for commercial use. The company has been set up to rapidly deliver a series of solar powered commercial applications, based on OPV, for mass production and usage worldwide. Solar Press is initially focusing on the delivery of solar modules for off-grid applications at unbeatable prices.

Quantum dots

"Quantum-dot solar power could boost output in cheap photovoltaics", expresses Arthur Nozik in Technology Review 2007.[68]

3.6 Solar Photovoltaic market

This chapter considers the current market for solar PV, and assesses the proportion which is currently accounted by nanotechnology.

3.6.1 Technologies market penetration

Photovoltaic global figures indicated that annual installations (GW) increased over 100% from 2007 to 2008, as seen in Table 1. The global photovoltaic market was estimated to decrease by 17% in 2009 and small companies were predicted to be worst affected by the financial crisis. Acquisition of smaller companies by the large players assesses to give them greater control over the solar market in the future[69]. However global solar photovoltaic installations increased in 2009 despite of downturn and reached 6.43GW, according to a new report from Solarbuzz published in 2010[70]. Displaybank reported that total global solar cell production was 9.6GW in 2009[71].

The subsidy models pioneered in Japan and Germany have spread many countries and the positive influences are showing up in increasing the domestic market take-up of PV. PV market was predicted to double and achieve US$48 billion size after the five years, reported Intertech Pira in 2009.[72] Table 2 shows that the EPIA and Greenpeace forecasted PV global market size reach 139 billion € by 2020. The prediction was made before the downturn.

	2007	**2008**	**2009**	**z**
PV annual installations, GW	2,4	5,6	6,8	56
PV accumulated capacity, GW	9,2	15		278
Electricity production, TWh	10			362
Grid-connection consumers, million	5,5			198
Off-grid connection consumers, million	14			757
Employment potential, thousands	119			2 343
Market value,€ billion/annum	13			139

**Advanced scenario for 2020 is based on the assumption that additional support mechanisms will lead to dynamic worldwide growth and the prediction is made before the year 2009 downturn by EPIA and Greenpeace.*

Table 2. Global PV-market figures and predictions for the 2009 and 2020[73], [74]

The EPIA projected in 2009 that thin film solar PV will have a production capacity of 4 GW by 2010 and 9 GW by 2013, accounting for about 25% of the global total (Figure 8)[74]. Assuming that market share and production capacity are directly linked, this implies that the market share of nanotechnology-enabled approaches are growing by 15 percentage points during the period 2007 to 2013. Displaybank, announced in 2010 that share of thin film solar cells market increased and represented 19.8% of globally produced solar cells in 2009[71].

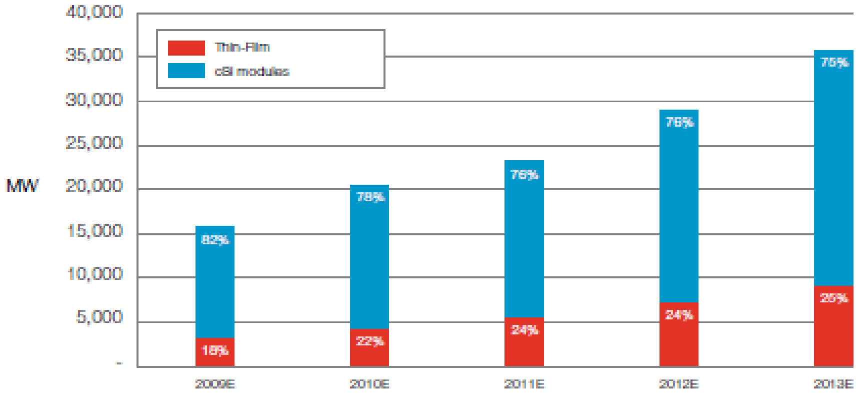

Figure 8. Production capacity outlook - Crystalline technologies vs. Thin film (nanotechnology-enabled production)[74]

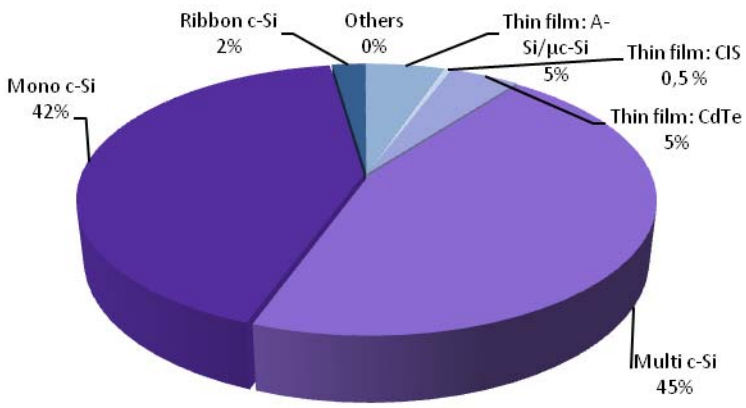

Figure 9. Market shares of solar PV technologies in 2007, Photon International[73]

In 2007 the share of thin film technology was only 10% and was split to a-Si and CdTe, whereas CIS was just entering the market with 0,5% share, as shown in Figure 9. It is interesting to note that in the beginning of 2010 the amount of European nanotechnology based solar photovoltaic cell and module producers concentrating to CdTe technology is smaller than companies focusing on CIS technology, as seen from Figure 10. At the moment there are on the market a few large USA-based companies and at least 5 others entering the market in the near future, whereas the focus of European companies seems to be in other competitive technologies which are coming to the market in near future. One reason might be that in European Union is more cautious about the toxicity of cadmium and cadmium compounds.

Figure 10 is based on the ObservatoryNano-project research done in 2010 by evaluating European companies indicating on their published material that they currently produce nanotechnology-enables solar photovoltaics, or plan to do so in the near future. Adoption potential of the products was estimated with scale 1 to 4, where 1 indicates novel technology with difficulties for market adoption whereas 4 refer to major breakthroughs. On market penetration 0 refers R&D phase, 3 production starting phase and 5 mature products in which the product has been on the market for at least 2 years.

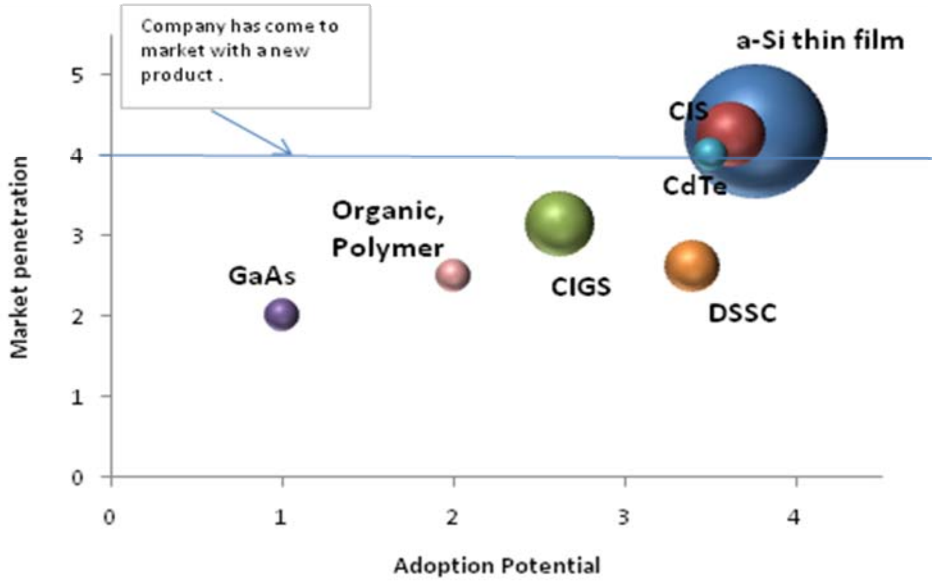

Figure 10. European companies currently producing nanotechnology-based solar photovoltaics or companies planning to enter the market in near future. The size of bubble indicates the amount of companies. (Adoption potential and market penetration are estimates is based on internet research done by ObservatoryNano-project in 2010.)

3.6.2 Applications market share

The market share of grid-connected solar PV applications has increased dramatically since 2004 and it has become dominant (Figure 11). High feed-in tariffs supports the trend. Other trends recognised in 2008 were growing interest to building-integrated PV (BIPV) and utility scale over 200 kW solar PV. [75] The trend towards building integrated systems will increase the role of nanotechnology as well.

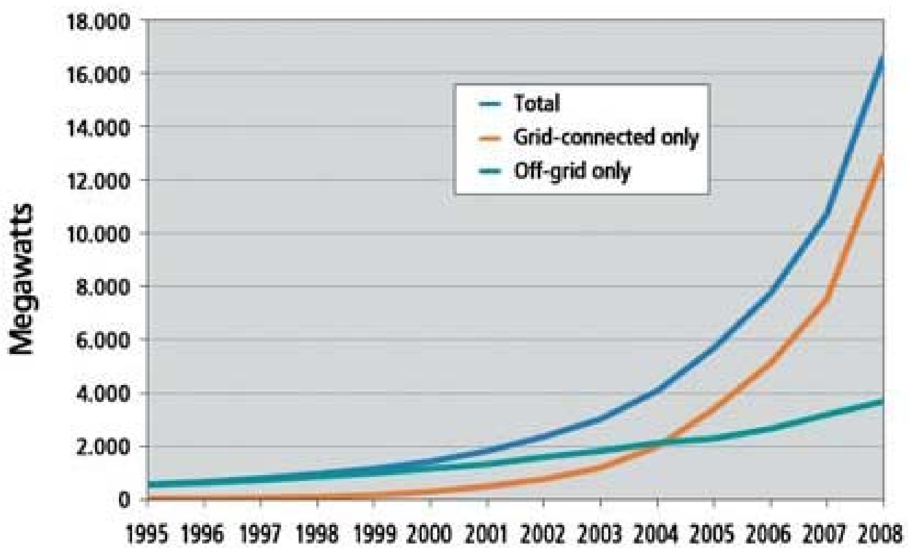

Figure 11. Solar PV, Existing World Capacity, 1995-200875

Off-grid applications have potential, especially for electricity production in rural areas in developing countries. Small home systems and power for summer cottages also belong to this category. The benefits of nanotechnology are seen also in the innovative consumer good –sector.

3.6.3 Geographical spread of activities

Europe is leading the solar PV market. In 2008 it´s share was over 65% of the Global cumulative PV installed capacity, with Japan and US following behind. The intensive increase in 2008 was mainly due to the development of the Spanish market representing 45% of the Global market.[74]

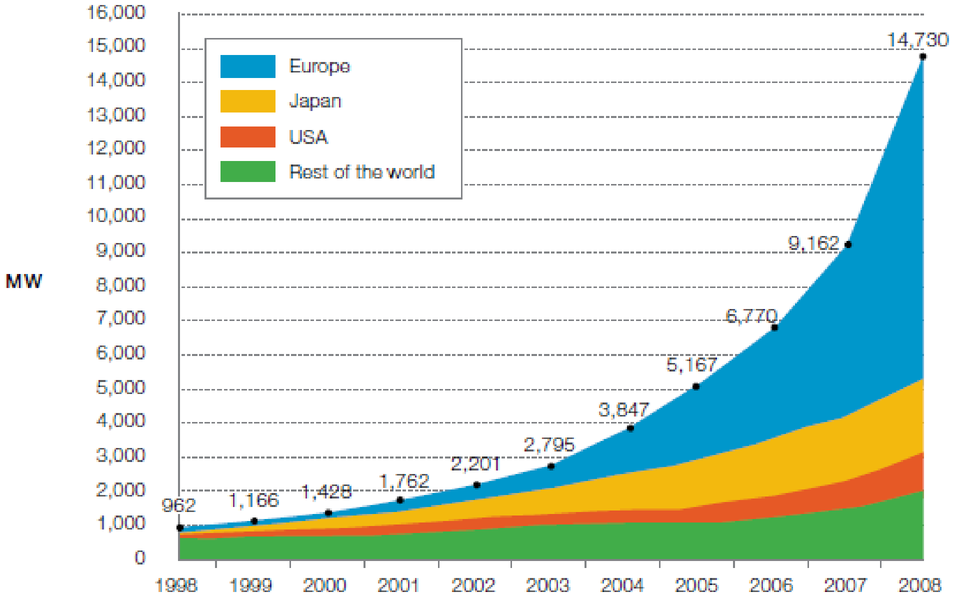

Figure 12. Development of Global cumulative PV power installed per Region 74

The EPIA evaluated that Germany will take the market leader position again due to the Spanish cap which has been set at 500MW for 2009 - 2011. This is supported by that fact that it is the most mature market with FIT schemes, financing opportunities, high potential for future development and skilled PV companies. The United States is predicted to be one of the top markets also in future, because of its support schemes. Japan's growing market size is based on ambitious objectives, and PV technology is well-established and widely integrated in buildings.[74]

Nanotechnology will enable solar PV integration to building materials. According to the Pira studies, thin film and flexible PV growth will start from Europe (especially from Germany) and the US in the short to medium term, whereas Japan, China and Asia will adapt the technology strongly in the medium term. Sales to Africa and other developing nations are predicted to increase in the long term, when organic flexible products are fully viable.[76]

Production location, %	
China	29
Japan	22
Germany	20
Taiwan	11
Rest of Europe	7
Others	11

Table 3. Solar Photovoltaic production location in 200773

China led solar photovoltaic production with 29% share followed by Japan and Germany in 2007, Table 3. China and Japan has kept the leader position in 2008 as well[77] The European Commission´s Joint Research Centre report suggests that China's share is predicted to increase and reach 32% by 2012[78].

3.6.4 Solar Photovoltaic business in Europe

Research carried for this study indicated that the number of European companies producing solar photovoltaic cells and modules utilizing nanotechnology now or in the near future is about 60. 75% of these companies are small or medium sized, and almost 90% of the companies focused only on solar photovoltaic. Most of the companies are located in Germany where the share of small and medium size companies was a little under 60%. More specific company size distribution in diverse countries is presented in Figure 10 and company lists in appendix 1.

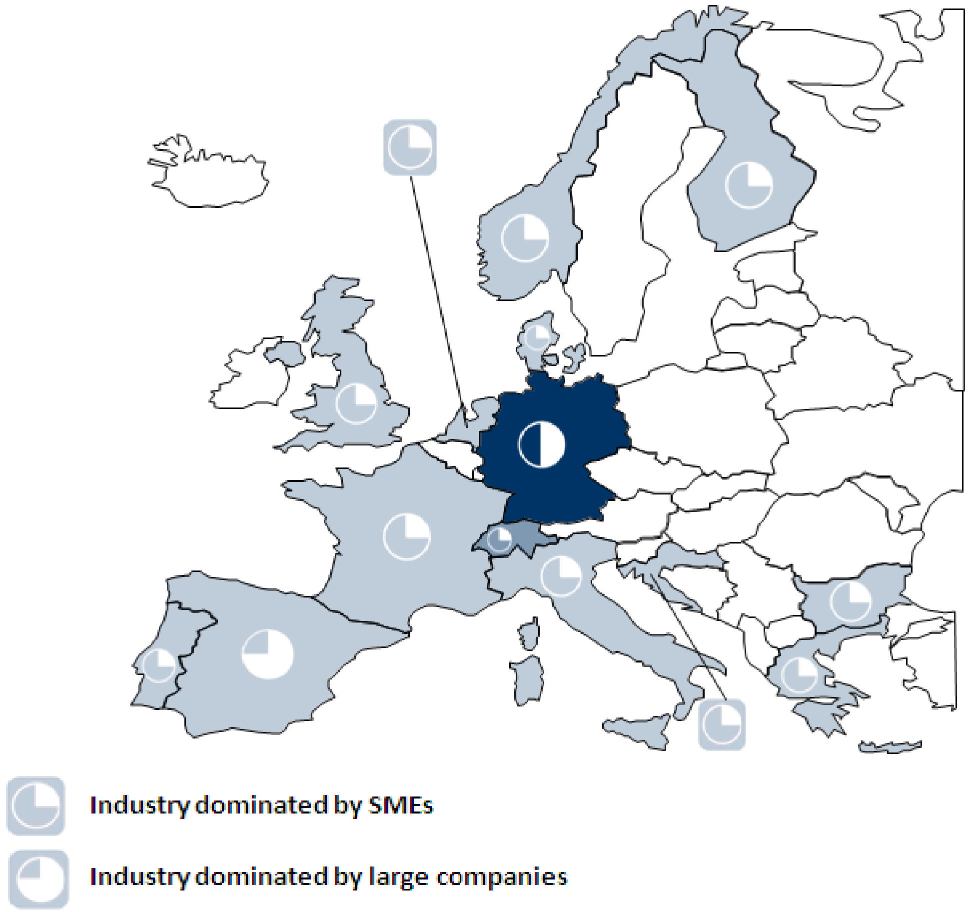

Figure 13. European companies producing now or in near future nanotechnology based solar photovoltaic cells/modules. The darker the colour, more companies located on that country. SME: under 250 employee. (Amount of companies is based on internet research done by ObservatoryNano-project in 2010.)

Appendix 1:

List of European Companies indicating in internet to produce nanotechnology based solar photovoltaic now or in future. (Internet search done in beginning of 2010.)

Annex: Expert Engagement

Dr. Bernhard Dimmler, CEO, Wuerth Elektronik Research GmbH

Mr. Alexandre Closset, CEO, VHF-Technologies SA (Flexcell), Switzerland

Dr. Toby Meyer, CEO, SOLARONIX SA, Switzerland

Dr. Morten Schaldemose, CEO, SunFlake A/S, Denmark

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