1
Towards a Solar Energy Revolution

1.1
Flexible Solar Cells

> Topic: Thin film solar company seeking partners
>
> Started By: Paul Norrish Sep 4, 2007 04 : 17 a.m.
>
> G24 Innovations is a UK based manufacturer of Dye sensitised solar cells. We are interested in partnering with an LED manufacturer and distribution partners to launch a Solar powered light in Africa/Asia.
>
> If this is of interest please respond to Paul.Norrish@g24i.com
>
> Regards
> Paul

Needless to say, this post on the Lighting Africa Business Forums [1] received a large response and the company has formed a number of partnerships in Africa with which to commercialize its photovoltaic (PV) flexible technology, one of the main topics of this book.

In general, flexible electronic devices that are ready to enter the market will shortly become predominant in the market (Figure 1.1). For example, the production of flexible displays using organic light-emitting diodes (OLEDs) started in 2008 with an initial capacity of more than a million display modules per year. Used in displays, these organic materials applied in thin layers over flexible plastic make electronic viewing more convenient and ubiquitous.

The thinness, lightness and robustness enabled by the flexibility of OLED-based displays will enable the manufacture of electronic reader products that are as comfortable and natural to read as paper, whether at the beach or on a train. Thus far, in fact, people have been reluctant to read on laptops, phones and PDAs, even in this age of pervasive digital content. The first manufacturing facility targeted at flexible active-matrix display modules has been built by Plastic Logic in Dresden, Germany [2]. Wireless connectivity will allow users to purchase and

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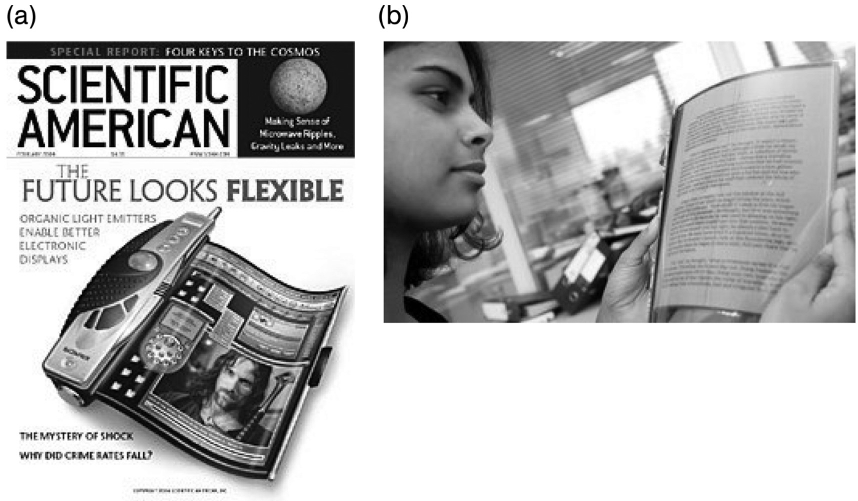


Figure 1.1 Long awaited flexible electronics ((a) shows the cover of *Scientific American* for February 2004) is now a reality with OLED displays (b) enabling ubiquitous, comfortable reading (Photo courtesy: Plastic Logic).

download a book or pick up the latest edition of a newspaper wherever and whenever they desire.

In its turn, a flexible plastic solar module (Figure 1.2) of the types described in the following chapters, might easily power the OLED device enabling unlimited access to thousands of pages.

The vision is that of the so-called *plastic electronics*, namely to print circuits and devices on flexible substrates, at room temperature (low energy) and with roll-to-roll

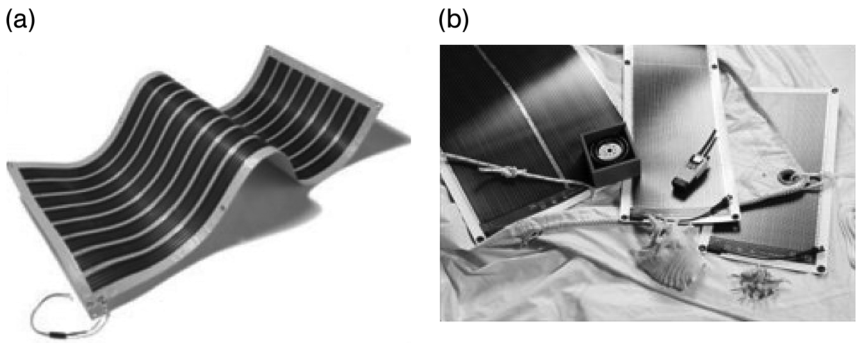


Figure 1.2 Plastic solar cells such as (a) that entirely organic (Photo courtesy: Konarka) or (b) that using amorphous Si (Photo courtesy: Flexcell) are lightweight (25–50 g m^{-2}), and ideally suited for customized integrated solutions.

processes (high throughput). Flexible solar PV devices offer an alternative energy source at low cost, ample surface area, flexible, light, silent and clean energy for indoor and outdoor applications.

In general, their advantages over existing technologies are clear [3].

highly flexible
The true mechanical flexibility of flexible solar PV modules allows for the integration with elements of various shapes and sizes and the design of innovative solar products.

customised & integratable
The roll-to-roll manufacturing processes allow for the production of PV modules of various lengths and widths, thus rendering the technology very attractive for customised integrated solutions.

thin & lightweight
The lightness of flexible solar PV foil makes it suitable for applications where weight is important.
Such very thin PV foil enables the aesthetic integration with various different materials.

unbreakable
Unlike conventional crystalline silicon PV modules, which are based on bulky and brittle glass substrates, flexible solar PV modules are made of thin and flexible polymers, which are tough, durable and safe to use.

environmentally friendly
In addition to these unique properties, flexible solar PV foil is environmentally friendly. The electricity produced is clean and the manufacturing processes is based on abundant, recyclable materials. The energy payback of flexible products is 3-5 times faster than products based on conventional PV technologies.

The photovoltaic material is printed on a roll of conductive plastic [4] using fast newspaper printing technology. Printing enables one to achieve high materials utilization of the photoactive material. As a result, this simple, highest-yield technique in plain air is capital-efficient and eliminates the need for costly vacuum deposition techniques such as conventionally used to fabricate thin-film solar cells (Figure 1.3).

These chemistry-based cells are lightweight, flexible and more versatile than previous generations of products. The result is a new breed of coatable, plastic, flexible photovoltaics that can be used in many applications where traditional photovoltaics cannot compete. The photovoltaic functionality is integrated at low cost into existing structures, printing rolls of the stuff anywhere, from windows to

(a) (b)

Figure 1.3 (a) Roll-to-roll manufacturing of photovoltaic Plastic Power (photo courtesy: Konarka) is analogous to (b) ink printing of semiconductor CIGS on aluminum foil (photo courtesy: Nanosolar).

roofs, through external and internal walls. Flexible solar cells, indeed, replace the traditional installation approach with an *integration* strategy (Figure 1.4).

In general, man is eventually learning how to efficiently harness the immense amount of solar energy that reaches the Earth every second by mimicking Nature and by operating at the nanoscale. In other words, we are learning how to deliver cost-efficient solar electricity.

The average price for a PV module, excluding installation and other system costs, has dropped from almost $100 per watt in 1975 to about $4 per watt at the end of 2007 (Figure 1.5).

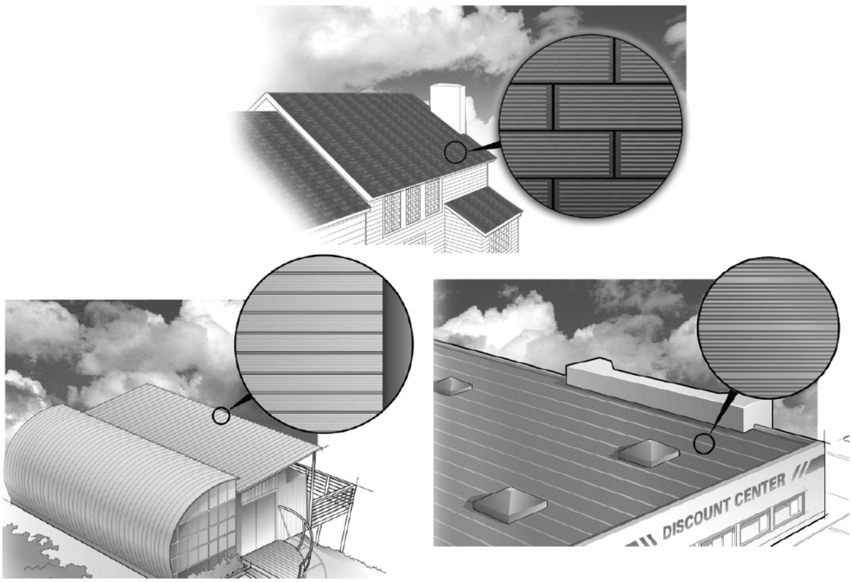


Figure 1.4 New flexible solar modules are integrated, rather than installed, into existing or new buildings (adapted from Konarka).

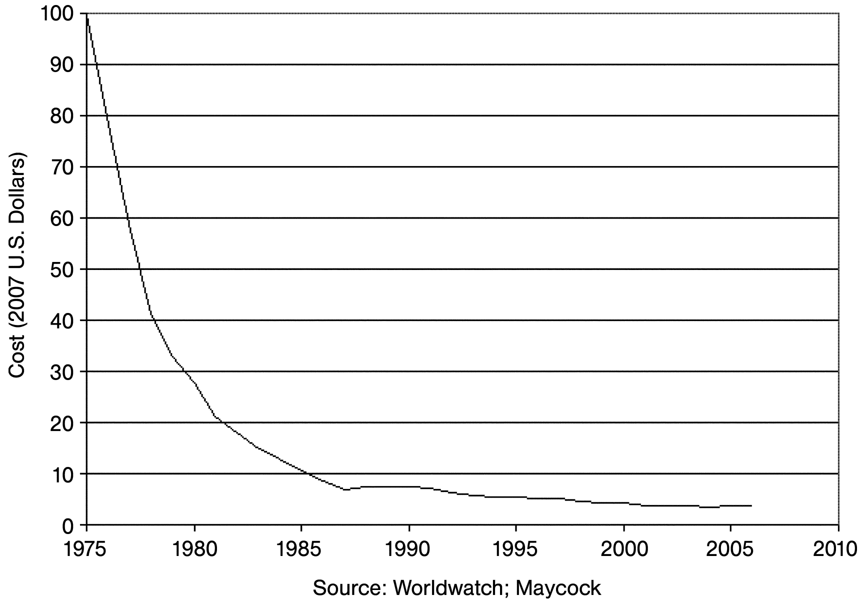


Figure 1.5 Average cost per watt of PV module 1975–2006. (Source: Earth Policy Institute, 2007).

In 2004, a prediction of an industry's practitioner concluded that for "thin-film PV alone, production costs are expected to reach $1 per watt in 2010" [5], a cost that makes solar PV competitive with coal-fired electricity.

Adding relevance to this book's arguments, however, the first flexible thin-film solar modules profitably generating electricity for 99 cents a watt (i.e., the price of coal-fired electricity) were commercialized in late 2007, concomitant with the commercial launch of the first plastic solar cells.

These high-performance wafer-thin solar cells are mass-produced printing on aluminum foil with an ink made of inorganic semiconductor CIGS (Chapter 3).

1.2 Why We are Entering the Solar Age

With concerns about rising oil prices and climate change spawning political momentum for renewable energy, solar electricity is poised to take a prominent position in the global energy economy (Figure 1.6).

However, claiming that we are ready to enter the solar age, when the global consumption of oil is steadily on the rise may sound as a green-minded false prophecy. All predictions of an oil peak made in the 1960s were wrong [6]: We never experienced lack of oil as was doomed inevitable after the 1973 oil shock, and the exhaustion of world oil reserves is a hotly debated topic. For example, an oil industry geologist tackling the mathematics of Hubbert's method suggests that the oil peak occurred at the end of 2005 [7].

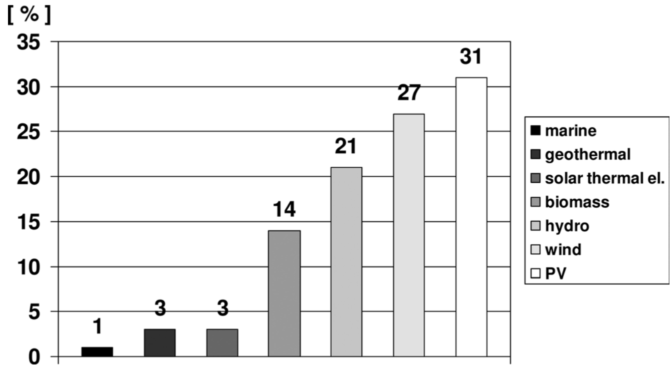


Figure 1.6 Predicted scenario by 2040. Out of a total electricity consumption of 36.346 TWh (from 15.578 TWh in 2001, IEA) renewable energy sources will cover 29.808 TWh, with solar energy becoming largely predominant. (Source: EREC).

On the other hand, the price of oil has multiplied by a factor of 10 in the last few years, whereas in the US, for example, domestic petroleum now returns as little as 15 joules for every joule invested compared to the 1930s when the energy return on energy invested (EROI) ratio was 100 [8].

The demand for oil has boomed in concomitance with globalization and rising demand from China and India. In China and India, governments are managing the entrance to the industry job market of some 700 million farmers, that is about twice the overall amount of workers in the European Union.

Global energy demand will more than double by 2050 and will triple by the end of the century. At the same time, an estimated 1.64 billion people, mostly in developing countries, are not yet connected to an electric grid.

Finally, the world's population is rapidly learning that climate change due to human activities is not an opinion: it is a reality that in the US has already hit entire cities (New Orleans, 2005), and in southern Europe hurt people and the whole ecosystem with temperatures close to 50 °C in mid-June 2007.

Overall, these economic, environmental and societal critical factors require us to curb CO_2 emissions soon, and switch to a massive scale use of renewable materials and renewable energy (RE) until the day when cheap and abundant solar energy becomes a reality.

Access to affordable solar energy on a large scale, admittedly, is an enormous challenge given that presently only 0.2% of global energy is of solar origin. The low price of oil in the 1990s ($10–$20 a barrel) put a dampener on scientific ingenuity for the whole decade, since many developments were put on the shelf until a day in the future when their use would become "economically viable."

All is rapidly changing with booming oil prices. Solar electricity generation is now the fastest-growing electricity source, doubling its output every two years (Figure 1.7) [9]. The solar energy market has grown at a rate of about 50% for two years, growing to 3800 MW in 2007 from 2521 MW in 2006.

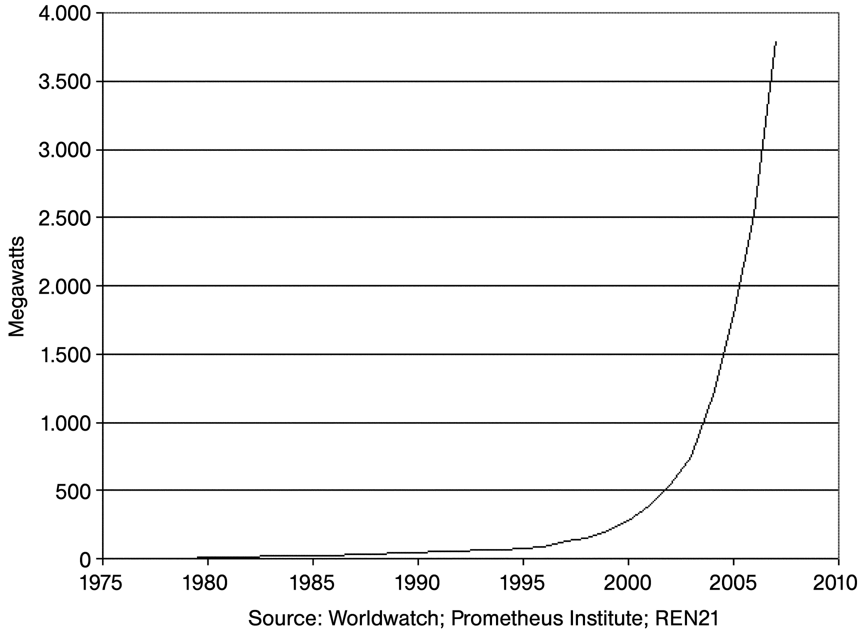


Figure 1.7 World annual PV production, 1975–2007: 3.8 GW by the end of 2007, is doubling every two years. (Source: Earth Policy Institute, 2007).

Competitiveness that was already proven in industrial off-grid, consumer and rural electrification application, is rapidly expanding to in-grid systems, first in local replacement of peak tariff electricity kWh in liberalized southern European countries and in some US states, and soon afterwards in the rest of the world.

Figure 1.8, for example, clearly shows that the electrical energy fed into the grid from an office in Spain reaches its maximum in the high tariff time range whereas the electricity supplied by the utility is drawn at periods of low tariff [10].

This competitiveness explains why the sector is now attracting government and venture capital investments on an unprecedented scale, with some 71 billion dollars of new investment in 2006 alone, amounting to a 43% increase relative to the previous year [9].

Yet, even at this large pace of growth, in order to make solar energy a significant contributor to the global energy production, we need to go through a revolutionary process.

In place of the 11 billion dollars photovoltaic global industry, largely based on silicon panels introduced in the early 1970s, which currently contributes <0.1% to the global energy industry (15 terawatt, which adds every 10 years the equivalent of the current US yearly consumption), we need a new photovoltaic technology of distinctly superior efficiency, versatility, and availability, compared to traditional silicon-wafer-based photovoltaic devices.

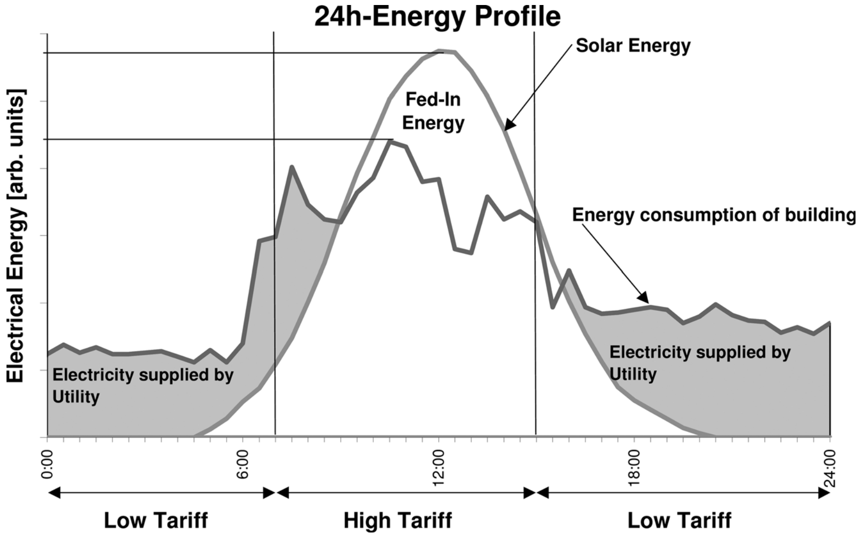


Figure 1.8 Correlation between daily PV power production and energy consumption of an office building in Spain. (Source: EPIA, 2004).

And even if it still an open question as to which photovoltaic material will be used, this technology evolution (Figure 1.9) will first go through massive adoption of thin films of inorganic and organic materials; and then likely though new quantum technologies employing multiple cells and newly synthesized materials such as epitaxial GaAs and graphene (Chapter 6).

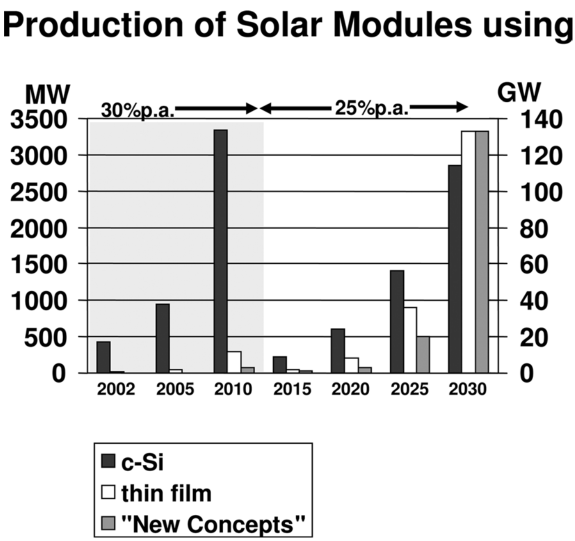


Figure 1.9 PV Technology evolution. (Source: EPIA, 2004).

1.3 Capturing Solar Light and Transferring Energy Efficiently

Whether an electron is powering a cell phone or a cellular organism makes little difference to the electron; it is the ultimate currency of modern society and biology, and electricity is the most versatile and relevant energy available to man.

The ability to capture light and then to transfer that energy to do work are the two main steps in a photovoltaic system. In Nature, such steps happen too fast for energy to be wasted as heat and in green plants (Figure 1.10) the light energy is captured by highly effective photosynthetic complexes and then transferred with almost 100% efficiency to reaction centers, where long term energy storage is initiated.

Traditional silicon-based solar PV systems, however, do not follow Nature's model.

In Nature, the energy transfer process involves electronic quantum coherence (Figure 1.11). Indeed, this wavelike characteristic of the energy transfer within the photosynthetic complex can explain its extreme efficiency, as it allows the complexes to sample vast areas of phase space to find the most efficient path.

Two-dimensional electronic spectroscopy investigation [11] of the bacteriochlorophyll complex has, in fact, shown direct evidence for remarkably long-lived electronic quantum coherence. The lowest-energy exciton (a bound electron–hole pair formed when an incoming photon boosts an electron out of the valence energy band into the conduction band) gives rise to a diagonal peak that clearly oscillates. Surprisingly, this quantum beating lasted the entire 660 femtoseconds, contrary to the older assumption that the electronic coherences responsible for such oscillations are rapidly destroyed.

It may therefore come as no surprise that the first plastic solar cells are largely based on biomimetics, that is, on artificial photosynthesis based on human ability to gather and organize complex materials and organic molecules to replicate photosynthesis in a practical way.

Figure 1.10 Green plants harvest light's energy with almost 100% efficiency.

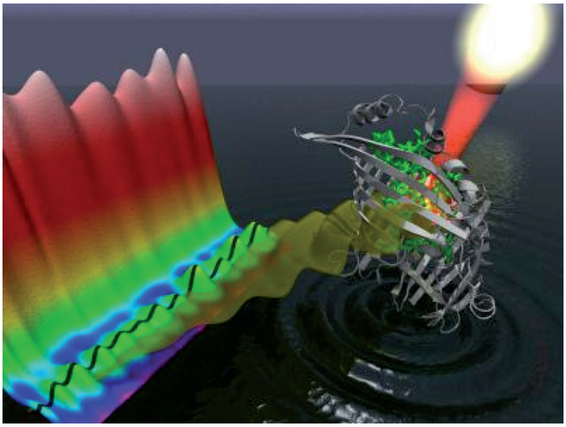


Figure 1.11 Sunlight absorbed by bacteriochlorophyll (green) within the FMO protein (gray) generates a wavelike motion of excitation energy whose quantum mechanical properties can be mapped through the use of two-dimensional electronic spectroscopy. (Image courtesy of Greg Engel, Lawrence Berkeley National Laboratory).

A typical cell contains a porous film of nanostructured titania formed on a transparent electrically conducting substrate and photosensitized by a monolayer of a ruthenium dye. The dye ensures complete visible light absorption thanks to efficient electron transfer from the excited chromophore into the conduction band of the semiconductor oxide (which requires a high electronic coupling between the dye and the semiconductor for efficient charge injection).

An electrolyte, based on an $I_2 - I_3^-$ redox system is placed between the layer of photosensitized titania and a second electrically conducting catalytic substrate (Figure 1.12).

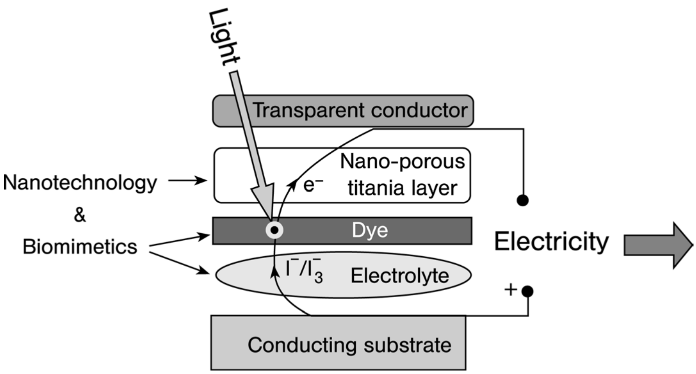


Figure 1.12 State-of-the-art dye-sensitized solar cells show greater than 11% light-conversion efficiency.

Like plants that are effective at capturing energy over a wide range of light conditions, dye-sensitized solar cells work in lower light levels than traditional PV. Thus, the outdoor environments of hospitals, airports, station windows and surfaces become energy sources at low cost.

The first full-size production cells achieve close to 10% efficiency, whereas a technology roadmap aims to reach 20% in the next ten years. This breakthrough puts the materials on a par with, or in some cases exceeding, second-generation materials, but at lower cost and with more options in the product form factor.

The environment on the nanoscale largely influences the photoelectric effect and the electron transfer process on which photovoltaics is based. Hence, through better chemical control of the properties of the photoactive material on the nanoscale – namely through nanochemistry [12] – we are learning how to build more efficient means of collecting, storing, and transporting solar energy.

For example, in dye-sensitized solar cells (DSC) structural organization of the material improves the performance. Thus, organized mesoporous TiO_2 films exhibit solar conversion efficiency about 50% greater than films of the same thickness made from randomly oriented anatase crystals (Figure 1.13) [13].

Improvement here results from a remarkable enhancement of the short circuit photocurrent which in turn is due to fivefold enhanced roughness of a 1-μm-thick film and thus to an accessible huge surface area.

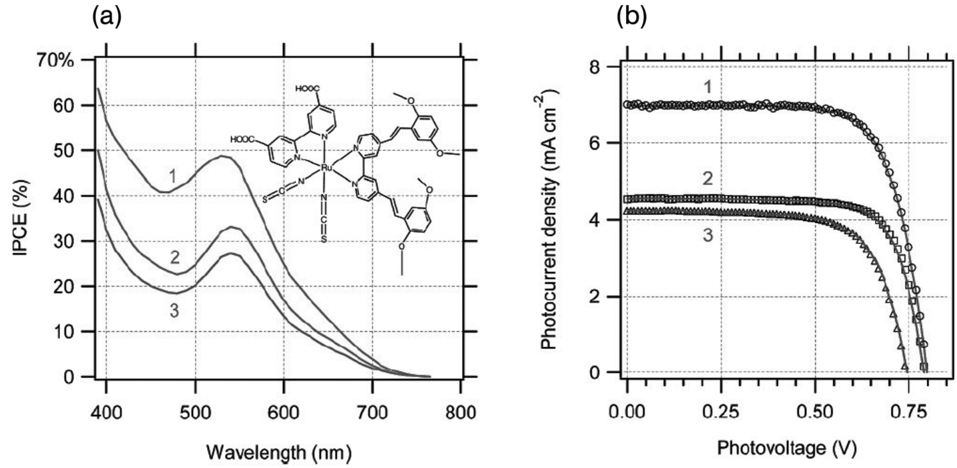


Figure 1.13 Efficiency (a) and photocurrent–voltage characteristics (b) of a solar cell based on TiO_2 films sensitized by N945 (inset shows its chemical formula). Pluronic-templated three-layer film (1); nonorganized anatase treated with $TiCl_4$ (2); nonorganized anatase not treated with $TiCl_4$ (3). (Reproduced from Ref. [11], with permission).

1.4
Three Waves of Innovation

In the early 2000s, the improvements in efficiency targeted by industry for 2020 were clear [9].

- For monocrystalline silicon cells from 16.5 to 22%
- For polysilicon from 14.5 to 20%
- For thin film (a-Si/mc-Si, CIS, GIGS and CdTe) up to 10–15%.

Architectonic integration was highly recommended to reduce the price of PV adoption in real estate; and advancements in organic cells and the use of advanced materials such as GaAs were recommended.

Remarkably, major advancements indeed took place shortly after these recommendations, and many of them are discussed in the following. In general, solar power technology evolved in three waves of innovation (Table 1.1).

The *First Wave* started with the introduction of silicon-wafer based solar cells over three decades ago. While ground-breaking, it is clear until today that this technology came out of a market environment with little concern for cost, capital efficiency, and the product cost/performance ratio.

Despite continued incremental improvements, silicon-wafer cells (Figure 1.14) have a built-in disadvantage of fundamentally high materials cost and poor capital efficiency. Because silicon does not absorb light very strongly, silicon wafer cells have to be very thick. And because wafers are fragile, their intricate handling complicates processing all the way up to the panel product.

Table 1.1 The evolution from wafer cells through thin film on glass and then on foil has led to a reduction in payback from 3 years to less than 1 month. (Source: Nanosolar).

Technology wave	I. Wafer cells	II. Vacuum-based thin film on glass	III. Roll-printed thin film on foil
Process:	Silicon wafer processing	Sputtering, evaporation in a vacuum chamber	Printing in plain air
Process control:	Fragile wafers	Expensive metrology	Built-in bottom-up reproducibility
Process yield:	Robust	Fragile	Robust
Materials utilization:	30%	30–50%	Over 95%
Substrate:	Wafer	Glass	Conductive Foil
Continuous processing:	No–wafer handling	No–glass handling	Yes
Cell matching:	Yes	No	Yes
Panel current:	High	Low	High
Energy payback:	3 years	1.7 years	<1 month
Throughput/Cap.Ex.	1	2–5	10–25

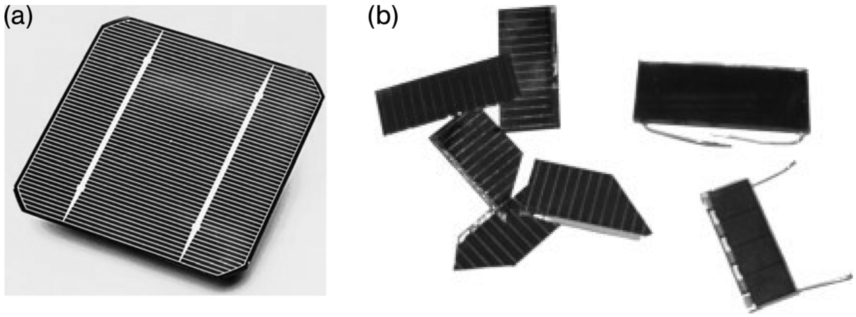


Figure 1.14 (a) A solar cell, made from a monocrystalline silicon wafer and (b) polycrystalline silicon PV cells deposited as thin films. (Photo courtesy: Wikipedia).

The *Second Wave* came about a decade ago with the arrival of the first commercial thin-film solar cells. This established that new solar cells based on a stack of layers 100 times thinner than silicon wafers can make a solar cell that is just as good. However, the first thin-film approaches were handicapped by two issues:

1. The cell's semiconductor was deposited using slow and expensive high-vacuum based processes because it was not known how to employ much simpler and higher yield printing processes.
2. The thin films were deposited directly onto glass as a substrate, eliminating the opportunity of using a conductive substrate directly as the electrode (and thus avoiding bottom-electrode deposition cost).

Indeed, the prediction of greatly reduced costs for thin film solar cells made by thin epitaxial deposits of semiconductors on lattice-matched wafers (Figure 1.14) has yet to be achieved.

The *Third Wave* of solar power combines the materials-cost advantage of thin films and of organic photovoltaics (OPV) with the process cost advantage of faster process technology.

Inorganic thin solar films are more than 100 times thinner than silicon-wafer cells, and thus have correspondingly lower materials cost, but are printed in plain air using a stable, nanostructured ink of photoactive material. The result is the world's most cost-efficient solar modules (Figure 1.15)

By testing the products under much harsher conditions than mandated by official certification standards, including harsh outdoor environments such as the Arizona desert and the Antarctic (Figure 1.16), modules have been developed that are supplied with the 25-year durability and longevity warranty of conventional rooftop PV solar cells (which improves on the low performance of thin-film amorphous silicon solar cells which revealed unexpected degradation rates that were not identified in the laboratory).

Organic-inorganic solar cells also show excellent durability, ranging from 13 to 22 years depending on whether they are employed in Central or Southern European climates (Figure 1.17).

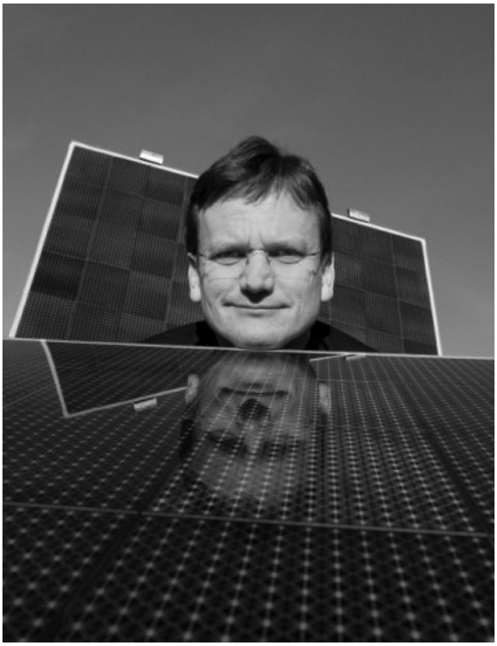


Figure 1.15 The first solar panels based on CIGS printed on aluminum foil yielding electricity at 1$/W were delivered on December 2007. (Photo courtesy: Nanosolar).

Placing this in a Green context, the path to a sustainable energy future based on the sun's energy is a technological challenge that can be met [14]; and the new generation PV technologies that are being discovered and commercialized at increasing pace will assist in ensuring that change will indeed take place "on a reasonable timescale."

Figure 1.16 Testing of thin-film solar panels in the Antarctic. (Photo Courtesy: Nanosolar).

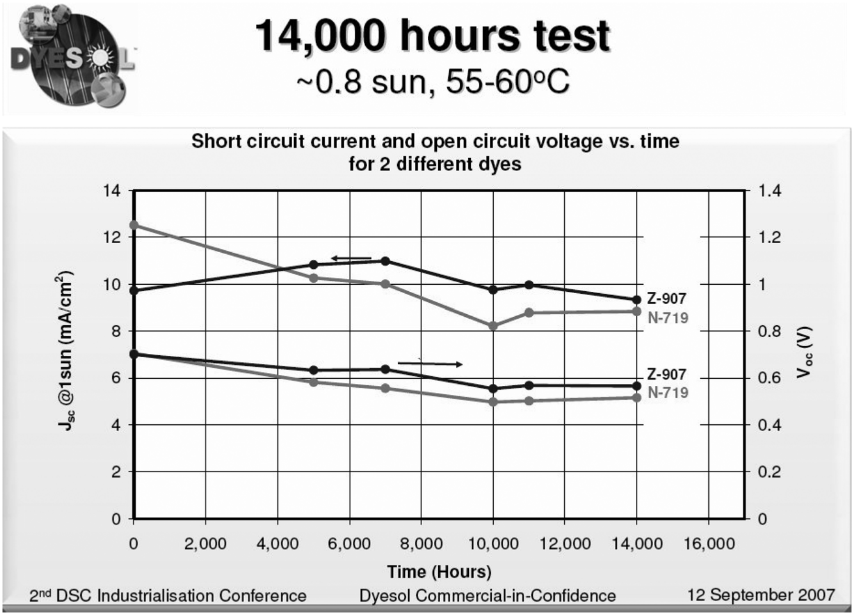


Figure 1.17 Real PV modules based on DSC last 13 or 22 years depending on whether they are in a Southern or Central European climate, respectively. (Source: Dyesol).

1.5
Solar Design

From energy saving and architecturally inelegant, shiny black panels mounted awkwardly on the roof of remote buildings, photovoltaic architecture has created elegant PV elements that are increasingly conceived as building-integrated (BI) components. Clearly, the improved esthetic impact of PV systems increases their acceptance and diffusion, especially in wealthy regions where immaterial values increasingly drive consumer's choice.

Panels installed recently in New York City (Figure 1.18), for example, were "a deep indigo blue framed with a border of white stone ballast that keeps them earthbound" [15]. Clearly, a crucial aspect as innovative modules are characterized by a significant upgrading of their value, and thus price, by extra (cost-relevant) production steps in comparison to standard modules.

Dye solar cells, for example, can be processed in different colors and adapted to different and demanding esthetic requirements actually expanding, rather than limiting, the design possibilities, as shown by the Toyota exhibition pavilion at the Aichi's 2005 Expo (Figure 1.19).

By incorporating color and design in solar power products, designers will be able to use the cells not only on the roof or out of sight locations, but also as a primary element of housing and environment design.

Figure 1.18 Solar panels on the garage roof of this apartment building in New York City Washington Heights gather sunlight from dawn to dusk. Here, the streets were bathed in orange hues from streetlights. (Photo courtesy: The New York Times).

Just like newspapers can include text, images and a variety of colors, new generation solar cells can include a vast range of colors and drawings. It becomes possible to design entire networks of PV polymer without adding weight to the structure.

Cost-effective thin-layer technology is used increasingly for large façades and large roofs. Thin-layer modules, indeed, are installed directly onto the roofing, without frames, without covers and without assembly frameworks. Hence, their integration prevents problems of statics. For example, the PV roof on a factory store in the Belgian town of Halle consists of thin film modules in amorphous silicon achieving a total output of 330 kWp (kilowatt peak performance). The modules are each over 5 m in

Figure 1.19 DSC-based modules coating the windows of the pavilion house of Toyota at Aichi's 2005 Expo. (Photo courtesy: Toyota).

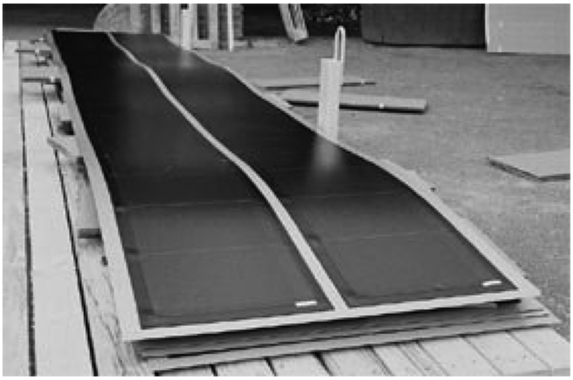


Figure 1.20 Large plate system module achieving an output of 2×136 Wp, primarily aimed at the agricultural and industrial sectors. (Photo courtesy: Biohaus).

length and weigh only 50 kg (Figure 1.20), so they can be stuck directly onto the roof. With the triple-junction technology used, these modules achieve excellent output, even if the pitch of the roof is minimal – in the present case the pitch is a mere 3° – and regardless of whether the buildings are facing to the East or the West.

Transparent PV facades establish contact with the outside world and allow impressive lighting effects in the inside of buildings. Even from an economical point of view, the replacement of conventional façade elements may be of interest, because solar systems not only supply solar energy but also fulfill the tasks of building shells. Thus a photovoltaic façade can replace expensive natural stone tiles or stainless steel elements and can also represent a high prestige value.

For example, the façade-integrated CIS modules with their uniform matt black surface at a silo tower in Ulm, Germany (Figure 1.21a), reaching a height of 102 m, are made up of 1300 CIS modules with a total nominal output of 98 kWp. Every year this produces about 70 000 kWh of solar power and thus avoids approximately 50 000 kg of CO_2 emissions. The prominent position of the building at the entrance to the city led to construction and planning companies paying particular attention to the visual appearance of the tower.

Similarly, the $8 \times 80\,m^2$ shining black solar façade integrated in 2007 at Berlin's Ferdinand-Braun Institute (Figure 1.21b) is made of 730 elegantly shaped anthracite-colored CIS modules achieving 39 kWp.

In general, new thin film PV modules provide architects with better ways of integrating PV into new and existing buildings, well beyond the employment of solar tiles (Figure 1.22) that use the strength of a glass laminate to form a framing system for solar panels [16].

For example, the 120 m tall and 40 years old skyscraper in Manchester has recently been covered with over 7000 photovoltaic panels (Figure 1.23) on each of three sides of its 25 stories. These modules now freely supply 30% of the power needs for the building; the panels replace the original facade of the building and also weatherproof

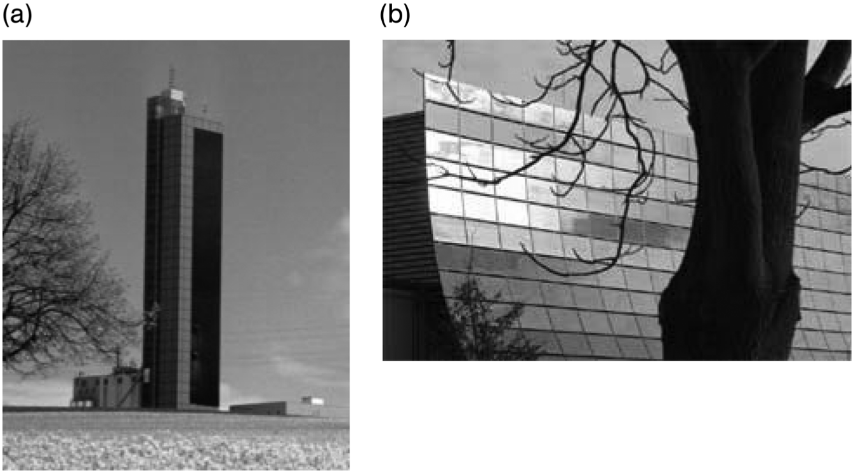


Figure 1.21 (a) The façade of Ulm's wheat silo that consists of 1300 CIS photovoltaic modules with a total output of 98 kWp (Photo courtesy: Solarserver.de). (b) The solar wall of 640 m^2 at Berlin's Braun Institute. (Photo courtesy: Forschungsverbund Berlin).

Figure 1.22 Tiles are a better option for building traditional Si-based PV roofs. (Photo courtesy: PV Tiles Inc.).

its core as the original facade of the tower was composed of small mosaic tiles which over time had begun to fall off, exposing the concrete structure to the weather.

The first 38 guidelines for an esthetically pleasant integration of solar power plants into old buildings, monuments, existing urban districts and landscapes have been available since 2006 in the book *Solar Design* (Figure 1.24), originating from an EU-financed seminal project [17] aimed at improving the esthetics, and thus the market potential, of photovoltaic modules through innovative design.

The same project resulted in the creation of a range of PV prototype panels, based on CIS thin-film technology, harmonized with the scale, color, materials and decorative elements of four demonstration sites in Italy and in Germany, including old buildings, historical sites, the urban space and landscapes.

Figure 1.23 Dark blue solar panels in thin film Si undergoing integration on the façade of a 120 m tall skyscraper in Manchester. (Photo courtesy: Inhabitat.com).

Today architects are involved in PV projects as early as possible to avoid conflicts between esthetics and solar technology; and solar power modules are now deliberately used as design elements. The homogeneous black color and pinstriped appearance of the CIS modules, for instance, give an additional advantage in comparison to other PV material products, whereas a variety of design options like semitransparency, with a wide range of transparency values and designs, provides unprecedented design opportunities. For example, when planning a glass administrative building the design team developed a combined shading and photovoltaic system (Figure 1.25).

The high level of incident energy as a consequence of the high proportion of glass facade clearly had to be limited in the summer months to avoid the need for additional

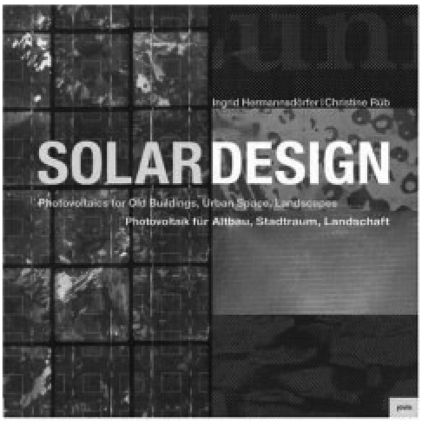


Figure 1.24 The first book with 38 guidelines for designing building integrated PV was published in 2005. (Photo courtesy: Jovis Verlag).

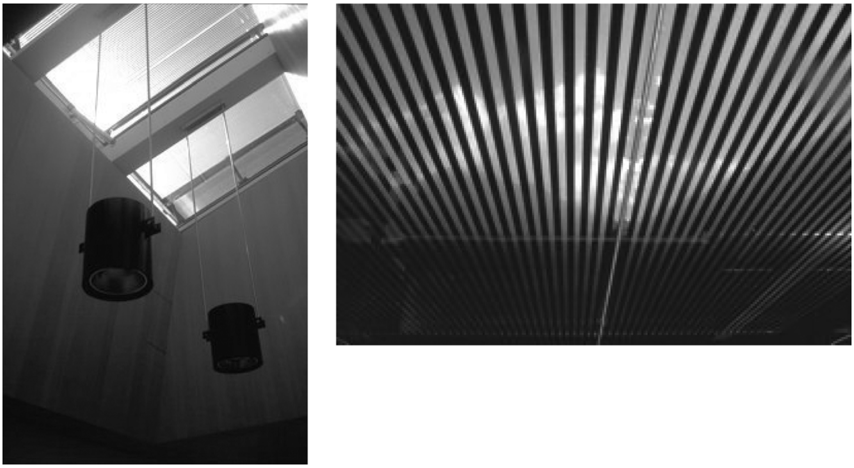


Figure 1.25 New seminstransparent PV modules using CIS as photoactive material create a combined shading and photovoltaic system. (Photo courtesy: Würth Solar).

cooling loads. At the same time, it was necessary to ensure that sufficient daylight enters the atrium, such that it is possible to avoid artificial lighting during the daytime. These requirements were smoothly met by using ten rows of skylights in the building, each 12 m long on average, that were equipped on the outside with a motor-powered, adjustable blanking system alternating with fixed, partially transparent CIS photovoltaic modules.

This configuration led to an optically appealing chessboard pattern for the entire skylight area. All CIS shading elements include ventilation. This avoids permeation of the radiant heat energy into the building. As part of a coordinated energy concept, adjustable glass plates were installed on the facade to complement the skylight solution. The overall strategy applied made it possible to regulate the lighting and incident radiation conditions within the atrium, to effectively block the penetration of incident sunlight and, at the same time, to generate power.

Similarly, new semitransparent CIS modules can be integrated sensitively on cultural heritage sites, as shown by a wall-integration in the medieval town of Marbach am Neckar (Figure 1.26). A square photovoltaic plant in front of the southern city wall welcomes visitors, thereby promoting the town as Schiller's birthplace, and as a clean energy user. The electricity gained is fed into the grid via an inverter and taken from the grid to illuminate the plate at night.

A different solution was conceived for lighting the inner courtyard of the listed monument Castello Doria in Porto Venere (Figure 1.27). Here three "solar flags" hang on steel wires, in each of six wall arches. Intervention in the historical walls was minimized by using existing holes to fix the wires. The modules are transparent, slightly curved acrylic glass components with imbedded semitransparent gray solar cells integrated with light emitting diodes (LED).The power generated by the 18 solar flags is stored in a battery and used to power the LED at night and thus light up the modules.

Figure 1.26 Semintransparent CIS solar panels coating the entrance of Schiller's home in Marbach am Neckar. (Photo courtesy: EU Commission).

Both the modules and the integrated lighting may also be produced in different colors and since any number of them can be added and mounted in various ways and on various sub-structures, they are just as suited for the – also temporary – design of public squares as for use in solar trees.

The positive results of the life cycle analysis for these PV modules indicate a clear reduction in the overall environmental impact, which contributes positively to the energy balance of our urban environments and opens a bright future for architecturally-integrated applications of advanced PV technology.

Finally, a comparison of the three thin film technologies (silicon, CIS and CdTe; Figure 1.28) clearly shows that the payback time for thin-film modules is largely shorter than conventional silicon-based panels which shows, also in the case of

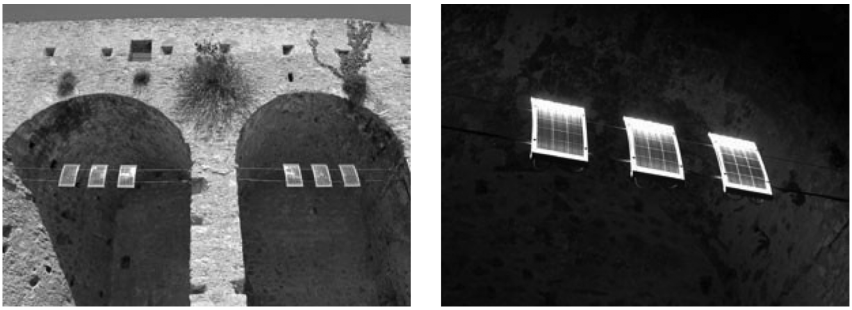
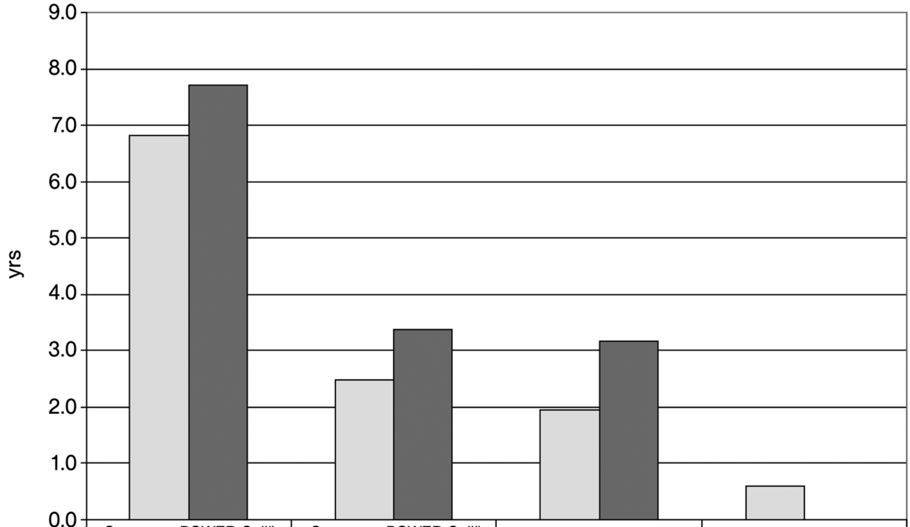


Figure 1.27 Solar flags equipped with LED lights collect solar energy by day and use it by night to light a monument in Porto Venere (Italy). (Photo courtesy: EU Commission).



	Sunways „POWER Cell“ mc-Si „worst case“	Sunways „POWER Cell“ mc-Si „best allocation“	Wuerth CIS	Antec CdTe
EPBT (frameless)	6.8	2.5	1.9	0.6
EPBT (PVACCEPT)	7.7	3.4	3.2	

Figure 1.28 Payback time for three different PV technologies shows considerable reduction in payback time for thin-film modules. Results for the Si-based systems are given in two separate columns, one for the worst case scenario, essentially representative of older-generation PV systems, and one for the best case scenario. (Reproduced from Ref. [16], with permission).

elegantly designed modules, that thin-films are indeed the photovoltaic technology of the near future [18] .

1.6 New Solar Companies

A number of solar firms and companies manufacture, sell and develop solar modules that do not use crystalline silicon as the photovoltaic material. Most were founded in the last five years. All use thin-film PV technologies, and in the following chapters we shall refer extensively to the leading representatives of each technology segment. Here, we focus on the strategic factors that made possible such rapid industrial evolution which will have a profound impact on the future of the PV industry as well as, in general, on future energy generation.

Many analysts considered 2006 the “year of the solar IPO,” as solar PV companies continued to make up the largest portion of existing and additional companies in the top 140 publicly traded renewable energy companies worldwide. Several renewable energy companies went through high profile initial public offerings (IPOs), generating market capitalization above or near $1 billion during 2006/2007. These

Figure 1.29 Honda's Kumamoto CIGS-based cells production factory. (Source: Honda Soltec).

included the solar PV companies First Solar (USA), Trina Solar (USA), Centrosolar (Germany), and Renesola (UK). First Solar was the largest IPO, with market value in excess of $4 billion by 2007. Several Chinese PV companies also went public in 2006 and early 2007.

Large companies which were entirely absent from the PV market entered into the solar cell business. For example, in 2006 the motor manufacturer Honda established a wholly-owned subsidiary, Honda Soltec, to produce 27.5 MW thin film solar modules annually using copper, indium, gallium and selenium (CIGS) semiconductor (Figure 1.29) [19]. The company achieves a major reduction (approximately 50%) in the amount of energy consumed during the manufacturing process compared to what is required to produce conventional crystal silicon solar cells. This makes the new solar cell more environmentally friendly by even reducing the amount of CO_2 generated in the production stage.

Similarly, the Würth Group created Würth Solar (Figure 1.30) and built a production plant, the Schwäbisch Hall plant in Germany, where it manufactures CIS-based solar modules. The investment of some 55 million € is the highest single investment in the company history.

In general, all these technologies offer major development opportunities in terms of product properties and production technologies.

According to some analysts, photovoltaics would not be an arena where private energy companies were likely to make the required technology breakthrough [20]. However, major advances realized in academic laboratories are currently in the

WÜRTH SOLAR

Figure 1.30 Würth Solar's trademark.(Source: Würth Solar).

process of being commercialized by start-up companies financed by venture capital funds and led by the inventor scientists.

Human ingenuity is opening new paths in practically every respect, by greatly improving existing PV technology and creating entirely new technologies such as those described in Chapter 6.

For example, Global Warming Solutions has developed a new hybrid photovoltaic/thermal (PV-T) solar energy conversion technology which makes possible the year-round production of thermal and electric energy by increasing the electric power 1.5–2 times as compared to traditional Si cells, and the thermal output by 170% [21]. This technology allows the storage of energy and solves the problem of solar power traditionally being hampered by a lack of storage capability.

Dispatchability of energy supply indeed has great value, because it means that the energy supply is guaranteed or predictable. The more predictable it is, the higher its value. Fossil fuel driven power plants and nuclear power are dispatchable. Renewable energy sources alone are generally not. Therefore, the renewable energy sources must be configured with a means of “energy storage” (that is, batteries or hybrid systems (renewable energy and another energy source)) to provide customers with an experience analogous to that enjoyed using grid electricity of fossil origin.

The light electric and thermal generator (LETG) technology uses a solar collector combined with photovoltaic cells that have been coated with a liquid luminophor (a novel organic polymer) which works in the Stokes spectrum area effectively cooling the silicon photocell.

In practice, the module has a shell where liquid luminophor circulates (Figure 1.31). Solar irradiation passes through the layer of this luminophor and is transferred to a longer-wavelength area of the spectrum near a maximum of solar cell sensitiveness on the basis of c-Si, covered by a special dielectric optical layer. Thus, a part of the luminescence energy is expended on luminophor heating. In addition, the layer of liquid luminophor actively absorbs solar radiation in the infrared range of the spectrum. This collateral heat can be used for domestic needs or transformed into electricity.

Critical to all this is the fact that in these hybrid PV cells not only can all types of silicon (monocrystalline, c-Si, polycrystalline (poly-Si) and amorphous silicon, a-Si) be used, but also all new semiconductor materials with even greater potential for transforming light into electricity.

Additional expenses associated with the production of hybrid modules based on luminophors are small in comparison with those of the ordinary cells that are its component part. The increase in electric power compensates these expenses and results in reduction in the price of the modules, calculated per unit of generated power (Table 1.2).

Thus, by coupling thermal and photovoltaic energy generation, the integrated LETG technology greatly extends what solar power can deliver, providing solar power in winter when days are short or by night (when there is no sunlight).

In an industry constantly striving to reduce costs and increase efficiency in an effort to make solar power more affordable and accessible, the new coating and the manufacturing process will be beneficial to the whole solar industry.

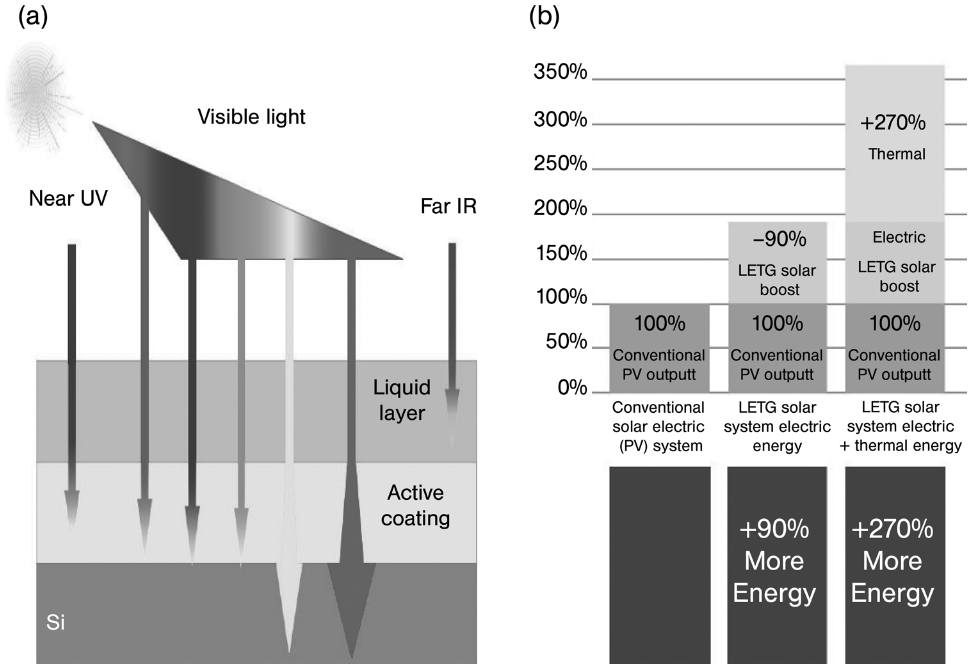


Figure 1.31 (a) Structure of a hybrid PV thermal cell covered by a liquid and an active luminophore layer. (b) The resulting enhancements results in electricity and heat generation. (Source. Global Warming Solutions).

In another development that aims to make alternative energy generation more efficient and more affordable, the Finnish company Braggone has discovered a method of capturing more light in a solar cell.

The shiny nature of silicon (Figure 1.32) means that about 30% of sunlight is reflected back into the sky. To help trap as much photo energy and convert it into as much electricity as possible an anti-reflective coating is used. This is prepared by hydrogenation and chemical vapor deposition (CVD) processes that are costly for manufacturers.

The new technology reduces the optical loss in the cell or module in addition to improving the efficiency of electrical conversion within the cell. The product is

Table 1.2 Solar module index retail price per watt (peak).

System	USD/Wp	Notes
Standard silicon PVC module	4.9	Solarbuzz.com
The hybrid PVC module (prototype)	3.65	With a two-sided silicon photocell
The hybrid PVC module	2.55	With a two-sided silicon photocell and reflecting surfaces

Source: Global Warming Solutions.

Figure 1.32 The efficiency of traditional silicon panels is significantly increased by spraying an anti-reflecting coating. (Source: Braggone).

used by spray coating it onto the solar cell, or glass, then curing it at an elevated temperature. A pre-coat (LUX-MH10) enables the passivation of the surface of a single crystal or of the bulk in multi-crystalline Si cells. Coupled with an anti-reflective coating (LUX-ME), it increases the efficiency and replaces the costly hydrogenation and CVD anti-reflective process with increased throughput with a simple spray coat process [22].

The innovative new product line is a breakthrough for crystalline silicon makers, but can also be used in thin film photovoltaics as well as in solar module manufacturing to further improve their power output.

While interest in alternative energy is increasing across the United States, interest in solar power, especially, is increasing in California. Eight of more than a dozen of the US companies developing photovoltaic cells are based in California, and seven of those are in Silicon Valley [23]. California, is poised to be both the world's next big solar market and its entrepreneurial center. Three-quarters of the nation's demand for solar power comes from residents and companies in California, where the State has earmarked $3.2 billion to subsidize solar installation, with the goal of putting solar cells on one million rooftops.

The subsidies have prompted a surge in private investment, led by venture capitalists. California received roughly half of all solar power venture investments made in 2007 in the United States, with $654 million in 33 solar-related deals in California, up from $253 million in 16 deals in 2006 [24].

San Jose-based SunPower, manufacturer of silicon-based cells, reported 2007 revenue of more than $775 million, more than triple its 2006 revenue, while its stock price grew 251% in 2007. In the same city, Nanosolar recently started making CIGS photovoltaic cells in a large factory, making it one of the biggest producers in the world. The company uses the newspaper printing roll-to-roll technology by spraying

Figure 1.33 Easy installation by Solar Integrated of a lightweight white single-ply roofing membrane, and thin-film photovoltaic membrane transforms commercial and industrial roofs in clean energy generators. (Source. Solar Integrated).

the CIGS material onto giant rolls of aluminum foil and then cutting it into pieces the size of solar panels, as described in Chapter 3.

Another company, Solar Integrated, based in Los Angeles, has developed a low-cost approach to integrating flexible photovoltaic modules made of a-Si directly into the roofs of commercial buildings (Figure 1.33).

All of these companies have the chance to be billion-dollar operators [25]. Yet, to ensure that solar PV is not just for a green elite, and to make it the basis for the economy, we should start from the fact that solar energy represents less than one-tenth of 1% of the $3 trillion global energy market.

There are two intrinsic major differences from the unfulfilled promises of the 1970s, and two external drivers – the skyrocketing oil price and global warming – that will profoundly affect the evolution of solar energy (Chapter 7).

Considering the main two factors: first, through innovation and volume, prices are coming down to such an extent that Nanosolar claims electricity generated through its panels has the same price as electricity from coal. Second, there is a wide consensus that large scale electricity generation will take place through systems

Figure 1.34 Flat reflectors move following the position of the sun and reflect the energy of the sunlight to the fixed pipe receiver above, where water is heated and becomes the steam needed to power a turbine. (Source: Ausra).

that concentrate sunlight from reflecting mirrors to ensure we reach the scale we need to really solve the planet's problems given that, in the meantime, coal-burning power plants, the main source of CO_2 emissions linked to global warming, are being built around the world at a rate of more than one a week.

One such solar thermal plant is the 177-megawatt plant that Ausra, a Palo Alto start-up backed by the investor Vinod Khosla and his former venture capital firm, is building in central California to generate power for more than 120 000 homes beginning in 2010. Its core technology is the compact linear Fresnel reflector (CLFR) solar collector and steam generation system, originally conceived in the early 1990s at Sydney University, that is now being refined and built at large scale by Ausra around the world (Figure 1.34) [26].

The company develops large-scale power projects incorporating CLFR solar fields, and helps utilities generate clean energy for millions of customers. Remarkably, the system uses water as the thermal liquid, eliminating any toxic, corrosive and expensive fluids. Within a year, the company claims it will match the price of natural gas plants, which generate electricity at about 9.2 cents per kilowatt hour; and within three years, it will match the cost of coal-fired plants, which is about 6–8 cents per kilowatt hour.

Another example is that of eSolar, a company in Pasadena (co-financed by Google.org, the philanthropic division of the Internet company) that builds heliostats designed from the ground up to minimize every possible cost [27]. eSolar has designed a solar field layout (Figure 1.35) made of small size heliostats (for higher reliability in all wind conditions and more power plant up-time) that minimizes installation time and cost. By employing a repeating frame structure and a new calibration system, the company has eliminated the need for high-precision surveying, delicate installation,

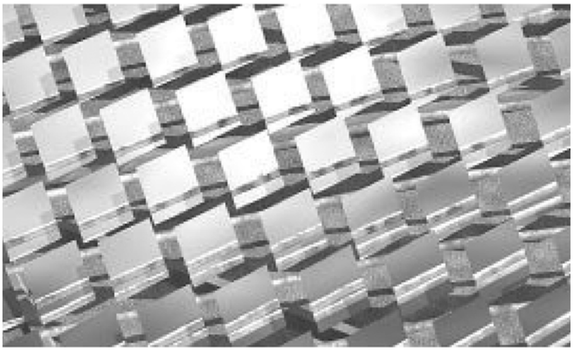


Figure 1.35 New heliostats are designed to fit efficiently into shipping containers to keep transportation costs low, and are pre-assembled at the factory to minimize on-site labor. (Source: eSolar).

and individual alignment of mirrors. Minimal skilled labor is needed to build the solar field, allowing mirror deployment efficiencies that scale with project size and deadlines.

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