Advances and Trends in Photovoltaics (PV)

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Abstract

Solar photovoltaic (PV) power has a particularly promising future. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our greenhouse gas emission goals. Every major country and sector of the economy must be involved. It seems that the technology race is in full swing, with production technology in particular constantly facilitating new developments. A good price-performance ratio is key.

Keywords: world cell/module production, limitations, overview PV technologies, prognoses, perspective

1. Introduction

Since 2000, total PV production increased almost by two orders of magnitude, with annual growth rates between 40 % and 80 % (see Figure 1).

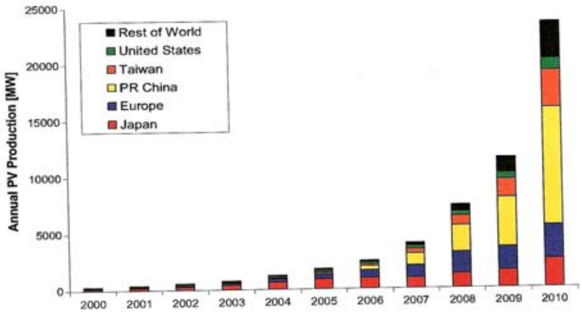

Figure 1. World PV cell/module production from 2000 to 2010 (*conf.* [1])

The most rapid growth in annual production over the last five years could be observed in Asia, where China and Taiwan together now account for more than 50 % of worldwide production.

Photovoltaic has enormous potential: from small roof tops to large solar parks, whether grid-connected or off-grid, it works maintenance-free, quietly and with high reliability.

The first energy storage devices have now also been launched and will make solar energy available during the night and on cloudy days.

Business analysts are confident that the industry fundamentals as a whole remain strong and that the overall photovoltaics sector will continue to experience a significant long-term growth.

The current solar cell technologies are well established and provide a reliable product, with sufficient efficiency and guaranteed energy output for at least 25 years of guaranteed power output.

This reliability, the increasing potential of electricity interruption from grid overloads, as well as the rise of electricity prices from conventional energy sources, add to the attractiveness of PV systems.

About 80 % of the current production uses wafer-based crystalline silicon technology[1] external electric and magnetic fields, or by altering sample geometry and/or topology.

The Dirac electrons behave in unusual ways in tunnelling, confinement, and the integer quantum Hall effect. The electronic properties of graphene stacks vary with stacking order and number of layers. Edge (surface) states in graphene depend on the edge termination (zigzag or armchair) and affect the physical properties of nanoribbons. Different types of disorder modify the Dirac equation leading to unusual spectroscopic and transport

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[1] A major advantage of this technology is that the complete production lines can be bought, installed and be up and producing within a relatively short time-frame. However, the temporary shortage in silicon feedstock and the market entry of companies offering turn-key production lines for thin-film solar cells led to a massive expansion of investments into thin-film capacities between 2005 and 2010.

properties. The effects of electron-electron and electron-phonon interactions in single layer and multilayer graphene are presented in [3].

Similar to other technology areas, new products will enter the market, enabling further cost reduction. Concentrating Photovoltaics (CPV) is an emerging market. There are two main tracks:

(i) either high concentration >300 suns (HCPV),

(ii) low to medium concentration, where the concentration factor is 2 to approx. 300.

In order to maximise the benefits of CPV, the technology requires high Direct Normal Irradiation (DNI) and these areas have a limited geographical range – the "Sun Belt" of the Earth. The market share of CPV is still small, but an increasing number of companies are focusing on CPV.

In order to maintain the extremely high growth rate of the PV industry, different pathways have to be pursued at the same time:

(a) Continuation to expand solar grade silicon production capacities in line with solar cell manufacturing capacities;

(b) Accelerated reduction of material silicon solar cell and Wp, e.g. higher efficiencies, thinner wafers, less wafering losses, etc.;

(c) Accelerated ramp-up of thin-film solar cell manufacturing;

(d) Accelerated CPV introduction into the market, as well as capacity growth rates above the normal trend.

The first 100 MW thin-film factories became operational in 2007. If all expansion plans are realised in time, the thin-film production capacity could be around 22 GW (or 32 % of the total 69.4 GW, in 2012), and about 30 GW (see Figure 2).

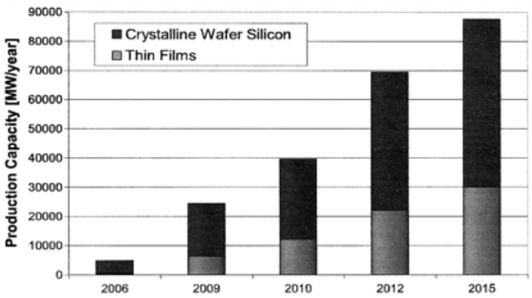

Figure 2. Actually and planned PV production of thin-film and crystalline silicon-based solar modules (*conf.* [1])

The first thin-film factories with GW production capacity are already under construction for various thin-film technologies[2].

Concentrating Photovoltaics (CPV[3]) is an emerging technology which is growing at a very high pace, although from a low starting point.

More than 50 companies are active in the field of CPV development and almost 60 % of them were founded in the last six years. Over half of the companies are located either in the USA and Europe (primarily in Spain).

This variety of technologies is an insurance against a roadblock for the implementation of solar PV electricity, if material limitations or technical obstacles restrict the further growth or development of a single technology pathway.

The PV industry has changed dramatically over the last few years. China has become the major manufacturing place followed by Taiwan, Germany[4] and Japan.

Amongst the 15 biggest photovoltaic manufacturers in 2010, only three had production facilities in Europe.

Even with the current economic difficulties, the increasing number of market implementation programmes world-wide, as well as the overall rising energy prices, the need to re-evaluate the validity of a nuclear option after the tragic events in Fukujima,

[2] The majority of companies are silicon-based and use either amorphous silicon or an amorphous/microcrystalline silicon structure.

[3] The main parts of a CPV system are the cells, the optical elements and the tracking devices. The recent growth in CPV is based on significant improvements in all of these areas, as well as the system integration. However, it should be pointed out that CPV is just at the beginning of an industry learning curve with a considerable potential for technical and cost improvements. The most challenging task is to become cost competitive with other PV technologies quickly enough in order to use the window of opportunities for growth.

[4] Despite that Europe – especially Germany – is still the biggest world market, the European manufacturers are losing market shares in production. This is mainly due to the rapidly growing PV manufacturers from China and Taiwan and the new market entrants from companies located in India, Malaysia, Philippines, Singapore, South Korea, UAE, etc. Should the current trend in the field of worldwide production capacity increase continue, the European share will further decrease, even with a continuation of the growth rates of the last years. Europe remains the leading market. Three quarters of capacity, i.e. around 30 GW, is installed there. Japan (3.6 GW) and the USA (2.5 GW) come next, but are far behind. China will reach the 1 GW threshold during 2011 but this figure is still relatively tiny compared with individual European countries, for instance Italy (3.5 GW), Spain (3.8 GW), let alone Germany (17.2 GW).

and the pressure to stabilise the climate, will continue to keep the demand for solar systems high.

In the long-term, growth rates for PV will continue to be high, even if the economic frame conditions vary and can lead to a short-term slow-down. According to investment analysts and industry prognoses, solar energy will continue to grow at high rates in the coming years.

The projections show that there are huge opportunities for the photovoltaics industry in the future if the right policy measures are taken.

The PV industry is developing into a fully fledged mass-producing industry; this development is connected to an increasing industry consolidation, which presents a risk and an opportunity at the same time.

2. Short overview of PV technologies (see Table 1)

Table 1. Current efficiencies of different PV technology commercial modules [3]

sc-Si	mc-Si	a-Si; a-Si/µc-Si	CdTe	CIS/CIGS
14-20 %	13-15 %	6-9 %	9-11 %	10-12 %

The *crystalline silicon* (c-Si)[5] modules represent 85-90 % of the global annual market today. The C-Si modules are subdivided in two main categories:

i) single crystalline (sc-Si)

ii) multi-crystalline (mc-Si).

The *multi-junction solar cells*[6] are extremely popular in large-scale solar plants, located in areas rich in sunlight, feeding power into the grid, on the grounds that they can achieve efficiencies of up to 43 %. This is twice the level of conventional solar cells made of crystalline silicon.

Thin films currently account for 10 % to 15 % of global PV module sales. They are subdivided into three main families:

(i) amorphous (a-Si) and micromorph silicon (a-Si/µc-Si),

(ii) Cadmium-Telluride (CdTe),

(iii) Copper-Indium-Diselenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

The *emerging technologies* encompass advanced thin films and organic cells. The latter are about to enter the market via niche applications.

The c*oncentrator technologies* (CPV) use an optical concentrator system which focuses solar radiation onto a small high-efficiency cell. CPV technology is currently being tested in pilot applications.

The *Novel PV concepts* aim at achieving ultra-high efficiency solar cells via advanced materials and new conversion concepts and processes. They are currently the subject of basic research: Wafer-based c-Si; thin films.

A new technique for producing nanowire meshes using the power of light could open up a range of applications including transparent solar panel coatings [6]. (Nanowires are being developed as a vital component for quantum computing - the smallest ever silicon nanowire is in the works).

Researchers at MIT [7] have developed a way of making a high-temperature version of a kind of materials called photonic crystals, using metals such as tungsten or tantalum. The new materials - which can operate at temperatures up to 1200 °C - could someday power everything from smartphones to spacecraft. The microsystem-enabled photovoltaics (MEPV) concepts [9] consist of the fabrication of micro-scale crystalline silicon and GaAs solar cells, the release of these cells into a PV ink solution and the printing of these cells onto a substrate using fluidic self-assembly approaches.

Recently, the company “HelloVolt” [10] has developed a reactive transfer process for CIGS absorber formation that had the benefits of good compositional control and a fast, high quality CIGS reaction. The reactive transfer process is a two-stage CIGS fabrication method. Precursor films

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[5] Silicon is the mainstay of today’s PV industry [7]. Incorporating it into an ink, however, is a more recent innovation and is one of many technologies that aim to increase photovoltaic conversion efficiencies above their current level of around 18%. Two very different approaches are being pursued: screen printing the ink onto conventional silicon cells and fabricating thin-film polycrystalline silicon cells from the ink by a low temperature sintering process. Equally, these techniques are at very different commercial stages: the first is in production while the second remains under development.

[6] Multi-junction solar cells consist of several semiconductor layers that combine to transform the entire spectrum of sunlight into electrical energy. This technology, used in concentrator photovoltaics, employs lenses that focus the light of the sun 500 times onto tiny solar cells, producing solar electricity on a large scale. The multi-junction solar cells themselves consist of some 30 semiconductor layers built up, layer for layer, on ultra-pure crystals of germanium or gallium arsenide [8].

are deposited onto substrates and reusable cover plates in the first stage, while in the second stage the CIGS layer is formed by rapid heating with Se confinement. With conversion efficiency level around 14 % for cells and 12 % for modules, "HelloVolt" started commercializing the process on its first production line in Austin (TX). CIGS films with large grains on the order of microns are routinely produced, and exhibit optimal crystallographic orientation.

3. An example: The situation in New York State [4]

New York State is a national leader in the deployment and production of renewable energy. This leadership is attributable to New York's strategic pursuit of policies designed to develop a diverse portfolio of renewable energy resources, including solar, wind, hydropower and biomass. New York's diverse portfolio approach capitalizes on the State's many renewable resources – this diversity is New York's strength. The success of this approach is reflected by the fact that New York has developed more than 1,800 MW of renewable energy, exclusive of hydropower, more than any other state in the Northeast. Including hydropower, New York's renewable energy capacity is comparable to the entire renewable energy capacity of the other eight states in the Northeast.

Given the major uncertainties in PV technology cost reductions and the continued availability of USA federal tax credits over this time period, there is a significant range in the potential cost estimates to ratepayers of meeting a 5,000 MW goal by 2025. The magnitude and range of this cost uncertainty (USD 300 million – USD 9 billion) is substantial, and strongly suggests the need for a policy response and investment strategy that is both flexible and responsive. Nevertheless, even with this range of cost uncertainty, given the many potential benefits that PV has to offer and the long-term potential for lower-cost PV technology, New York State should support continued investment in the steady and measured growth and deployment of PV as part of a sound and balanced renewable energy policy.

4. Perspectives

The year 2011 was relatively flat in terms of MW sales compared to 2010.

In 2020, shipments will be nearly 200 GW and the dollar volume of module sales around USD 150 billion (based on historic learning curve projection).

The cost reduction scenario and PV system development PV2030+ are showen in figure 3.

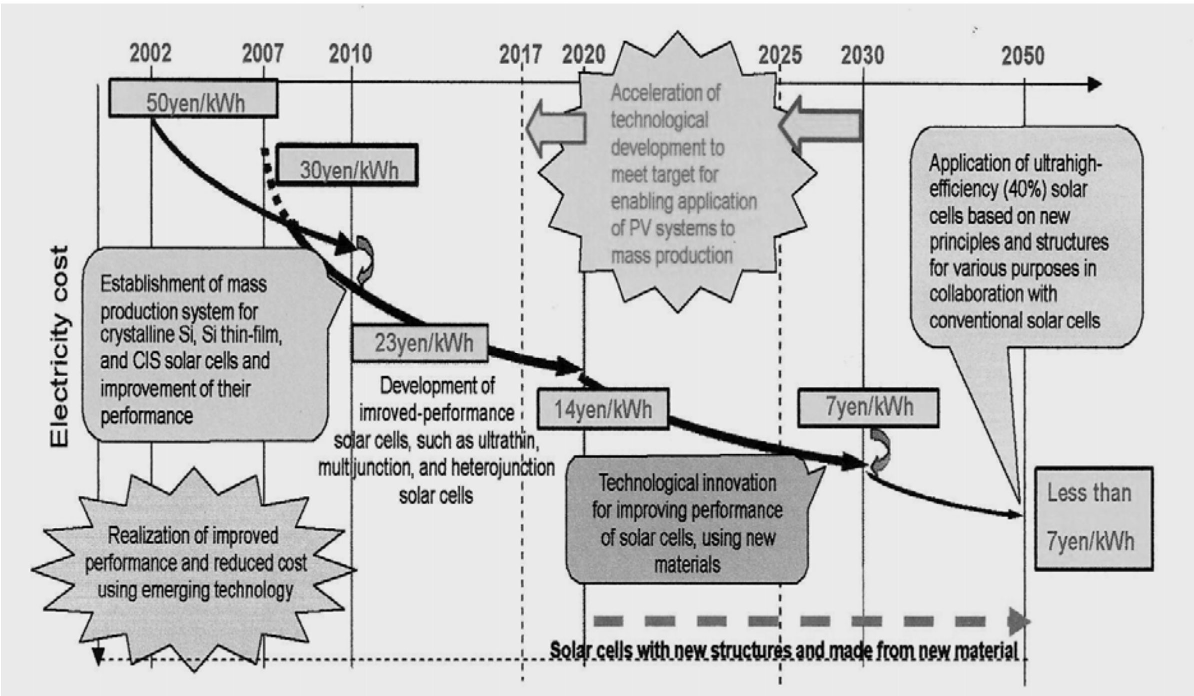

Figure 3. Cost reduction scenario and PV system development PV2030+

The installed PV generation capacity will be approaching an terawatt representing about 5 % of the world electric energy production. (This is to be compared with 0.4 % this year). More important, however, PV will be positioned then to transition in a major role in electric power generation, alongside wind and natural gas.

If we allow for 2 %/annual growth in electric power demand and a 50-year retirement schedule on existing plants, then we might expect 4 % of 5 TW or 200 GW being the order of sustainable long-term total available annual market for new electric-generation power plants. At issue, this is what the fraction of this will be won by PV. The next 10 years will see a maturation of the industry (see Table 2).

Table 2. "Japanese roadmap for development of PV systems, PV2030+" (This is a revised version of PV2030 prepared in 2004 from NEDO website http://www.nedo.go.jp/content/100107259.pdf)

Target year (completion of development)	**After 2010**	**2020 (2017)**	**2030 (2025)**	**2050**
Generation cost	Equivalent to residential use (23 yen/kWh)	Equivalent to business use (14 yen/kWh)	Equivalent to industrial use (7 yen /kWh)	Equivalent to general-purpose power source use (less than 7 yen/kWh)
Module conversion efficiency (R&D level)	16 % for practical modules (20 % for R&D-level cells)	20 % for practical modules (25 % for R&D-level cells)	25 % for practical modules (30 % for R&D-level cells)	40 % for ultrahigh-efficiency modules
Annual production for Japanese market (GW/year)	0.5 ~ 1	2 ~ 3	6 ~ 12	25 ~ 35
Annual production for overseas market (GW/year)	~1	~3	30 ~ 35	~300
Major purposes	individual houses, public facilities	individual houses, condominiums, public facilities, offices, etc.	individual houses, condominiums, public facilities, consumer business use, charging of electric cars	consumer use, general purpose, industrial use, transportation use, off-grid power source

PV has exhibited a classic experience curve behaviour with 19 percent price reduction in constant dollars for every doubling of cumulated production since 1975 [2]. The SunShot[7] goal of USD 0.50/W in 2017 will definitely require a breakthrough.

The cost reduction will come from new developments such thinner wafers, kerfless wafering, higher efficiency, etc., as well as increased scale and manufacturing sophistication. Note that the lower cost (per watt) to manufacture some of the module technologies, namely thin films, is partially offset by the higher area-related system costs (costs for mounting and the required land) due to their lower conversion efficiency.

The dye-sensitized solar cells (DYSC) provides a technically and economically credible alternative concept to present day *pn* junction photovoltaic devices. In contrast to the conventional systems, where the semiconductor assumes both the task of light absorption and charge carrier transport, the two functions are separated here. Light is absorbed by a sensitizer which is anchored to the surface of a wide band gap semiconductor. Charge separation takes place at the interface via photo-induced electron injection from the dye into the conduction band of the solid [12][14].

[7] The DOE (US Department of Energy) SunShot initiative aims to dramatically decrease the total costs of solar energy systems by 75% before the end of the decade. Reaching this goal will make solar energy cost-competitive with conventional forms of electricity without subsidies and enable widespread deployment across the United States.

5. Instead of conclusion

1) 40 % efficiency goal of NASA-sponsored research

Recently, it was announced [11] that the Optoelectronics Research Lab at the University of Ankansas will receive a USD 1.3 million grant from the U.S. Air Force to attempt two approaches:

a) *The first* is to use CIGS variant semiconductor material ($CuInSe_2$ and $CuInGaSe_2$) to grow nanocrystals. The resultant nanocrystals are then made functional and either converted into thin films, or combined with titanium dioxide or zinc oxide nanotubes to create solar cells.

b) *The second approach* uses a "molecular beam epitaxy" method to deposit the nanocrystals, to create "quantum dots" – nanosized particles of semiconductor material – of indium arsenide. The researchers will then test the resultant photovoltaic cells.

Figure 3 gives an overview of the cost and performance of different PV technologies.

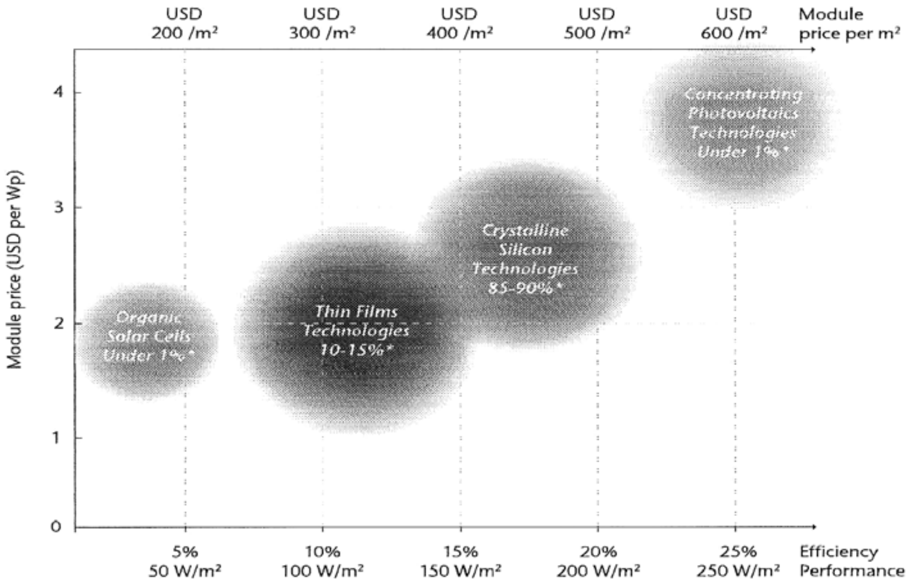

Figure 3. Performance and price of different PV module technologies of 2008 market (After [3])

2) A new hybrid solar cell

Silicon solar cells cannot extract all the energy in a photon and much of the energy from the more energetic blue photons is lost. Usually a solar cell generates one electron from each photon captured. Scientists at the University of Cambridge [13] have developed a new hybrid solar cell which is capable of converting 44 percent of sunlight into electrical power, 29 percent more than traditional cells' capability of 34 percent. They present the first hybrid solar cell that utilizes a phenomenon called *singlet exciton fission* to generate two electrons for each absorbed photon in the organic material.

Abbreviations

a-Si	Amorphous silicon
a-Si/µc-Si	Micromorph silicon
BIPV	Building-integrated PV systems
CAES	Compressed air energy storage
CCS	Carbon capture and storage
CdTe	Cadmium Telluride
CIGS	Copper-Indium-Gallium-Diselenide
CIS	Copper-Indium-Diselenide
CPV	Concentrating photovoltaics
c-Si	Crystalline silicon
CSP	Concentrating solar power
EPIA	European Photovoltaic Industry Association
ESCOs	Energy service companies
GBI	Generation Based Incentives
IEA	International Energy Agency
PV	Photovoltaic
R&D	Research and development
RD&D	Research, demonstration and development
RED IEA	Renewable Energy Division of IEA
SAI	Solar America Initiative
SET	Strategic energy technology
SHC	Solar heating and cooling
SMES	Superconducting magnetic energy storage

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7. Biography

Titu I. BĂJENESCU was born in Câmpina (Romania) on April 2, 1933; he received his engineering training at the Polytechnic Institute Bucharest. He served for the first 5 years in the Army Research Institute, including tours on radio and telecommunications maintenance, and in the reliability, safety and maintainability office of the Ministry of Defence (main base ground facilities). *Experience*: R&D: design and manufacture of experimental equipment for army research institute and for air defence system. He joined Brown Boveri (today: Asea Brown Boveri) Baden (Switzerland) in 1969, as research and development engineer. *Experience*: R&D: design and manufacture of new industrial equipment for telecommunications. In 1974 he joined Hasler Limited (today: Ascom) Berne as Reliability Manager (recruitment by competitive examination). *Experience*: Set up QRA and R&M teams. Developed policies, procedures and training. Managed QRA and R&M programmes. As QRA Manager monitoring and reporting on production quality and in-service reliability. As Switzerland official, contributed to development of new ITU and IEC standards. In 1981 he joined "Messtechnik und Optoelektronik" (Neuchâtel, Switzerland, and Haar, West Germany), a subsidiary of Messerschmitt-Bölkow-Blohm (MBB) Munich, as Quality and Reliability Manager (recruitment by competitive examination). *Experience*: Product Assurance Manager of "intelligent cables". Managed applied research on reliability (electronic components, system analysis methods, test methods, etc.). Since 1985 he has worked as an independent consultant and international expert on engineering management, telecommunications, reliability, quality and safety. Mr. Băjenescu is the author of many technical books - published in English, French, German and Romanian. He is university professor and has written many papers and articles on modern telecommunications, and on quality and reliability engineering and management; he lectures as invited professor, visiting lecturer or speaker at European universities and other venues on these subjects. Since 1991 he won many Awards and Distinctions, presented by the Romanian Academy, Romanian Society for Quality, Romanian Engineers Association etc. for his contribution to reliability science and technology.