1

Capturing Sun's Energy

1.1

Solar Power: Now

Electricity is silent, clean, and easily transported and converted into work. Unsurprisingly, therefore, electric power is the most useful and desirable form of energy available to modern society. Yet, exactly like hydrogen, electricity is an energy *vector* and not an energy source. This means that we need to produce electric power by converting primary energy sources into electric power. At present, besides a 16% share from nuclear fission (www.world-nuclear.org), we produce electricity mainly by burning hydrocarbons and, sadly, much cheaper coal. For example, still, in 2006 nearly half (49%) of the 4.1 trillion kilowatt-hours (kWh) of electricity generated in the USA used coal as its energy source (www.eia.doe.gov).

Overall, presently, close to 80% of the energy supply worldwide is based on fossil fuels like coal, oil, and gas [1]. Over the next decade, China alone will need to add some 25 GW of new capacity each year to meet demand – equivalent to one large coal power station every week. Coal, unfortunately, contains mercury and, along with production of immense amounts of climate-altering CO_2, its combustion is causing pollution of the oceans and of the food chain. To abate emissions and stop climate change, the biggest challenge of our epoch is to obtain electricity directly from the sun.

The conclusions of the United Nations Intergovernmental Panel on Climate Change (IPCC) analyses concerning the potential impact of various scenarios of CO_2 emission trajectories (www.ipcc.ch) provide evidence that if the global average temperature increases beyond 2.5–3.0 °C serious, and likely irreversible, negative consequences to the environment will result, with a direct impact on agriculture, water resources, and human health [2]. In the absence of serious policies to reduce the magnitude of future climate changes, the globe is expected to warm by about 1–6 °C during the twenty-first century. The estimated carbon dioxide (CO_2) concentration in 2100 will

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lie in the range 540–970 ppm (parts per million), which is sufficient to cause substantial increases in ocean acidity as well as *irreversible* modifications to climate and nature [3].

Clearly, to satisfy our growing energy needs (a predicted *doubling* of energy demand by mid-century and a *tripling* by the end of the century) [21] and resolve the world's sustainability crisis, we urgently need to use a fraction of the immense solar energy amount that the Earth receives annually from the sun: 3.9×10^{24} joules, namely four orders of magnitudes larger than the world energy consumption in 2004 (4.7×10^{20} J), and enough to fulfill the yearly world demand of energy in less than an hour.

Realization of such a change will require a massive effort to discover and develop new technology solutions to capture vast amounts of dilute and intermittent, but essentially unlimited, solar energy to sustain our forecasted needs; and also to scale its conversion into high power densities and readily storable forms. The energy and societal challenge before us in developing CO_2-neutral, solar energy differs in two ways from past large-scale challenges, namely, in:

1) the large magnitude and relatively short time scale of the transition;
2) the cost-competitive aspect of the transition.

Solutions will be achieved by exploiting advances in nanoscale science and technology. Revolutionary nanotechnology-enabled photovoltaic materials and devices are being developed to satisfy the world demand in sustainable electricity at a price level of less than $0.10 per kWh. Similarly, nanotechnology-based disruptive devices for electric energy storage, such as new batteries and capacitors, are required to enable massive deployment of solar power. Most importantly, this transformation must be accomplished in an economically and environmentally feasible manner in order to achieve a positive global impact. Hence, the cost of battery technologies must plummet from the current $1000 per kWh to a level approaching $10 per kWh to become cost competitive.

1.2
Never Trust the Skeptics

Exactly in the same way that the Internet was not invented by taxing the telegraph, so cheap and abundant electricity from the sun will not be obtained by adding taxation on carbon dioxide emissions, but rather by inventing new, affordable clean technologies [4]. Nanoscale science and technology will play a crucial role in reaching this aim.

Solar power currently provides only a very small fraction of global electric power generation, about 12 GW of installed capacity globally, as of 2009, but newly installed capacity is growing at approximately 30% per year and

Figure 1.1
The Solucar 11 MW solar thermal plant outside Seville, Spain, produces enough electricity to power 6000 homes. CSP is a large-scale technology capable of satisfying massive electricity demand. Photograph courtesy of the BBC; reproduced with permission.

is accelerating. Concentrated solar power (CSP) has already been identified as a clean technology that can satisfy the world's rapidly growing energy demand.[1] Accordingly, investments are finally flowing and the first CSP plants, such as that in the Spain's city of Seville (Figure 1.1) serving 6000 families, are starting operation.

In Europe, France's President Sarkozy and Germany's Chancellor Merkel seem to have understood the situation. In establishing the new Union for the Mediterranean (Figure 1.2) they and all other government leaders of the member States have agreed to explore feasibility of large-scale generation of solar electricity in North Africa to supply Europe and Middle East countries through solar thermal technologies. Meanwhile, the often invoked two billion citizens of developing countries lacking access to an electric grid will start to self-generate electricity for their basic needs using photovoltaic modules whose price has dropped from almost $100 per watt in 1975 to $1.6 per watt at the beginning of 2009.

Direct conversion of the sun's radiation into electricity, namely photovoltaics (PVs), is being developed rapidly. After 40 years of losses and governmental subsidies, the $37 billion photovoltaics industry has turned into a profitable business, growing for the last decade at 30% per annum [5]. In this context, the installation of thin-film (TF) systems more than

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1) One of the world's leading solar thermal CSP technologies in terms of reduced cost and safety is that of the US company Ausra: www.ausra.com.

Figure 1.2
Established in 2008, the Union for the Mediterranean consists of 42 countries and has a major project: a Mediterranean Solar Plan to install concentrating solar power in the deserts and feed huge amounts of electricity to all member States, thereby ending energetic dependency on oil and natural gas. Reproduced from wikipedia.org, with permission.

doubled last year and now accounts for some 12% of solar installations worldwide [2]; the revenue market share of TFPV was expected to rise to 20% of the total PV market by 2010 (Figure 1.3) [6]. Thin-film modules are less expensive to manufacture than traditional silicon-based panels and have considerably lowered the barrier to entry into the photovoltaic energy business. From the heavy, fragile silicon panels coated with glass the sector is thus rapidly switching to thin film technologies using several different photovoltaic semiconductors.

Four years of high and increasing oil prices and the first ubiquitous signs of climate change have been enough to assist the market launch of several photovoltaic technologies based on thin films of photoactive material that had been left dormant in academic and industry laboratories for years. For example, in 2004 a leading manager in the PV industry, exploring the industry perspectives, concluded:

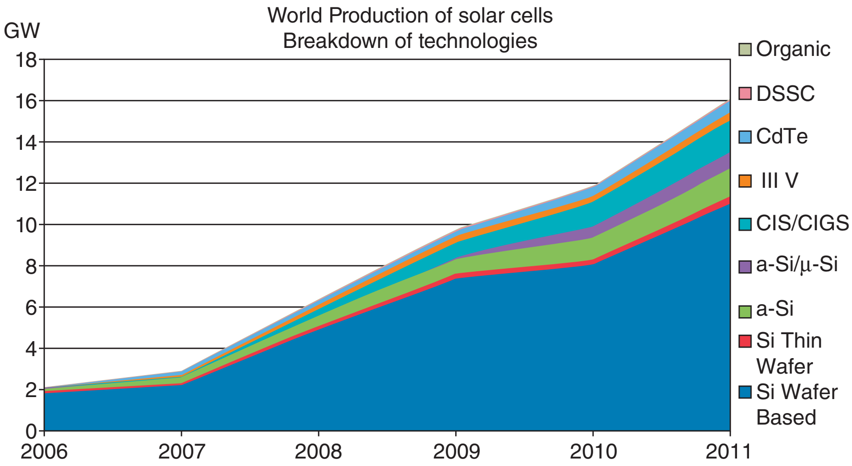

Figure 1.3
The forecast for the photovoltaic market, with a breakdown per technology, points to an annual growth rate of 70% for TFPV from 2007 to 2010 Reproduced from yole.fr, with permission.

> "thin-film PV production costs are expected to reach $1 per watt in 2010, a cost that makes solar PV competitive with coal-fired electricity" [7].

However, the first thin-film solar modules profitably generating electricity for $0.99 per watt (i.e., the price of coal-fired electricity) were commercialized in late 2008 by the US company First Solar.

Now, regarding the "feed-in" tariff schemes by which, initially, governments in countries like Germany and Spain and now Italy, France, and Greece aim to incentivize production of solar electricity, the "skeptical environmentalist" Bjørn Lomborg [8] (Figure 1.4) would probably tell you that this is just another example of the poor (through an extra tax on the electric bill) financing the rich (purchasing the solar modules). But Bjørn, in this case, would be wrong.

The governments of these countries established the incentives to develop a large and modern photovoltaic industry that, thanks to the large profits fueled by the incentives, could finance innovation and lower the price of solar electricity. How right they were! Indeed, a large body of new commercial PV technologies has emerged in the last five years and last month the US-based company First Solar announced a reduction in production costs to 1$ W^{-1} (one dollar per watt), from 5$ W^{-1} in 2005 when the company started production of its modules based on cadmium telluride (a readily available and non-toxic inorganic salt). Cumulative

Figure 1.4
"The poor financing the rich" would say the "skeptical environmentalist" Bjørn Lomborg commenting on the "feed-in tariff" scheme adopted by Germany (and many other states). But Bjørn, in this case, would be wrong. Photograph by Emil Jupin, reproduced from lomborg.com, with permission.

production planned for 2009 by this company alone is 1 GW, that is, the power similar to that generated by a new-generation large nuclear power plant.

In management, as in politics, never trust the skeptics too much!

1.3
Solar Power for the Masses

So-called "thin film" photovoltaics are opening the route to low cost electricity. In this context, thin films are 100 nm–100 μm thick and made of organic, inorganic, and organic–inorganic solar cells deposited over rigid or flexible substrates by high-throughput (printing) technologies. If, for example, 35 μm of silicon were used to manufacture a solar cell instead of the state of the art 300 mm – such as in the case of the *SilFoil* technology based on large area, multi-crystalline silicon foils developed by NanoGram (www.nanogram.com) (Figure 1.5) – the cost of silicon-based solar modules would be below $\$1\,\mathrm{W}^{-1}$.

While similar small start-ups eagerly compete to introduce new solar technologies, First Solar already manufactures the equivalent of one large

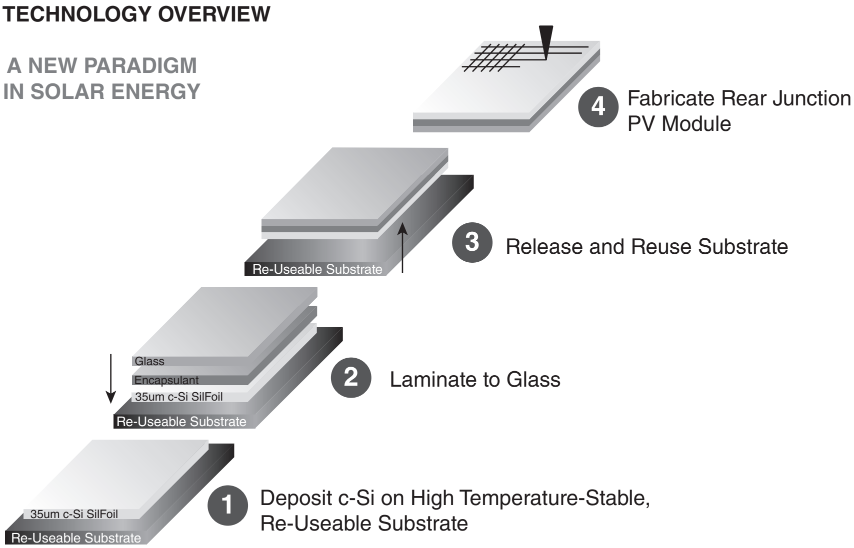

Figure 1.5
Nanogram plans to start production of its *SilFoil* modules in 2010 in a US-based production facility; 5 MW of capacity on ultra-thin crystalline silicon, which it says will reduce the cost of silicon-based solar cells to below $1 per watt by an innovative technology based on large area, multi-crystalline silicon foils. Reproduced from nanogram.com, with permission.

nuclear power station, using a deposition technique of inorganic nanocrystals of cadmium telluride. Floated on the New York Stock Exchange (NASDAQ) in November 2006 the company's stock price rapidly recovered from the financial turmoil due to the 2008 financial crisis (Figure 1.6) as production – and sales – increased 100-fold and the company has become the world's second largest in the photovoltaic business.

The above is due to technical control of the deposition process using a technique called chemical vapor deposition. Without such control, such a *disruptive* technology would not be on the market. It is disruptive because, in the face of the new threat posed by this highly competitive technology, manufacturers of traditional silicon solar panels reacted by ramping production, aiming to reduce cost by economies of scale. This, in its turn, led to oversupply of polysilicon (the raw material for Si-based solar cells) from silicon manufacturers.[2] The overall result is that, in early 2009, solar modules in Europe and in the rest of the world were selling at 1.7€ W^{-1}. Solar energy for the masses is now a reality!

[2] The mean price of polysilicon to be supplied in 2009 in contracts already signed is 43% lower than the mean price of polysilicon supplied in 2008. (New Energy Finance, 2008).

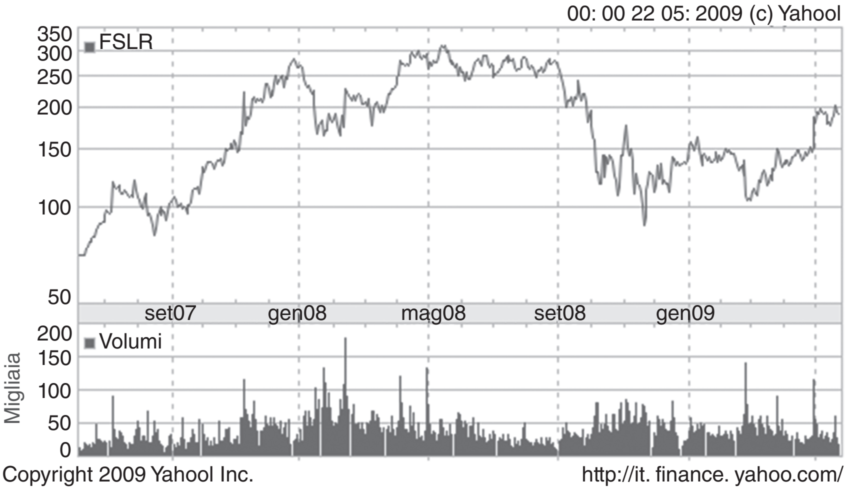

Figure 1.6
Price of First Solar stock, 2007–2009 (as of May 2009). Reproduced from google.com, with permission.

At present, most existing production tools in the solar industry have a 10–30 megawatt (MW) annual production capacity. A single machine with a gigawatt throughput would be highly desirable, leading to far higher returns on the capital invested. In late 2008, thus, Nanosolar opened a factory in California that can produce 430 MW of solar capacity a year, nearly the size of an average coal-fired power plant, by simply printing a nanoparticle ink. More precisely, the company manufactures thin film copper-indium-gallium-selenide (CIGS) solar cells by printing the active CIGS material onto mile-long rolls of thin aluminum foil (Figure 1.7), which is later cut into solar panels.

The new ink (Figure 1.8) is made of a homogeneous mix of CIGS nanoparticles stabilized by an organic dispersion. Chemical stability ensures that the atomic ratios of the four elements are retained when the ink is printed, even across large areas of deposition. This is crucial for delivering a semiconductor of high electronic quality and is in contrast to vacuum deposition processes where, due to the four-element nature of CIGS, one effectively has to "atomically" synchronize various materials sources.

Printing is a simple, fast, and robust coating process that further lowers manufacturing costs. Rolls that are meters wide and miles long are thus processed efficiently with very high throughput. Somewhat ironically, the company has been established by the heir of a wealthy German family that became rich selling, since the 1920s, electricity obtained by burning coal [9].

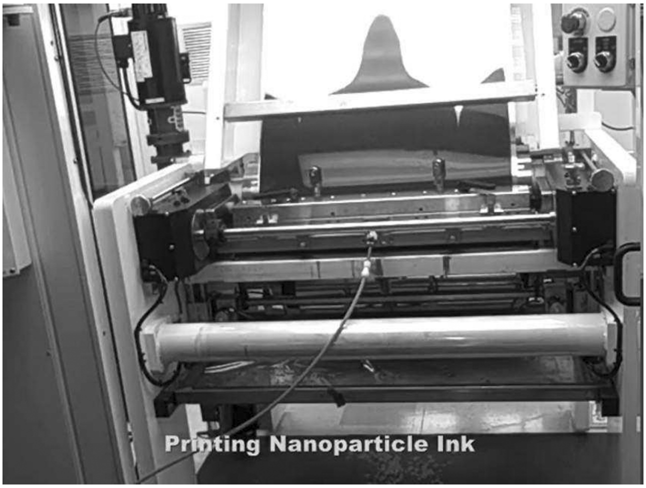

Figure 1.7
Nanosolar states that its 1GW CIGS coater costs $1.65 million. Working at speeds of 100 feet min^{-1} speed, the process is an astonishing two orders of magnitude more capital efficient than a high-vacuum process: a 20-times slower high-vacuum tool would have cost about ten times as much. Reproduced from nanosolar.com, with permission.

Figure 1.8
Nanosolar's nanostructure CIGS ink. The ink serves a useful purpose by effectively "locking in" a uniform distribution even across large areas of deposition. Photograph courtesy of nanosolar.com, reproduced with permission.

1.4
Why Nanoscience is Relevant to the Solar Energy Industry

From a scientific viewpoint, thin film solar cells are the result of advances in nanochemistry. Interestingly, the inventor of the silicon solar cell had already in 1954 clearly forecasted that thin films would be the configuration of forthcoming industrial cells. Indeed, it has been our chemical ability to manipulate matter on the nanoscale for *industrial* applications that has recently made possible the synthesis of the photoactive layers needed to carry out the photovoltaic conversion with the needed stability required for practical applications. Almost unnoticed among more glamorous scientific disciplines, chemistry in the last 20 years has extended its powerful synthetic methodology to make materials where size and shape are as important as structure. In other words, we have learned how to make nanoscale building blocks of different sizes and shapes, composition, and surface structure such as in the case of the "nano ink" developed by Nanosolar to make its CIGS panels.

The unique physicochemical features that only become accessible on the nanoscale, to achieve improved functionality and efficiency, are the optimal match of time and length scales for energy carrier transport and conversion, which can be achieved via nanoscale design of the photocatalytic site (Figure 1.9).

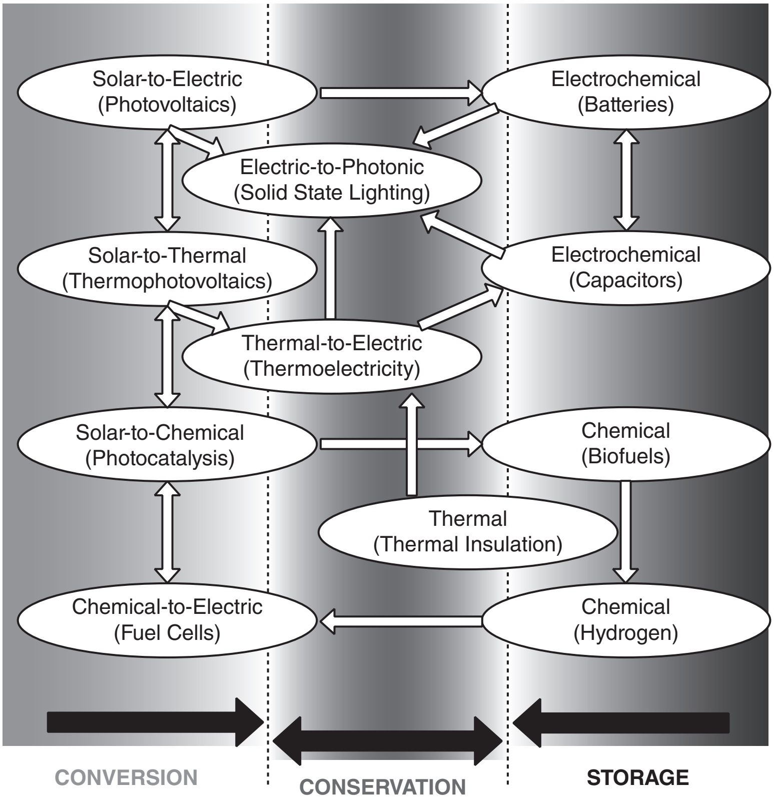

Figure 1.9
Portfolio of solar/thermal/electrochemical energy conversion, storage, and conservation technologies, and their interactions, that are the focus of the discussion. The electric grid is also shown in this figure as a network of connecting multiple elements (technology boxes), allowing them to act as a coherent whole. Reproduced from Reference [10], with permission.

Table 1.1 Characteristic length and time scales for energy carriers under ambient conditions. Reproduced from Reference [10], with permission.

	Wavelength (nm)	Mean free path (nm)	Relaxation time (ns)
Photons (solar/thermal radiation)			
In liquids/gases	100–30 000	>1000	$>10^{-6}$
In semiconductors	25–30 000	>10	10^{-7}–10^{-6}
In conductors/metals	–	0.1–10	10^{-10}–10^{-9}
Electrons			
In semiconductors/dielectrics	1–50	1–500	$1–10 \times 10^{-3}$
In conductors/metals	0.1–1	1–10	$10–100 \times 10^{-6}$
Phonons			
In semiconductors/dielectrics	0.5–10	1–500	10^{-3}–1
Molecules/ions			
In gas/plasma	10^{-2}–1	10^{3}–10^{7}	1–100
In liquid/electrolyte	–	0.1–1	10^{-3}
In solid/electrolyte	–	0.1–1	10^{-3}

An understanding of the general characteristics of fundamental energy carriers is important in appreciating the connections between nanotechnology and energy. Table 1.1 summarizes the characteristic length and time scales for energy carriers in liquids, gases, and solids. These scales define the space–time envelope within which, if accessible, the manipulation of matter should critically affect the energy carrier transport and conversion processes, thereby enabling drastic improvement in the performance of energy systems [10].

Because the length scales in Table 1.1 are generally of the order 1–100 nm, this size regime naturally falls into the domain of nanoscale science and engineering by virtue of the match between the length scales of the energy carriers and the materials that control their transport. Revolutionary improvements (i.e., an order of magnitude or greater enhancement when scaled to practical sizes) in the delivery of usable energy can be facilitated by advancing nanoscale design of both materials and associated energy conversion processes and systems.

For example, the present photovoltaic technologies rely on the quantum nature of light and semiconductors that are fundamentally limited by the band-gap energies. A revolutionary new approach suggested by Bailey in 1972 that revolves around the wave nature of light is now becoming a reality thanks to advances in nanochemistry [11]. The idea is simple: to use broadband rectifying (nano)antennas for direct conversion of solar radiation into electricity. The challenges in actually achieving the dream are many. The antenna concept relies on the fact that solar radiation is electromagnetic in nature. In other words, the waves are oscillating electric and magnetic fields propagating from the Sun to the Earth. In-coming light waves oscillate

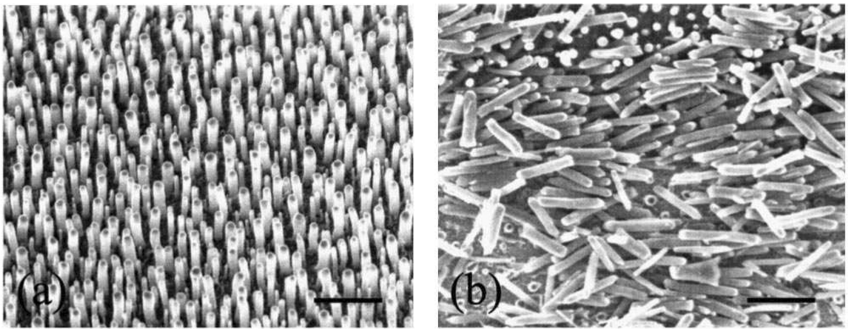

Figure 1.10
Aligned (a) and scratched (b) random arrays of MWCNTs are an array of dipole antennas. Each nanotube in such arrays is a metallic rod about 50 nm in diameter and about 200 to ca. 1000 nm long. Reproduced from rsc.org (Royal Society of Chemistry), with permission.

electrons in an antenna tuned to the wavelength of light – hence the devices have to be of the order of a few hundred nanometers. The broadband incoherent nature of the solar spectrum also requires a wide range of antenna sizes to match all the wavelengths and the need to arrange two directions of polarization.

These *rectennas* would not have the fundamental limitation of a semiconductor band-gap limiting their conversion efficiencies. How then can we manufacture rectennas with dimensions of the order of the wavelengths of solar radiation (mostly in the sub-micron range)? Using carbon nanotubes, a new form of highly conductive carbon accidently discovered in 1991.

Cheap and readily available multi-walled carbon nanotube (MWCNT) arrays grown on a metal substrate (Figure 1.10), in particular, behave as excellent optical rectennas, receiving and transmitting light at ultraviolet (UV), visible and infrared (IR) frequencies. In other words, these materials behave exactly like macroscopic antennas, namely they show a resonant response behavior as a function of the radiation wavelength. This arises from the condition that the induced current oscillations must fit into the antenna length.

Chemistry-enabled nanotechnology here resolves the biggest problem in achieving the ability to rectify electromagnetic waves at the high frequency range of visible and IR radiation. Although infrared rays create an alternating current in the nanoantenna, in fact, the frequency of the current switches back and forth ten thousand billion times a second, much too fast for electrical appliances, which operate on currents that oscillate only 60 times a second. Indeed, the *desired* length and diameter of the carbon nanotubes (CNTs) are achieved by accurate chemical control of the growth parameters. New nanochemistry strategies for the chemical synthesis of nanotubes developed in the early 2000s are therefore crucial to

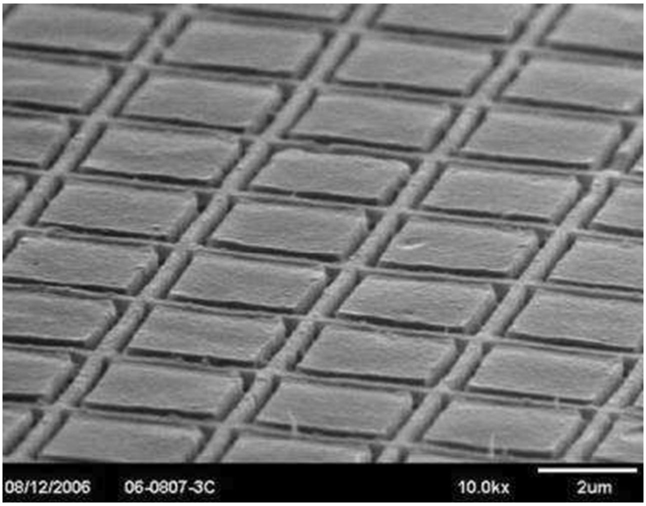

Figure 1.11
An array of loop nano-antennas imprinted on plastic and imaged with a scanning electron microscope. The deposited wire is roughly 200 nm thick. Photograph courtesy of Idaho National Laboratory.

manufacturing solar rectennas. The manufacturing process patented by the Idaho National Laboratory clearly demonstrates that nano-scale features can be produced on a larger scale [12].

The process stamps tiny square spirals of nanoantennas onto a sheet of plastic that is a flexible substrate. Each interlocking spiral nanoantenna is as wide as 1/25th the diameter of a human hair (Figure 1.11).[3] The nanoantennas absorb energy in the infrared part of the spectrum, just outside the range of what is visible to the eye. Since the sun radiates a lot of infrared energy, some of which is soaked up by the earth and later released as radiation for hours after sunset, nanoantennas can take in energy from both sunlight and the earth's heat, with higher efficiency than conventional solar cells. Double-sided panels could absorb a broad spectrum of energy from the sun during the day, while the other side might be designed to take in the narrow frequency of energy produced from the earth's radiated heat.

Present day light-to-electricity conversion efficiencies – measured under standard and *unrealistic* conditions – are in the 3–15% range, but in real applications the overall productivity of thin-film second-generation PV technologies is high. This, along with the lower price, renders the new PV technologies ready to provide cheap, clean electricity to both the 2 billion people who lack access to the grid and to energy eager companies and

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[3] See the Idaho National Laboratory Feature Story Archive at http://www.inl.gov/featurestories/2007-12-17.shtml.

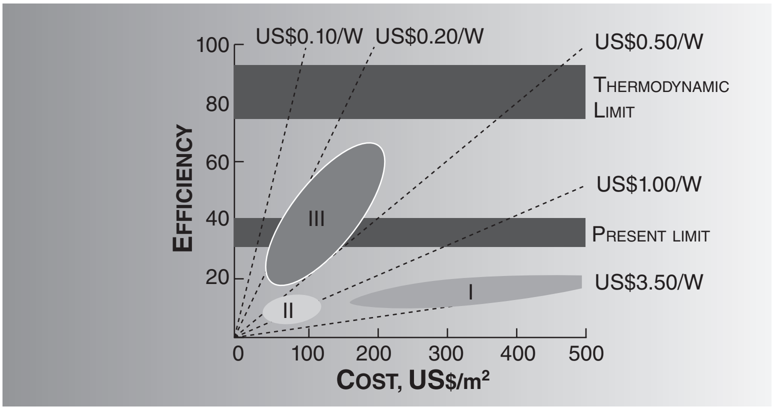


Figure 1.12
Efficiency and cost projections for first-, second- and third-generation photovoltaic technology (wafers, thin-films, and advanced thin-films, respectively). Reproduced from pv.unsw.edu.au, with permission.

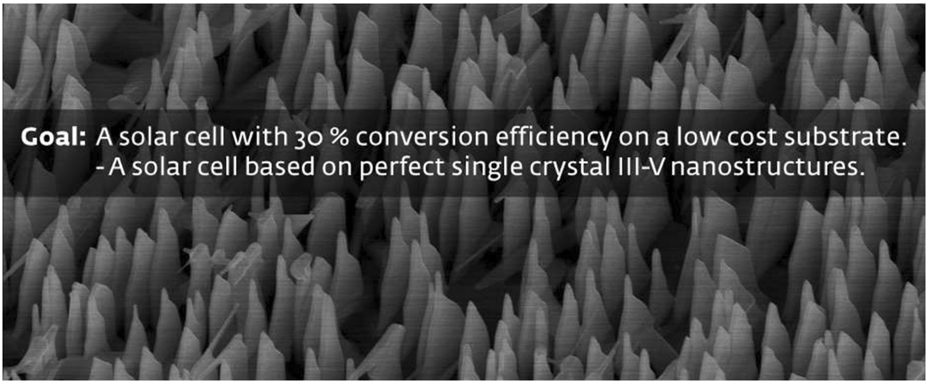


Figure 1.13
The objective of Sun Flake is clear: 30% efficient solar cells on all sorts of cheap substrates Reproduced from sunflake.dk, with permission.

families in the developed world facing the increasing cost of electricity generated with fossil fuels. In fact, much higher conversion efficiencies are to be achieved with the introduction of third-generation PV technologies (Figure 1.12).

The Danish company SunFlake (Figure 1.13) claims to be able to manufacture a low-cost cell that has an efficiency of about 30% – roughly double the efficiency of the average solar cell available today – through nanowire crystalline structures ("nanoflakes") of a semiconductor that can absorb nearly all light directed at them.

In conventional solar cells made of slabs of crystalline material, greater thickness means better light absorption, but it also means that it is more difficult for electrons to escape. This forced trade-off is overcome with *nanowires* [13]. Each nanowire is 10–100 nm wide and up to 5 µm long. Their length maximizes absorption, but their nanoscale width permits a much freer movement and collection of electrons. The light is absorbed essentially perpendicular to how electricity is collected and so the dilemma is overcome. The surface of the material consists of extremely tiny crystals of InAs, grown by molecular beam epitaxy (Figure 1.13), which provide a huge surface area in which sunlight can be caught.

A similar approach relies on nanowires containing multiple layers of group III–V materials, such as gallium arsenide, indium gallium phosphide, aluminum gallium arsenide, and gallium arsenide phosphide. It creates tandem or multi-junction solar cells that can absorb a greater range of the light spectrum than silicon [14] In conventional crystalline solar cells, group III–V materials have much higher efficiencies than silicon, but the great cost of these materials has limited their use. In addition to reducing costs by using less active material, this approach can cut the cost of the substrate that the nanowires are grown on, by using more plentiful and relatively cheaper silicon, glass, and polymer films for inexpensive roll-to-roll manufacturing.

1.5
Expanding the Solar Business

Two other new nanotechnology-based PV technologies are plastic and dye solar cells. Like CIGS-based cells, organic solar cells (OSCs) are particularly attractive because of their ease of processing, mechanical flexibility, and potential for low cost printing of large areas. Once higher efficiency is achieved such polymeric solar cells will rapidly find widespread application [15]. Indeed plastic solar cells are intrinsically cheap and easily manufactured, and being lightweight and flexible they will be rapidly integrated into existing buildings.

According to a set of design rules specifically derived for organic tandem cells, maximum efficiencies of 15% are expected for an optimized material couple [16].

Organic solar cells can be easily produced by roll-to-roll inkjet printing technology, as first demonstrated by Konarka Technologies (www.konarka.com) in early 2008 when the company, which specializes in organic photovoltaics, successfully carried out the first demonstration of manufacturing solar cells by inkjet printing. As in the case of the printed CIGS-based solar cells manufactured by Nanosolar, the continuous roll-to-roll printing technology provides easy and fast deposition of PV films over large area

Figure 1.14
Translucent solar cell modules. Wiring density gradually increases from left to right. This is to allow customers to select their favorite density. Reproduced from konarka.com, with permission.

substrates. Cleanliness during deposition is important. However, rather than encase the whole production line in a clean room to keep out dust, only the coating stations are sealed off. This lets the entire line reside in an ordinary factory environment. Modules made of Power Plastic® (Figure 1.14) coming off Konarka's roll-to-roll line today feature an energy conversion efficiency of 3% inside a building and 3–4% outside, because their high circuit resistance impacts more as current increases.

Invented in the early 1990s, dye-sensitized solar cells (DSCs) were first commercially used in 2003; the first modules based on this versatile hybrid (organic–inorganic) technology were used to fabricate one wall at Australia's new CSIRO Institute (Figure 1.15). As with plastic solar cells, DSCs have a low weight and low cost of production. However, their typical 7% efficiency in commercial modules is about twice that of polymeric modules; whereas their good performance in diffuse light conditions is a feature they have in common with inorganic thin-film solar modules. Finally, dye cells work well in a wide range of lighting conditions and orientation, as they are less sensitive to partial shadowing and low level illumination, making DSC-based modules particularly well suited for architectonic applications.

Beyond its low cost (titania is widely used in toothpastes, sunscreen, and white paint) and ease of production, the unique advantages over Si-based cells lie in their transparency (for power windows), easy bifacial configuration (advantage for diffuse light) and versatility (the color can be varied by selection of the dye, including invisible PV-cells based on near-IR sensitizers). By 2015, it is expected that companies will attain 10%-efficient modules that approach the criteria for solar module certification.

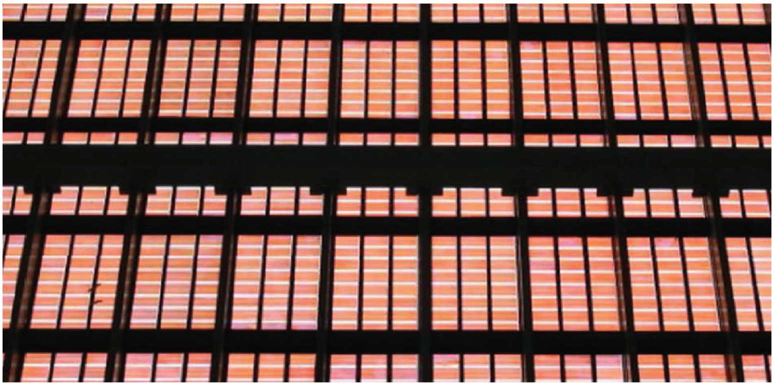


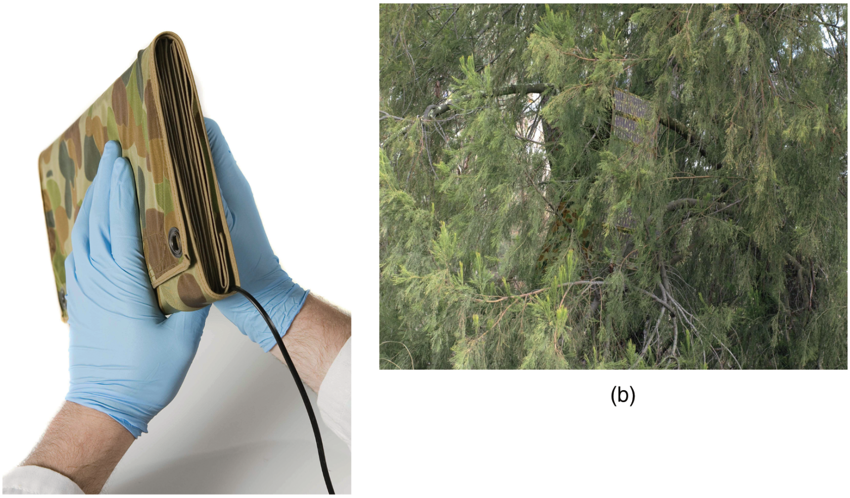
Figure 1.15
The first 4% efficient semitransparent orange windows consisting of DSC-based modules were used as elegant construction elements for the western façade of Australia's Energy CSIRO Institute in 2003. Photograph courtesy of Dyesol.

The Australian company Dyesol (www.dyesol.com) has pioneered the commercialization of DSC after obtaining a license from the inventors and has developed the technology in practically every aspect. The company has recently introduced a flexible, foldable, lightweight, and camouflaged solar panel for military applications that has been found to be superior to other PV technologies in maintaining voltage under a very wide range of light conditions – even in the dappled light under trees (Figure 1.16).

In general, DSCs are very tolerant to the effects of impurities because both light absorption and charge separation occur near the interface between two materials, which allows for roll-to-roll production, such as in the case of the G24 Innovations manufacturing process, transforming a roll of metal foil into a 45 kg half-mile of dye-sensitized thin film in less than three hours (see www.g24i.com).

This material is rugged, flexible, lightweight, and generates electricity even indoors and in low light conditions. In 2007, the US company G24 Innovations (www.g24i.com) started production in a factory based in the UK. Its modules are less than 1 mm thick and the original production capacity of 25 MW in 2007 is planned to be scaled up to 200 MW in a few years, following market response to initial commercialization. The first product is a solar charger series, working indoors and outdoors, compatible with mobile phones, laptops, audio players, and digital cameras. In Israel, the company 3GSolar (www.3gsolar.com) has developed inexpensive modules based on 15 × 15 cm dye cells, utilizing a low-cost method of depositing TiO_2 in a sponge-like array on top of flexible plastic sheets (Figure 1.17).

The company has developed a manufacturing line that costs 40% less than a silicon line per megawatt output, operating efficiently at 8 MW. This



(a)

(b)

Figure 1.16
The flexible DSC-based solar module developed by Dyesol for the Australian Army camouflages itself in trees, where it provides constant voltage under a wide range of illumination levels Photograph courtesy of Dyesol.

Figure 1.17
Cameroon Minister of Science and Research, Madeleine Tchuinte, visiting 3GSolar headquarters and demonstration site in Jerusalem, September 25, 2008. Photograph courtesy of 3GSolar.

means that manufacturing can be put in place at 15% of the capital cost of a typical silicon photovoltaic line.

1.6
Solar Hydrogen from Water

Solar energy is inherently intermittent and must be stored to fulfill demand when irradiation is low or simply absent. Hydrogen (H_2), in contrast, is an excellent energy vector, suitable for storing solar energy, as clearly demonstrated by several recent commercial technologies of disruptive potential.

In Italy the building "HydroLAb" located in San Zeno, Arezzo, Tuscany (Figure 1.18) is completely autonomous and disconnected from all ordinary facility grids: water (rain water collection), sewage (bioremediation plants and close cycle), electricity (PV panels and fuel cells), gas (electrolysis hydrogen), phone and web (via radio) (www.lafabbricadelsole.it). Fully authorized by the local public safety and hygiene authorities in 2007, the building is the daily work place of about 20 knowledge workers in the renewable energy business.

A high efficiency membrane electrolyzer is used to produce renewable hydrogen that is then stored in ordinary storage systems or converted into

Figure 1.18
The HydroLAb in San Zeno, Arezzo, Italy. The system has a nominal power of 3.5 kWp and can produce 4200 kWh y^{-1} because of an estimated safety ratio of 1200 kWh kWp^{-1}, typical of the Arezzo latitude and microclimate. Reproduced from lafabbricadelsole.it, with permission.

metal hydrides. The stored energy can be recovered by mean of two 1 kW portable fuel cells.

A solar photovoltaic roof made of 20 conventional 175 W photovoltaic panels provides the electricity needed to run an electrolyzer that splits water into hydrogen and oxygen, which are then collected separately at the electrodes. When electricity is needed, both gases are supplied to the fuel cell, which generates electric power. For at least two years, the HydroLAb building has shown convincingly that a solar-powered economy is entirely possible from both an economic and environmental viewpoint using present-day technologies, and that solar-generated hydrogen will play a central role in tomorrow's energy infrastructure.

On the larger scale required to make solar-based H_2O splitting a practical technology in terms of quantity and cost, a simple and robust catalyst, with manufacturability on a large scale at competitive costs, must be developed. Awarded the EU Descartes Prize in 2006, the Hydrosol project led by Athanasios Konstandopoulos has indeed resulted in the development of a method of producing hydrogen from water-splitting using only the energy of the sun [17].

The process – an endothermic reaction that requires energy input – employs a multichannel ceramic honeycomb reactor, resembling the familiar catalytic converter of automobiles, coated with active water-splitting materials that are heated by concentrated solar radiation to the desired temperature. The reactor contains no moving parts and is constructed from special ceramic multi-channeled monoliths that absorb solar radiation, coated with active water-splitting nanomaterials capable of splitting water.

When water vapor passes through the reactor, the coating material splits the water molecule by "trapping" its oxygen and leaving in the effluent gas stream pure hydrogen. In the next step, the oxygen "trapping" material is regenerated with the help of solar power (i.e., the material releases the oxygen absorbed) by increasing the amount of solar heat absorbed by the reactor; hence a cyclic operation is established on a single, closed reactor/receiver system. Multi-cyclic solar thermochemical splitting of water was successfully demonstrated on a pilot solar reactor (Figure 1.19) achieving constant hydrogen production exclusively at the expense of solar energy.

The work has attracted interest from several international organizations, including the UN, which foresees huge potential for technological transfer to developing countries with high solar potential, thereby offering the prospect for the creation of new markets, as well as new energy sources. Once again, nanochemistry makes it possible as it enables the synthesis, through "aerosol" and combustion techniques, of the iron-oxide-based redox catalysts capable of producing pure H_2 from water in 80% yield; the catalysts take oxygen from water at reasonably low temperatures (800 °C) and are regenerated at temperatures below 1300 °C. Eventually, the integration of solar energy concentration systems with systems that can split water will have an immense impact on energy economics, as it is the most promising

Figure 1.19
In March 2008 a 100-kW reactor for producing hydrogen through water splitting using solar energy was put into commission at the Plataforma Solar in Almería as part of the Hydrosol project. The reactor is located inside the tower on the right. Reproduced from dlr.de, with permission.

route to providing affordable, renewable solar hydrogen with virtually zero CO_2 emissions.

Early in 2009 the Austrian companies Fronius, Bitter, and Frauscher successfully presented Riviera 600, the world's first electric boat powered by hydrogen fuel cells, on Lake Traunsee in Austria; the boat is featured on the cover of this book. The concept is that of self-contained energy supply provided by hydrogen obtained simply by photovoltaic electrolysis of water (www.zukunftsprojektwasserstoff.at). Extracted from water using photovoltaics and electrolysis, H_2 is oxidized in the fuel cell and the only emission is clean water (Figure 1.20), thereby completing a zero emission energy production cycle.

The boat – 6 m long, 2.2 m wide, and weighing 1400 kg – has a range of 80 km with a full hydrogen tank and has been awarded a safety certificate by Germany's TÜV. Its 4 kW continuous power electric motor has twice the range of conventional battery-powered boats. The 47% efficiency of the noise-free fuel cell engine should be compared to the 18–20% efficiency of a conventional (steel) internal combustion engine.

Its main economic advantage compared with conventional electric boats is the fact that no time has to be spent charging the batteries. For conventional electric boats, 6–8 h of charging gives just 4–6 h of use. The hydrogen-powered electric boat requires only the time that it takes to change the cartridge: 5 min. The boat's fueling system consists of a 20 kg cartridge that can be charged with up to 0.7 kg of hydrogen kept at 350 bar. Refueling is

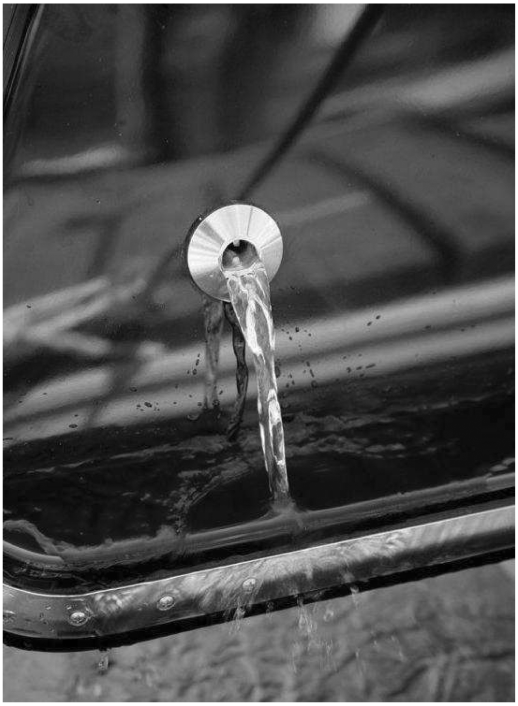


Figure 1.20
The only emission of the Frauscher Riviera 600 hydrogen-powered boat is clean water; the H_2 is obtained cleanly by photovoltaic electrolysis of water. Reproduced from fronius.com, with permission.

carried out using a standard filler coupling, on the one hand, plus the simple exchange of an empty cartridge for a full one on the other hand (Figure 1.21).

The energy filling ("Clean Power") station makes use of PV modules integrated in a 250 m^2 flat roof, and further connected to an electrolytic cell. Even at Austria's cold latitudes the station can produce an annual yield of 823 kg of hydrogen, which is equivalent to 1100 cartridges with a 27 200 kW power content, that is, enough hydrogen to run to boat for 8000 km. Its installation is simple thanks to the "container construction" design and can be carried out simply and quickly at many different locations. The station consists of electricity power charger, hydrogen, and payment units (Figure 1.22).

Renewables expert Claudia Bettiol from Italy rightly argues that renewable energy will be a local, hi-tech business with a global impact. We add to this our view that it will increasingly make use of alternative forms of financing such as international organizations and Islamic finance. It is thus remarkable to see how this is in practice occurring. All three companies involved in the "Future Project Hydrogen" are based in Austria, and are

Figure 1.21
The 600 Riviera Frauscher boat can be refueled in 5 min using a standard 350 bar filler coupling plus the simple exchange of an empty cartridge for a full one. Reproduced from frauscherboats.com, with permission.

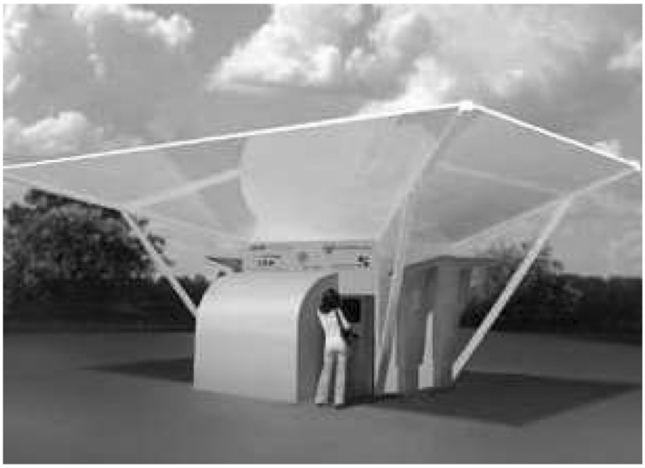


Figure 1.22
The Clean Power Station makes use of a 250 m^2 flat roof equipped with PV modules whose electric power output feeds an electrolyzer that splits water molecules. Reproduced from fronius.com, with permission.

very close to each other. Scientific and technical advice was provided by the Technical University of Graz, whereas the project was realized with support from the European Union regional programs and further funding from an Austrian region. The first 600 Riviera boat is commercialized at €150 000, with the first exemplars to be delivered to customers in early 2010.

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