Mario Pagliaro, Giovanni Palmisano,
and Rosaria Ciriminna

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To Bob Pirsig.
For the luminous light shed
on the concept of quality for all of us.

Preface

Nordhuas and Shellenberger are right [1]. The Internet was not invented by taxing the telegraph. Similarly, cheap and abundant electricity from the sun will not be obtained by adding taxation on carbon dioxide emissions, but rather by inventing new, cheap solar modules capable of performing the light to electric power conversion with >50% efficiency instead of the current 22%.

These modules, furthermore, will have to be flexible and lightweight in order to produce electricity reliably with little maintenance while being integrated into existing buildings, fabrics, tents, sails, glass and all sorts of surfaces. By so doing, the price of solar energy will be reduced to the level of coal-generated electricity (the cheapest electricity) so that people living in huge emerging countries will also rapidly adopt solar energy for their economic development.

The good news is that the first generation of such commercial modules – the topic of this book – is now ready, having entered the global energy market in the last two years. Their 5–15% efficiency is still too low and, despite a considerably lower price than that of traditional silicon-based panels, much higher conversion efficiency will have to be achieved. However, there is no doubt that these long awaited advances will take place.

Three years of high oil prices and the first ubiquitous signs of climate change have been enough to assist to the market a number of photovoltaic technologies based on thin films of photoactive material that have lain dormant in industrial laboratories for many years.

The 12 billion dollar photovoltaics industry with, for the last five years, an impressive 35% annual growth rate, is rapidly switching to thin film photovoltaics. Ironically, the inventor of the silicon solar cell had already in 1954 clearly forecast that thin film would be the configuration of forthcoming industrial cells.

From a scientific viewpoint, new flexible solar cells are the result of nanotechnology advances and in particular of nanochemistry. 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 necessary stability required for practical applications.

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Almost silent 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 size and shape, composition and surface structure, that can be useful in their own right or in a self-assembled structure [2], such as in the case of the "nano ink" developed by Nanosolar (Chapter 3) to make its CIGS panels, producing power at less than 1$/W (i.e., the price of coal electricity).

This book offers a treatment of its topic which includes both inorganic and organic photovoltaics over thin films with an emphasis on the (nano)chemistry approach by which these devices were conceived and eventually manufactured.

However, the solar energy revolution which is unveiling requires leadership engagement at the highest corporate and political levels. Readers of this book therefore will include policy makers and those from the top levels of management and management consultancy, as well as science and energy communicators.

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

We need to curb CO_2 emissions soon; thus, we need to use on a massive scale renewable materials and renewable energy.

In striking contrast, to fulfill our energy needs, we are still dependent on energy sources and conversion and storage technologies that are 100 to 150 years old, while virtually every other sector of the economy has transformed itself. To get an idea of the obsolescence of our energy devices, just think how often you need to recharge your mobile phone; and how cumbersome and polluting are batteries.

The whole energy industry has been particularly resistant to innovation thanks to its huge profits ensured by hydrocarbon extraction and refining. Put simply, companies had *no* reason to invest in changing this idyllic situation, and virtually every alternative energy source we have – solar, wind, nuclear, fuel cells – has resulted from taxpayer funded innovation.

All that, however, has changed for ever.

Today, not only has the price of oil reached and surpassed the threshold of 100 dollar per barrel, but the energy return on energy invested (EROI) is falling rapidly. Considering the US, for instance, the EROI has dwindled to 15 joules per joule invested, whereas in the 1930s the figure was 100 joules per joule [3].

By the same token, Italy's oil company Eni is, along with Shell, Total and ExxonMobil among the companies which own the rights to exploit the newly discovered huge oil field of Kashagan in Kazakhstan.Unfortunately, this oil lies underneath such a large amount of hydrogen sulfide that, even if the companies can solve the technical problems and start to drill it, the price of the solutions implemented will inevitably be reflected in significantly lower EROI and higher costs.

It is exactly this decreasing trend in EROI that, along with climate change due to increasing carbon levels in the atmosphere, is forcing society globally to switch from fossil to renewable fuels, until the day when cheap and abundant solar energy becomes a reality.

Along with the interest of citizens, companies and governments, private and public investments in solar energy are eventually booming. Numerous start-up photovoltaic companies are attracting financial investment from the world's leading venture capitalists and even from oil companies. Google, for example, largely funded Nanosolar in the US; whereas investors in Konarka, a manufacturer of plastic solar cells, include some of the world's largest oil companies.

Similarly, we think that Islamic finance will play a crucial role in making abundant, cheap and clean solar electricity a reality for mankind. Those same investors, politicians and their advisors will find in this book plenty of information on which to base their choices.

Two billion people lacking access to the electric grid will benefit immensely from the advances that are being made, as will companies and citizens in the developed world where the electricity bill has become a serious economic problem.

This book addresses the need to provide updated, exhaustive information on different thin film PV technologies that will rapidly find widespread use. However, there are entire volumes on *each* of the seven chapters of the present book.

Using therefore a concise style and numerous illustrations, the nanochemistry of thin film photovoltaics is discussed, along with relevant industrial/market information that is generally difficult to retrieve. An effort has been made to focus on the practical aspects of flexible solar cells, discussing their application in some detail. As we think in words, we have tried to "look after commas [4]" and use correct language to enable readers to think carefully about an important topic.

Our web site (qualitas1998.net) complementing the book has additional supplemental materials online. Readers will tell whether we have succeeded in producing a book that, as is our intention, should act as a lasting reference of scientific and practical usefulness in the field of solar energy.

Palermo, September 2008

Mario Pagliaro
Giovanni Palmisano
Rosaria Ciriminna

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Contents

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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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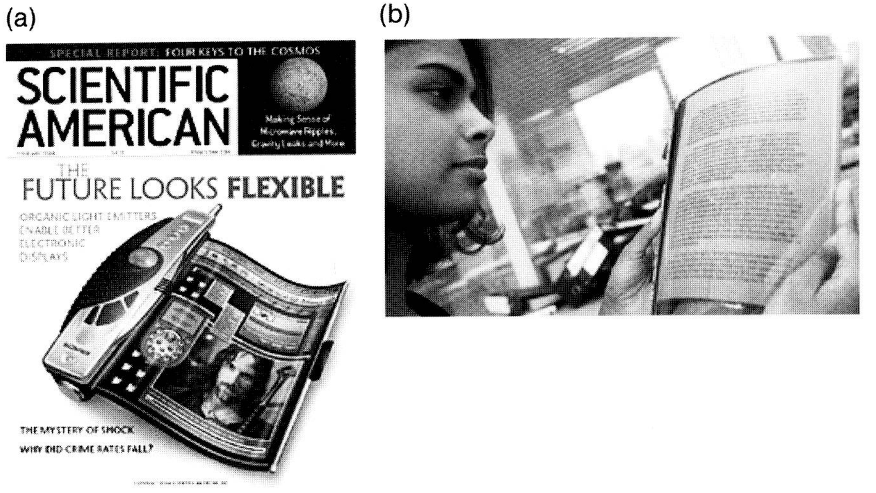

Figure 1.1 Long awaited flexible electronics ((a) shows the cover of *Scientific American* for February 2004) is now a reality with OLED displays (b) enabling ubiquitous, comfortable reading (Photo courtesy: Plastic Logic).

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

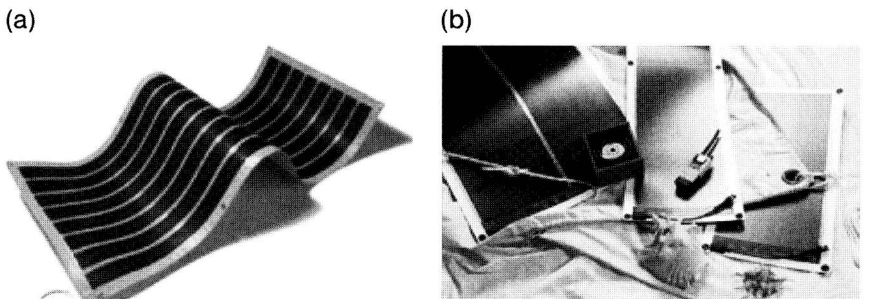

Figure 1.2 Plastic solar cells such as (a) that entirely organic (Photo courtesy: Konarka) or (b) that using amorphous Si (Photo courtesy: Flexcell) are lightweight (25–50 g m^{-2}), and ideally suited for customized integrated solutions.

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

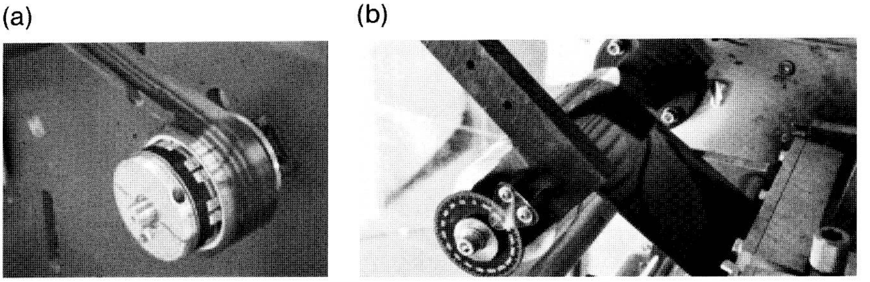

Figure 1.3 (a) Roll-to-roll manufacturing of photovoltaic Plastic Power (photo courtesy: Konarka) is analogous to (b) ink printing of semiconductor CIGS on aluminum foil (photo courtesy: Nanosolar).

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).

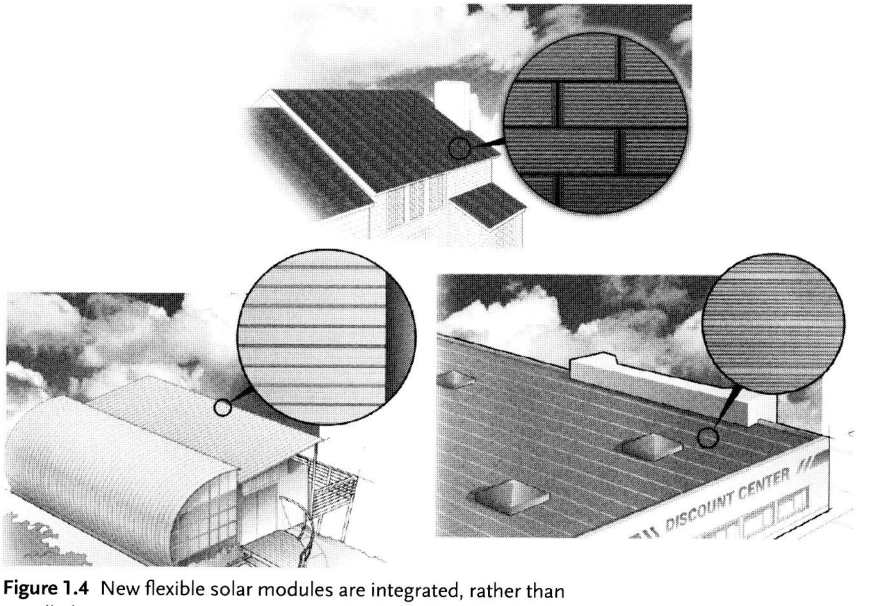

Figure 1.4 New flexible solar modules are integrated, rather than installed, into existing or new buildings (adapted from Konarka).

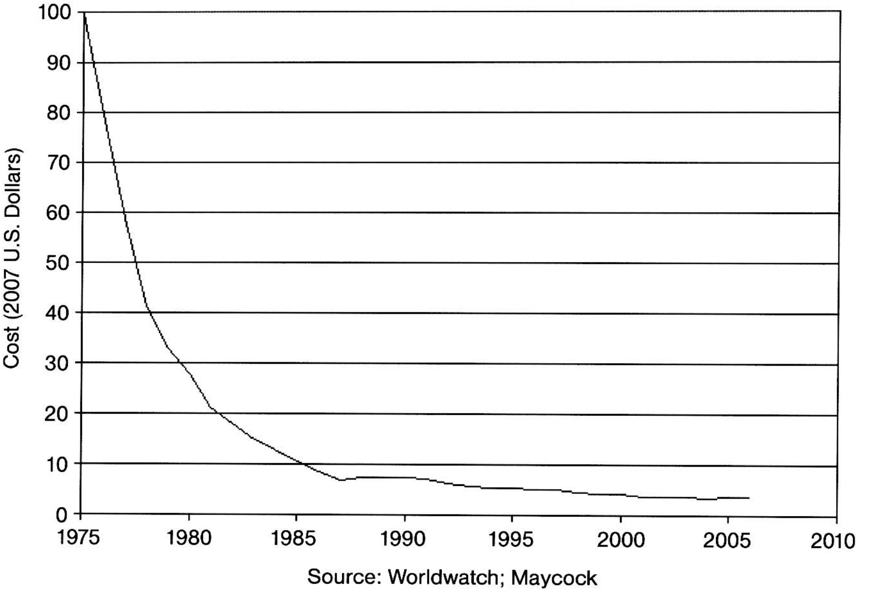

Figure 1.5 Average cost per watt of PV module 1975–2006. (Source: Earth Policy Institute, 2007).

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].

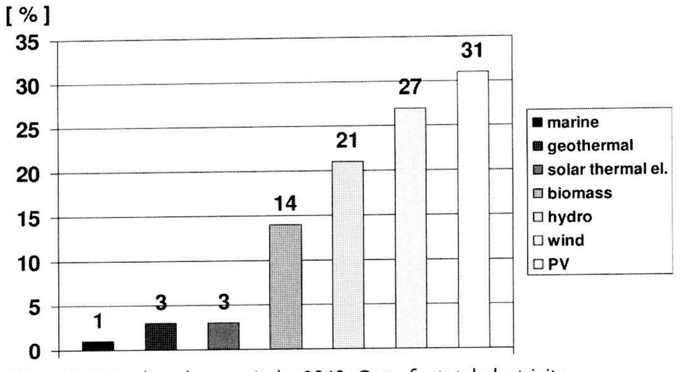

Figure 1.6 Predicted scenario by 2040. Out of a total electricity consumption of 36.346 TWh (from 15.578 TWh in 2001, IEA) renewable energy sources will cover 29.808 TWh, with solar energy becoming largely predominant. (Source: EREC).

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.