STATE OF THE ART OF PHOTOVOLTAICS

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1. INTRODUCTION

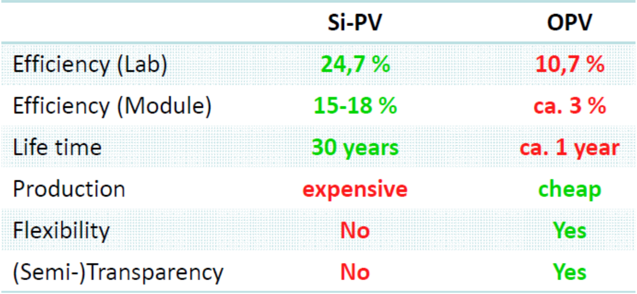
The PV effect was discovered in 1839 by Becquerel; solar cells developed rapidly only in the 1950s owing to space programs and used on satellites (crystalline Si, or c-Si, solar cells with efficiency of 6–10%). The energy crisis of the 1970s greatly stimulated research and development for PV. Solar cells based on compound semiconductors (III–V and II–VI) were first investigated in the 1960s. At the same time, polycrystalline Si (pc-Si) and thin-film solar cell technologies were developed (Fig. 2).

Current energy systems are locked into carbon-intensive energy sources, while many consumers use energy inefficiently, which create powerful inertia against change. And the political economy of implementing the policies necessary to make the transition is fraught with challenges. The reality of the marketplace will be more dynamic, uncertain and disruptive to existing business models than predicted by equilibrium economics.

Global demand for energy[1] is increasing rapidly, because of population and economic growth, especially in emerging market economies. Increased energy efficiency and the use of renewable energies are important measures to tackle these challenges. The environmental imperative to reduce CO_2 emissions in the energy sector coincides with a looming new investment cycle in power generation in most OECD countries. A large-scale transformation of the global energy sector is possible, although it will require significant investment [2]. By acting now, long-term costs can be reduced[2].

Solar electricity is more expensive than that produced by traditional sources. But over the past two decades, the cost gap has been closing. Solar photovoltaic (SPV) technology has emerged as a useful power source of applications such as lightning, meeting the electricity needs of villages, hospitals, telecommunications, and houses. Now PV technology is being increasingly recognized as a part of the solution to the growing energy challenge and an essential component of future global energy production. Cost, in terms of $/W, remains the greatest barrier to further expansion of PV generated power and cost-reduction is the prime goal of the PV sector.

Although photovoltaics[3] (PV) still has a small share, it is the fastest growing renewable[4] technology. In September 2009, the European Commission designated photonics as one of five key enabling technologies for our future prosperity. The technology roadmap of the next generation PV and OLED (organic light emitting diodes) promises new cheap, flexible and organic membranes, which will open new markets for mobile applications. Light plastics (= OLED) and power plastics (= organic photovoltaics – OPV) will probably merge into a hybrid membrane which will make it possible to transform light into power and vice versa (Fig. 1). Imagine a smart phone being charged with the little



	Si-PV	OPV
Efficiency (Lab)	24,7 %	10,7 %
Efficiency (Module)	15-18 %	ca. 3 %
Life time	30 years	ca. 1 year
Production	expensive	cheap
Flexibility	No	Yes
(Semi-)Transparency	No	Yes

Figure 1. Comparison Si-PV and OPV (after [3]).

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[1] At earth's surface average solar energy is ~$4x10^{24}$ J/year; global energy consumption in 2001 was ~$4x10^{20}$ J/year (increasing ~2% annually).

[2] Every US dollar that is not spent on investment in the energy sector before 2020 will require an additional USD 4.3 to be spent after 2020 to compensate for increased greenhouse gas emissions by building zero-carbon plants and infrastructure by 2035 [2].

[3] Photovoltaics (PV), also called solar cells, are electronic devices that convert sunlight directly into electricity. The modern form of the solar cell was invented in 1954 at Bell Telephone Laboratories.

[4] Renewable power generation can help countries meet their sustainable development goals through provision of access to clean, secure, reliable and affordable energy. Renewable energy has gone mainstream, accounting for the majority of capacity additions in power generation today. Tens of GW of wind, hydropower and solar photovoltaic capacity are installed worldwide every year in a renewable energy market that is worth more than a hundred billion USD annually. Other renewable power technology markets are also emerging. Recent years have seen dramatic reductions in renewable energy technologies' costs as a result of R&D and accelerated deployment. Yet policy-makers are often not aware of the latest cost data.

Nowadays, sensors are embedded in every smart application. While applications are increasingly becoming smarter, these tiny photonics devices can have major impacts. They are an enabler for reduced power consumption (think for instance of light management). And lasers improve efficiency by automated inspection. Optical communication technologies such as glass fibres lead to higher bandwidth and reduce power consumption at the same time.

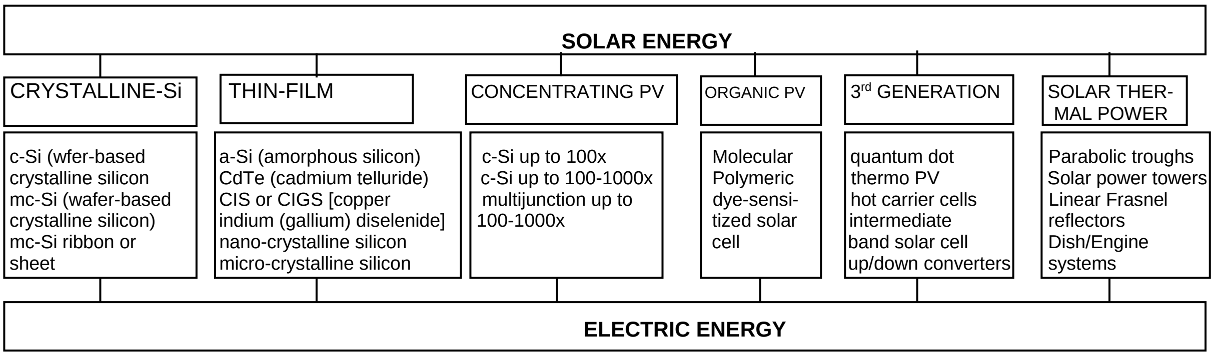

Figure 2. Solar technologies (after [9]).

Humans absorb more than 70% of information through light. Light is a universal tool and often provides revolutionary solutions. Though already significant solar energy[5] will become truly mainstream when it's $/W is comparable to other energy sources; at the moment it is around 4 times too expensive.

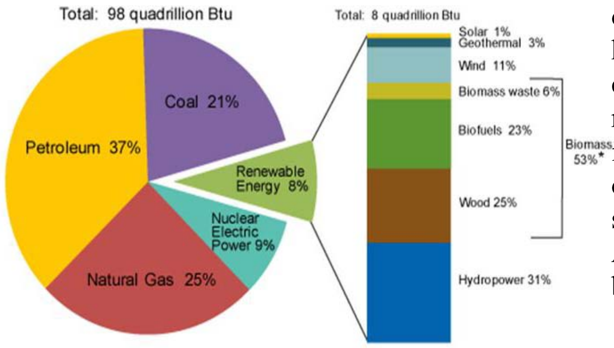

Figure 3. The market share of solar energy in USA today [4]. A Btu (British thermal unit) is the amount of heat energy required to raise 1 pound of water by 1 degree.

Within the Kyoto Protocol the EU committed itself to a reduction of at least 20% in greenhouse gases by 2020, rising to 30% if there is an international agreement committing other developed countries to "comparable emission reductions and economically more advanced developing countries to contributing adequately according to their responsibilities and respective capabilities."

The high reliabilities associated to PV modules are indirectly reflected in the output power warranties usually provided in this industry, which are currently in the range of 25 years, and may reach 30 years in a near future. (Forty-year module lifetimes may not sound as exciting as new photovoltaic materials, but it's essential to make solar power economic). Reliability evaluation based on degradation models is commonly applied in highly reliable products as a cost effective and confident way of evaluating their reliability. This reliability, the increasing potential of electricity interruption from grid overloads, as well as the rise of electricity prices from conventional energy sources, add to the attractiveness of PV systems. About 80% of the current production uses wafer-based crystalline silicon technology[6] [5]

PV modules can degrade their performance as a result of different factors such as: Degradation of packaging materials; loss of adhesion of encapsulants; degradation of cell/module interconnection; degradation caused by moisture intrusion; degradation of the semiconductor device [6].

The degrading reliability levels of each national grid are early warning signs of the need for a major technology shift. The negative impacts of current electric power production and declining levels of reliability will not be changed overnight; the process is complex and will involve many affected parties.

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[5] The solar energy occupies a small fraction of the current energy mix – about 0.01 percent for whole world. Developed country like the United States may have a little bit higher shares (Fig. 3).

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

There is scepticism on the reliability and reproducibility of the device performance of organic photovoltaic cell (OPVC); that is why the accurate and reproducible performance of organic electronic devices should be systematically studied and addressed [7]. Additional layer of LiF dramatically improves the reliability and reproducibility of the OPVC.

Benefits of PV

- Solar power is a renewable resource that is available everywhere in the world.
- Solar PV technologies are small and highly modular and can be rapidly installed and used virtually anywhere, unlike many other electricity generation technologies.
- Unlike conventional power plants using coal, nuclear, oil and gas; solar PV has no fuel costs and relatively low operation and maintenance (O&M) costs. PV can therefore offer a price hedge against volatile fossil fuel prices.
- PV, although variable, has a high coincidence with peak electricity demand driven by cooling in summer and year round in hot countries.
- Ambient temperature operation.
- No moving parts.
- High reliability over 30+ years.
- No emissions, combustion or radioactive waste.

Disadvantages of PV

- Fuel source is diffuse (sunlight is a relatively low-density energy);
- High initial (installed) costs;
- Unpredictable hourly or daily output;
- Lack of economical efficient energy storage.

Three generations devices

PV cell technologies are usually classified into three generations, depending on the basic material used and the level of commercial maturity [7]. *(i) First-generation* PV systems (fully commercial) use the wafer-based crystalline silicon[7] (c-Si) technology, either single crystalline (sc-Si) or multicrystalline (mc-Si). PV production is currently 90% "first-generation" solar cells that rely upon expensive bulk multi-crystalline or single crystal semiconductors. Dominated by silicon wafers they are reliable and durable but expensive. First-generation solar cells dominate the market with their low costs and the best commercially available efficiency. *(ii) Second-generation* PV systems (early market deployment) are based on thin-film PV technologies and generally include three main families: (1) amorphous (a-Si) and micromorph silicon (a-Si/μc-Si); (2) cadmium telluride (CdTe); and (3) copper indium selenide (CIS) and copper indium-gallium diselenide (CIGS). It reduces the active material cost, eventually the substrate will be the cost limit and higher efficiency will be needed to maintain the $/W cost reduction trend. Second-generation thin-film PV technologies are attractive because of their low material and manufacturing costs, but this has to be balanced by lower efficiencies than those obtained from first-generation technologies. *(iii) Third-generation* PV systems include technologies, such as concentrating PV (CPV) and organic PV (OPV) cells that are still under demonstration or have not yet been widely commercialized, as well as novel concepts under development. "Third generation" devices will utilise new technologies to produce high-efficiency devices. Other organic or hybrid organic / conventional (DSSC) PV technologies are at the R&D stage. They offer low efficiency, but also low cost and weight, and free-form shaping. Therefore, they could fill niche markets (e.g. mobile applications) where these features are required [8].

During many years, PV industry was based on the niche applications of powering satellites and remote locations. The tide has changed dramatically with growing recognition of the environmental impact of non-renewable energy sources and the economic volatility that comes from reliance upon oil.

Half of the cost of first-generation devices is the silicon wafer and efficiencies are limited to around 20%. Instead of using wafers, a cheaper "second-generation" of solar cells would use cheap semiconductor thin-films deposited on low-cost substrates to produce devices of similar efficiencies. As "second generation" technology reduces the active material cost, eventually the substrate will be the cost limit and higher efficiency will be needed to maintain the $/W cost reduction trend. "Third generation" devices will utilise new technologies to produce high-efficiency devices.

Tremendous advances outside the photovoltaic industry, in nanotechnologies, photonics, optical metamaterials, plasmonics and

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[7] The efficiency of crystalline silicon modules ranges from 14% to 19%. The highest efficiency for a PV material is usually the "laboratory" efficiency, where optimum designs are tested. PV cell efficiencies are less than this, because compromises are often required to make affordable cells. Module efficiency is somewhat lower than cell efficiency, given the losses involved in the PV module system.

semiconducting polymer sciences[8] offer the prospect of cost competitive photovoltaics based on new science and third-generation concepts. Within the next some 20 years it is reasonable to expect that cost-reductions, a move to second generation technologies and implementation of some new technologies and third-generation concepts can lead to fully cost competitive solar energy. Cost, in terms of \$/W, remains the greatest barrier to further expansion of PV generated power and cost-reduction is the prime goal of the PV sector.

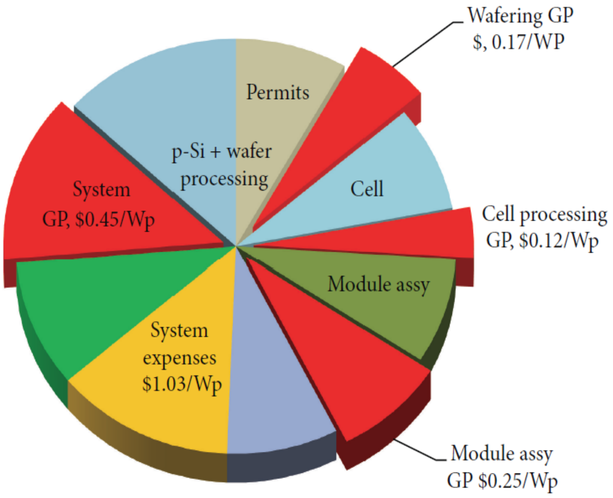

Figure 4. Price/watt (\$/W_p) of crystalline installed PV in the world market 2008-2011. W_p = Watt peak. [10].

The *first generation* (1G) technology is based on screen printing based device similar to that shown in figure 3. 1G silicon PV benefited greatly from its symbiosis with the IC industry which provided the materials, processing know-how, and manufacturing tools necessary to allow a rapid move to large scale production. The single crystal wafer silicon efficiencies is situated in the 18-21% range offering the potential for lower \$/W. But the multi-crystalline silicon (mc-Si) currently accounts for 63% of the world market, including manufacturers with cell efficiencies around 13-14%, at overall lower \$/W cost.

1G PV costs around US\$ 4/W, and this is still around 4 times too expensive for truly competitive commercial production.

Second generation (2G) PV technologies are single junction devices that aim to use less material whilst maintaining the efficiencies of 1G PV. 2G solar cells use amorphous-Si (a-Si), CuIn(Ga)Se_2 (CIS), CdTe/CdS) or polycrystalline-Si (p-Si) deposited on low-cost substrates such as glass (Figure 4). In the last 10 years, CdTe module efficiency increased from 7 % to 11 %.

CdTe, CIS and a-Si absorb the solar spectrum much more efficiently than c-Si or mc-Si and use only 1-10 μm of active material. The new technology p-Si produces ~11% efficient devices using light-trapping schemes to increase the effective-thickness of the silicon layer.

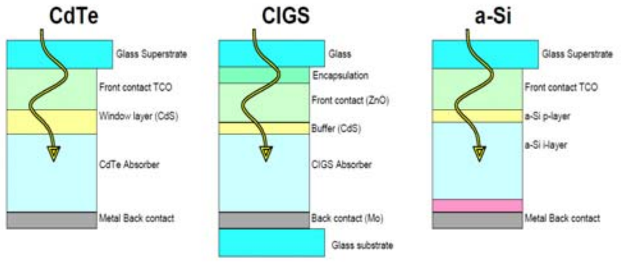

Figure 5. Schematic diagrams of thin-film CdTe, CIGS, and a-Si thin-film PV devices (after [11]).

Compared to 1G, the 2G PV offers the potential to slash costs, financial pay-back and energy pay-back times (the potential of thin-film PV is 16.5% for CdTe, and 18.4% for CIGS, but PV based on CdTe and CIGS has been slow to scale-up – Fig. 5). Given the impressive progress by thin-film silicon over the last few years, it seems that the potential of 2G is most likely to be realised by silicon based thin-film devices, bolstered by the development of production tools for the flat panel display sector.

The future is for *third generation* (3G) devices which exceed the limits of single junction devices and lead to ultra-high efficiency for the same production costs of 1G/2G PV, driving down the \$/W [12]. There are four types of third-generation PV technologies: *(i)* Concentrating PV (CPV); *(ii)* Dye-sensitized solar cells (DSSC); *(iii)* Organic solar cells; and *(iv)* Novel and emerging solar cell concepts.

The progress in PV technology should be measured in \$/W. Two routes can be possible to cheaper PV energy: The first is based on the pragmatic use of new technology to improve the performance or decrease the cost of current devices. The second might involve new whole device concepts. So, in recent years we have seen the emergence of *dye-sensitized*[9] [13], and polymer based solar cells (including organic/inorganic hybrids) [14, 15] as fundamentally new types of device; there is every chance that these devices might still demonstrate step-change improvements.

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[8] Poor durability and low efficiency have been key disappointments with polymer solar cells.

[9] Dye-sensitized cells still face difficult issues related to poor charge mobility and device stability.

There are different approaches to reduce the levelized costs of electricity from photovoltaics. On one hand, module costs decrease due to economies of scale, less material and energy consumption, or the use of cheap materials. On the other hand, system costs can be reduced by an increase in module efficiency, which also provides the advantage of smaller systems and less use of area. Hence, all components of a high-concentration photovoltaics (HCPV) system have to be further developed to reach highest efficiencies. Large progress can be observed, especially in the field of III–V multijunction solar cells[10], where record efficiencies above 41% have been reported by different groups in 2009 [16, 17]. However, despite the high concentration levels, the solar cell still represents up to 20% of the overall costs of a HCPV system [18]. Therefore, a key element for further energy cost reduction is a highly efficient multijunction solar cell. The state-of the art approach for highly efficient photovoltaic energy conversion is marked by the Ga0:50In0:50P/ Ga0:99In0:01As/Ge structure. This photovoltaic device is today well established in space applications and recently has entered the terrestrial market [19].

The biggest losses are due to the nature of the photovoltaic effect itself, because of the large volume of infra-red light that has insufficient energy to raise an electron into the conduction band (sub-bandgap losses) and because high energy photons can only raise one electron to the conduction band and wasting excess energy by heating the solar cell (hot-electron or thermalisation losses). These fundamental losses directly lead to an efficiency limit of ~ 40% for all commonly used semiconductors and 43.9% for single junction silicon solar cells. 3G concepts aim to harness some of this wasted energy.

Emerging technologies encompass advanced thin-films[11] and organic cells.

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

Novel PV concepts aim at achieving ultra-high efficiency solar cells via advanced materials and new conversion concepts and processes. They are currently the subject of basic research (wafer-based c-Si and thin-films). The levelized cost of electricity (LCOE) of utility-scale systems for both thin film and c-Si could decline to between USD 0.06 and USD 0.10/kWh by 2020. Under the International Energy Agency (IEA) scenario, the LCOE of PV systems will not reach grid parity in most countries until after 2020.

A new technique for producing nanowire meshes using the power of light could open up a range of applications including transparent solar panel coatings [22]. (Nanowires NW are being developed as a vital component for quantum computing - the smallest ever silicon nanowire is in the works).

The authors of paper [23] have developed highly efficient (12.8%) nanowire solar cells by employing a self-aligned selective emitter structure without costly optical patterning.

There are a number of novel solar cell technologies under development that rely on using quantum dots/wires, quantum wells, or super lattice technologies [24, 25]. These technologies are likely

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[10] The biggest problem for high-efficiency multijunction and GaAs cells is the high cost of the materials.

[11] Thin-film solar cells comprised successive thin layers, just 1 μm to 4 μm thick, of solar cells deposited onto a large, inexpensive substrate such as glass, polymer, or metal. As a consequence, they require a lot less semiconductor material to be manufactured in order to absorb the same amount of sunlight (up to 99% less material than crystalline solar cells). In addition, thin-films can be packaged into flexible and lightweight structures, which can be easily integrated into building components (Building-Integrated PV, BIPV). These are photovoltaic materials that are used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or façades. The advantage of BIPV is that the initial cost can be offset by reducing the amount spent on building materials and labor that would normally be used to construct the part of the building that the BIPV modules replace. These advantages make BIPV one of the fastest growing segments of the photovoltaic industry. Rather than using polysilicon, these cells use thin layers of semiconductor materials like amorphous silicon (a-Si), copper indium diselenide (CIS), copper indium gallium diselenide (CIGS), or cadmium telluride (CdTe). A thin photoactive film is deposited on a substrate, which can be either glass or a transparent film. Afterwards, the film is structured into cells. Unlike crystalline modules, thin-film modules are manufactured in a single step. Thin-film systems usually cost less to be produced than crystalline silicon systems but have substantially lower efficiency rates [20]. On average, thin-film cells convert 5%–13% of incoming sunlight into electricity, compared to 11%–20% for crystalline silicon cells. However, as thin film is relatively new, it may offer greater opportunities for technological improvement.

The silicon photovoltaic (PV) module has reached mature commercial status, capturing 86% of the global PV module market in 2011, with manufacturers offering very similarly configured, essentially interchangeable product designs. As a result of rapidly declining prices for silicon modules, the competing thin-film (TF) module market is experiencing a hiatus in manufacturing expansion. Many TF companies have curtailed expansion plans and several have actually gone bankrupt. New thin film products will struggle to gain bankability acceptance on the level of silicon products. [21]

to be used in concentrating PV technologies where they could achieve very high efficiencies by overcoming the thermodynamic limitations of conventional (crystalline) cells. However, these high-efficiency approaches are in the fundamental materials research phase. Furthermore from the market are the novel concepts, often incorporating enabling technologies such as nanotechnology, which aim to modify the active layer to better match the solar spectrum [26].

Organic-inorganic hybrid solar cells

These cells are typically thin film devices consisting out of photoactive layer(s) between two electrodes of different work functions. High work function, conductive and transparent indium tin oxide (ITO) on a flexible plastic or glass substrate is often used as anode. The photoactive light absorbing thin film consists out of a conjugated polymer as organic part and an inorganic part out of e.g. semiconducting nanocrystals (NCs). A top metal electrode (e.g. Al, LiF/Al, Ca/Al) is vacuum deposited onto the photoactive layer finally. A schematic illustration of a typical device structure is shown in Fig. 6 (**a**). Generally there are two different structure types for photoactive layers – the bilayer structure [(Fig. 6 (**b**)] and the bulk heterojunction structure [(Fig. 6 (**c**)].

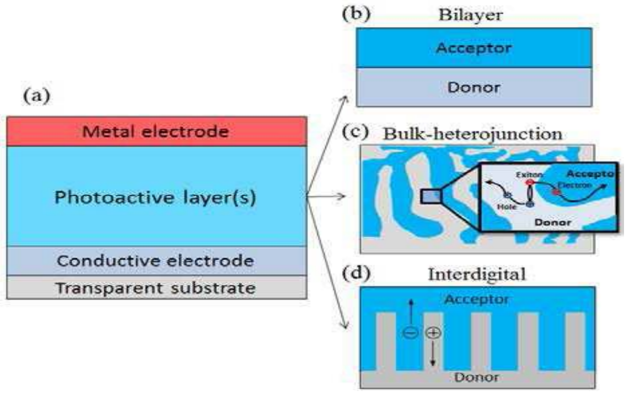

Figure 6. Schematic illustration of typical device structures for hybrid solar cells [27].

In hybrid solar cells, photocurrent generation is a multistep process. Briefly, when a photon is absorbed by the absorbing material, electrons are exited from the valance band (VB) to the conduction band (CB) to form excitons. The excitons diffuse to the donor/acceptor interface where charge transfer can occur leading to the dissociation of the excitons into free electrons and holes. Driven by the internal electric field, these carriers are transported through the respective donor or acceptor material domains and are finally collected at the respective electrodes. To sum up, there are four main steps: photon absorption, exciton diffusion, charge separation as well as charge carrier transport and collection. The physics of organic/hybrid solar cells is reviewed in detail elsewhere [28, 29].

Green Photonics

'Green photonics' [30] is the term used to encompass the application of photonics technologies that can generate or conserve energy, cut greenhouse gas emissions, reduce pollution, or yield environmentally sustainable outputs. Green photonics covers a broad range of photonic technologies and applications: photovoltaic electricity generation, highly efficient solid-state lighting (SSL), new energy-efficient communication technologies, optical sensing for improved energy efficiency and reduced pollution, and clean manufacturing using laser processing. Green photonics will impact the product design and manufacturing PV processes employed.

Green photonics is already a key technology for improving the global balance of atmospheric carbon dioxide and will become increasingly important in the decades to come. In spite of the recent recession the overall market demand for green photonics technology is expected to achieve a 2009-2020 compound annual growth rate (CAGR) of ~20% on average [31]. Significant drivers within the sector will be solid-state lighting and solar photovoltaics, where figures of 35% and 30% respectively for the 2009-2020 CAGR are predicted. These predictions show that green photonics will be a driver for profitable growth and so further stimulate employment. Europe is leading the world in solid-state lighting and photovoltaic technologies, and their system applications.

While fossil and nuclear-fuelled electric systems have an overall energy conversion efficiency that is quite low (<30%), greener alternatives remain less cost-effective or lack technological readiness for the reliability required by such an important global infrastructure.

Green growth strategies aim to build upon the complementarities between economic and environmental policy, taking into account the full value of natural capital as a factor of production and its role in growth. Energy efficiency is probably one of the main keys to long-term environmental sustainability. Greening energy will be among the earliest drivers of greener growth. Meeting growing energy demand will mean a total investment in the sector of USD 270 trillion over the next four decades [32].

Sustainability

Sustainability can be defined as ensuring that the needs of the present are met without compromising the ability of future generations to meet theirs. Thus sustainability not only includes products that have positive impact on the environment but rather comprises three categories of impact that are essential for the wealth of the society, i.e. ecological, economic and societal impact. Photonics will contribute to sustainability by offering improved environmental, economic and societal benefits (termed eco-efficiency) in three main areas: industrial design, products and production techniques [33].

"*Green*" or "*sustainable*" buildings use key resources like energy, water, materials, and land more efficiently than buildings that are just built to code. With more natural light and better air quality, green buildings typically contribute to improved employee and student health, comfort, and productivity. On average, green buildings use 30% less energy than conventional buildings. Green buildings provide financial benefits that conventional buildings do not.

To truly become green and play a major role in society's chosen path toward global sustainable development will require a major shift in the present centralized, base-loaded, fossil fuel paradigm toward a dispersed, multi-technologic, renewable-supported system of significantly greater complexity.

Strong public policy in shaping more sustainable futures for electric power will be required as has been demonstrated by the successes of several European nations and Japan. The solution to this complex issue will require a multi-faceted technological approach supported by strong public policy incentives [34]. *Renewables + increased efficiency = sustainability.*

Organic Photovoltaics OPV

OPV are less mature than conventional silicon based photovoltaic materials, but offer a number of highly attractive features, not least of which is the prospect of mass production of thin-film plastic solar cells. Organic solar cells (OSCs) are regarded as low-cost and potentially environmentally benign sources of power. Reel-to-reel fabrication offers large area production and substantially lowered costs, and would transform the range of deployment options for energy generation installations. To cope with the future energy demands of cities, huge areas of solar cells will be required, too large to be contemplated with conventional silicon-based PV. The big attraction of OPV technology is the potential for applying it directly in thin-film form to many urban surfaces, including windows and facades, without interfering with the existing functionalities of these building elements, thereby making it feasible to match accessible energy-harvesting capacity with energy consumption needs. Since more than 40% of global energy use derives from the requirements of buildings, this technology could have a dramatic impact.

The second major application for organic photovoltaics is in the mobile devices market, where the ability to integrate a thin film, flexible energy generating layer onto the device itself or serving as a portable foil, would have major implications towards becoming less dependent on the availability of electric current.

OSCs have achieved efficiencies in the research laboratory of ten percent. Great progress in this field has been driven by the development of new organic semiconductors that maximize the absorption of light and the transport of charge, transparent electrodes that do not rely on rare and toxic elements, barrier materials that reduce the rate of photochemical degradation, and substrate materials that improve mechanical robustness. One aspect of organic solar cells that has received far less attention by the research community is the production energy, toxicity, and costs associated with synthesizing organic semiconductors at the scale required to satisfy even a small fraction of the growing worldwide need for energy.

OSCs typically comprise a heterostructure of two types of semiconductors with offset frontier molecular orbitals (Fig. 7) [35]. This heterostructure is sandwiched between a low-work-function electrode (which collects the electrons) and a high-work-function electrode (which collects the holes). This sandwich-like structure sits on a thin substrate (*e.g.*, glass or polyethylene terephthalate, PET). Most, if not all, devices must be encapsulated to exclude water and oxygen. Upon the absorption of light, an electron is promoted in either the donor or the acceptor from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). Transfer of an excited electron in the LUMO of the donor to the LUMO of the acceptor produces free charge carriers. These carriers drift to opposite sides of the device, in part, because of the built-in electric field established by electrodes with different values of work function. This process is the basis of the photovoltaic effect in

OPV and other "*excitonic*" cells, and is in contrast to the mechanism of conventional solar cells, in which charge carriers are generated directly upon the absorption of photons, and are segregated by the internal field established by a p–n junction [36].

Organic photovoltaic cells are often cited for their potential to fulfill roles in unique applications such as wearable electronics [37], portable energy sources in the developing world [38], artificial retinas [39], and power generating polarizing filters [40]. Many of these applications are specifically targeted to the consumer market rather than to utility-scale generation of power. Considering the rate at which once-state-of-the-art consumer electronic devices are rendered obsolete by new models, it may be more important to minimize environmental impact than is it to maximize the lifetime - or even performance - of some devices for some applications.

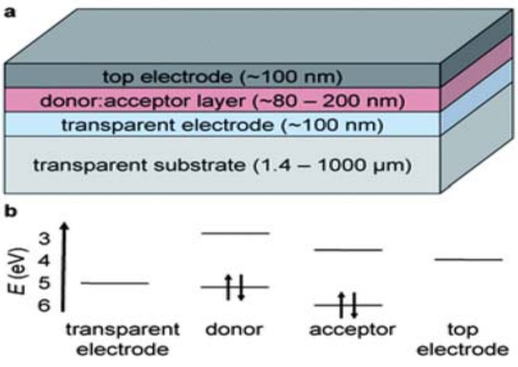

Figure 7. Schematic drawing and approximate energy levels of materials used in OSCs. ***(a)*** *A transparent substrate (not drawn to scale) supports a transparent electrode, a semiconducting layer comprising an electron donor and an electron acceptor, and a top electrode. In part **(b)**, the energy levels of the electrodes represent the values of work function, while the energy levels of the organic donor and acceptor represent the frontier molecular orbitals (highest occupied and lowest unoccupied molecular orbital, HOMO and LUMO). In the "conventional" geometry represented in the figure, the work function of the transparent electrode is higher than that of the top electrode; in the "inverted" geometry, the polarity is reversed [35].*

OSCs have the potential to show high efficiencies at low cost, as they exhibit favourable optical and charge generation properties, and are compatible with mass printing techniques. State-of-the-art record solar cells have almost reached 8% power conversion efficiency, and modules of above 200 cm^2 with 3.5%. Both are based on newly synthesised organic semiconductors [41]. For applications without the need for infrastructure such as inverters, low cost organic solar cells will be easier to realise.

A future vision envisaged for organic photonics will be the full integration of three functionalities; light generation (OLED), power generation (OPV) and digital processing (plastic electronics), into a single membrane. With such technology, it becomes possible to envisage readily applied membranes that provide a self-powering intelligent lighting system suitable for deployment in buildings, outdoor locations or vehicles [42].

The report [43] reviews the reliability of PV power plants and their components. The results focus on silicon-based PV technologies, but include available data on the smaller installed base of thin-film and concentration photovoltaics (CPV) modules.

Wireless nanosensor networks (WNSN)

WNSN will allow novel intelligent nanosensors to detect new types of events of the nanoscale in a distributed fashion over extended areas. Two main characteristics are important: their THz band wireless communication and their nanoscale energy harvesting process. WNSNs consist of nanosized communicating devices, which can detect and measure new types of events at the nanoscale. These networks are the enabling technology for unique applications such as intrabody drug delivery systems or surveillance networks for chemical attack prevention. One of the major bottlenecks in WNSNs is posed by the very limited energy that can be stored in a nanosensor mote in contrast to the energy that is required by the device to communicate. Recently, novel energy harvesting mechanisms have been proposed to replenish the energy stored in nanodevices. With these mechanisms, WNSNs can overcome their energy bottleneck and even have infinite lifetime (perpetual WNSNs), provided that the energy harvesting and consumption processes are jointly designed [44].

WNSNs will have a great impact in almost every field of our society ranging from healthcare to homeland security and environmental protection. Enabling the communication among nanosensors is still an unsolved challenge. The use of novel nanomaterials to build nano-antennas, nano-transceivers and nano-processors has pointed us to the terahertz band as the natural domain of operation of nanosensor devices. This frequency range supports very high transmission bandwidths in the short range. Despite nanosensor devices and networks are still in their very early stage, ICT are a key player in the development of this new paradigm. Many researchers are currently engaged in developing the hardware underlying future nanosensor devices [45].

In order to overcome their limitations, these nano-devices can be interconnected to execute more complex tasks in a distributed manner. The resulting nanonetworks are envisaged to expand the capabilities and applications of single nano-machines, both in terms of complexity and range of operation. Novel nanomaterials such as Carbon Nanotubes (CNTs) and Graphene Nanoribbons (GNRs) have been proposed as the building material of novel nano-antennas. Their development stems from the necessity of solutions which radiate in adequate frequencies. If we used the classical approach, antennas reduced to the nanoscale would radiate at extremely high frequencies, compromising the feasibility of the communication. The numerical results show that the electromagnetic (EM) wave propagation speed can be up to 100 times below that of speed of light in vacuum, for CNT and GNR in both edge configurations. For all this, a 1 µm long antenna radiates in the THz band (0.1 – 10 THz). Feasible input resistances are achieved with higher voltage or larger antenna dimensions [46].

Conclusions

Also resuming:

1st Generation : Crystalline silicon, relatively thick (100s µm); Higher efficiency, relatively expensive.

2nd Generation : Thin Film Technology (1 – 10 µms); Flexible, low cost, lower efficiency CdTe, CIGS, a-Si, DSC.

"Next Generation": Organic PV (OPV), plastic solar cells; Earth abundant inorganics (CZTS, pyrite) Quantum-dot (3rd Generation).

All technologies continue to grow: CdTe and Si growing fastest; other technologies getting squeezed.

Three possible future scenarios:

Status quo

Continued dominance by c-Si, mc-Si

CdTe an important component of utility market

Others: Niche markets in consumer/aerospace

Transition to new forms of crystalline silicon

Ribbon silicon

Ultrathin silicon

Breakthrough in thin film technology

CIGS: Compete with x-Si, CdTe in power sector

DSC: Consumer products, BIPV, selected climates

PV system prices have seen a slower decline than in the years before or even small increases, confirming that the speed of future cost reduction is likely reduced [49].

One key to the development of any photovoltaic technology is the cost reduction associated with achieving economies of scale. This has been evident with the development of crystalline silicon PVs and will presumably be true for other technologies as their production volumes increase. Worldwide production of terrestrial solar cell modules has been rapid over the last several years, with China recently taking the lead in total production volume [47].

Securing a solid future for photovoltaics requires both refining current technology to improve its cost, performance, and durability in the near future, and developing new materials for a new generation of technology.

More than 80% of the world PV industry is based on c-Si and pc-Si wafer technologies. Single-junction c-Si and GaAs solar cells are approaching their upper limits in terms of the theoretical maximum efficiency. Remarkable efficiency results have been achieved in the field of thin-film solar cells: 19–20% CIGS and 16–17% CdTe and Si polycrystalline thin-film solar cells. III–V multi-junction solar cells have obtained about 40% efficiency [48].

Perovskytes are much more cost-efficient than silicon PV-cells, don't contribute to global warming and are more flexible and manageable. Stacking perovskytes onto a silicon cell could boost the solar system's overall efficiency. In April 2016 the Hong Kong Polytechnic University (assembling a perovskite layer made of molybdenum trioxide, gold and molybdenum trioxide, each designed with an optimized thickness) realised the world's highest power conversion efficiency of 25.5% with the development of perovskyte-silicon solar cells [49].

References

1. ***Razykov T. M. et al.*** *Solar Photovoltaic Electricity: Current Status and Future Prospects, Solar Energy 85(2011), pp. 1580–1608.*

2. ***OECD & IEA.*** *Green Growth Studies; Energy, OECD Publishing, 2011.*

3. ***Organic Solar Cells*** *http://www.meerholz.uni-koeln.de/fileadmin/user_upload/Docs/Vorlesung/ Solar_cells_Handout. pdf*

4. Chu Y. (GENI) - Review and Comparison of Different Solar Energy Technologies, www.geni.org/globalenergy/.../review-and-comparison

5. Băjenescu T.-M. Advances and Trends in Photovoltaics (PV). EEA, Vol. 61, nr. 1(2013), pp. 7-13.

6. Quintana M. A., et al. Commonly Observed Degradation in Field-aged Photovoltaic Modules. Proc. of 29th Photovoltaic Specialists Conference, 2002; pp. 1436–1439.

7. Kim M.-S. Understanding Organic Photovoltaic Cells: Electrode, Nanostructure, Reliability, and Performance. Ph. D. Thesis, University of Michigan, 2009.

8. IRENA Working Paper 2012. Renewable Energy Technologies: Cost Analysis Series, Solar Photovoltaic Technologies, pp. 4-11.

9. Bosetti V. et al. The Future Prospects of PV and CSP Solar Technology. Review of Environment, Energy and Economics, Nota di lavoro 1/2012, www.feem.it/getpage. aspx?id=4401

10. Utpal G., Sukhendu J., Sayan D. State of Art of Solar Photovoltaic Technology. Conference Papers in Energy, Vol. 2013, Article ID 764132, 9 pages, http://dx.doi.org/10.1155/2013/764132

11. Boreland M., Bagnall D. Current and Future Photo-voltaics. users.ecs.soton.ac.uk/... /photovoltaics/Boreland%20an...

12. Green M. A. (publisher). Third Generation Photovoltaics: Advanced Solar Energy Conversion. Springer, 2006.

13. Gratzel M. Nature, vol. 414(2001), p. 338.

14. Kanicki J. In Handbook of Conducting Polymers, (T. A. Skotheim, editor); Dekker, New York, 1986.

15. Brabec C. J., Sariciftci S. N. Chemical Monthly, 132(2001), p. 421.

16. Guter W., Schöne J., Philipps S. P., Steiner M., Siefer G., Wekkeli A., Welser E., Oliva E., Bett A. W., Dimroth F. Appl. Phys. Lett. 94(22), 223504 (2009)

17. King R. R., Boca A., Hong W., Larrabee D., Edmondson K. M., Law D. C., Fetzer C. M., Mesropian S., Karam N. H. In Conference Record of the 24th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 21–25 Sep 2009, pp. 55–61

18. Lerchenmüller H., Bett A. W., Jaus J., Willeke G. In Conference Record of the 3rd International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, Scottsdale, AZ, USA, 1–5 May 2005, p. 6.

19. Simon P. Philipps, et al. Present Status in the Development of III–V Multi-Junction Solar Cells. In A. B. Cristóbal López, et al. (eds.), Next Generation of Photovoltaics, Springer Series in Optical Sciences 165, DOI 10.1007/978-3-642-23369-2 1, Springer-Verlag, Berlin and Heidelberg, 2012.

20. Efficiency. Which Measures the Percentage of the Sun’s Energy Striking the Cell or Module, is One Important Characteristic of a Solar Cell or Module. Over Time, Average Cell Efficiencies Have Increased, European Photovoltaic Industry Association, Solar Generation 6, Solar Photovoltaic Electricity Empowering the World, 2011.

21. Electrical Power Research Institute. Review of Photovoltaic System Reliability Challenges and Opportunities. 05 Dec. 2012, Product ID: 1024002.

22. Stanford sees the light with nanowire mesh; flexible and transparent electronics on the way. http://news.techeye.net/science/stanford-sees-the-light-with-nanowire-mesh

23. Um H.-D. et al. Incorporation of a self-aligned selective emitter to realize highly efficient (12.8%) Si nanowire solar cells. Nanoscale, 6(2014), p. 5193.

24. Nozik A. et al. Multiple Exciton Generation in Colloidal Quantum Dots, Singlet Fission in Molecules Quantum Dot Arrays, Quantum Dot Solar Cells, and Effects of Solar Concentration,” Presentation to the Symposium “Third Generations and Emerging Solar Cell Technologies, April 26-29, 2011, Golden CO.

25. Raffaelle R. P. Next Generation Photovoltaics. Presentation to the Symposium “Third-Generation and Emerging Solar-Cell Technologies”, April 26-29, 2011, Golden, CO.

26. Leung Siu-fung et al. Engineered Optical Absorption of Nano/Micro-pillar Arrays for Efficient Photovoltaics. Presentation to the Symposium “Third-Generation and Emerging Solar-Cell Technologies”, April 26-29, 2011, Golden, CO.

27. Zhou Y. et al. Organic-Inorganic Hybrid Solar Cells: State of the Art, Challenges and Perspectives. www.intechopen.com

28. Greenham N. C. Hybrid Polymer/ Nanocrystal Photovoltaic Devices, in Organic Photovoltaics (eds. C. Brabec, V. Dyakonov and U. Scherf), Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2008.

29. Saunders B. R., Turner M. L. Nanoparticle-Polymer Photovoltaic Cells. Advances in Colloid and Interface, 2008. Science, Vol. 138, Nr. 1, pp. 1-23, ISSN 0001-8686

30. The term Green Photonics is trademarked by the OIDA. (www.oida.org)

31. http://www.businesswire.com/news/home/20090324006339 /en/OIDA-Proposes-Criteria-Optoelectronics-Carbon-Economy -European

***32. IEA** (2011a), World Energy Outlook 2011 (WEO-2011), OECD Publishing, doi: 10.1787/weo-2011-en*

***33. Wessler B., Tober U.** Green Photonics – the Role of Photonics in Sustainable Product Design. In Proceedings- SPIE "The International Society For Optical Engineering," 2011, 8065; 8065 15 SPIE Eco-Photonics: Sustainable Design, Manufacturing, and Engineering Workforce Education for a Green Future Conference, https://getinfo.de/app/Green-photonics-the-role-of-photonics-in-sustainable/id/BLCP% 3ACN079692009*

***34. Jansson Peter M., Michelfelder Richard A.** Greening Electricity Infrastructures: Increasing System Complexity, Reliability and Sustainability. esd.mit.edu/symposium/pdfs/papers/jansson.pdf*

***35. Gregg B. A.** J. Phys. Chem. B, 107(2003), 4688–4698.*

***36. Gregg B. A.**, In Organic Photovoltaics: Mechanisms, Materials, and Devices, ed. S. S. Sun and N. S. Sariciftci, CRC Press, Boca Raton, FL, 2005, Ch. 6, pp. 139–159.*

***37. Krebs F. C., Biancardo M., Winther-Jensen B., Spanggard H., Alstrup J.** Sol. Energy Mater. Sol. Cells, 2006, 90, 1058–1067.*

***38. Krebs F. C., Nielsen T. D., Fyenbo J., Wadstrom M., Pedersen M. S.** Energy Environ. Sci., 2010, **3**, 512–525.*

***39. Ghezzi D., M. R.** Antognazza, R. Maccarone, S. Bellani, E. Lanzarini, N. Martino, M. Mete, G. Pertile, S. Bisti, G. Lanzani and F. Benfanati, Nat. Photonics, 2013 DOI:10.1038/ nphoton.2013.34.*

***40. Zhu R., Kumar A., Yang Y.** Adv. Mater., 2011, **23**, 4193–4198.*

***41. Deibel C., Dyakonov V.** Polymer–Fullerene Bulk Heterojunction Solar Cells. Progr. Phys. 73, 096401(2010)http://dx.doi.org/10.1088/0034-4885/73/9/096401;arXiv:[cond-mat.mtrl-sci]30 Aug 2010*

***42. Wessler B., Tober U.** Green Photonics – the Role of Photonics in Sustainable Product Design. In Proceedings- SPIE "The International Society For Optical Engineering," 2011, ISBN 9780819486516; 8065; 8065 15; SPIE Eco-Photonics: Sustainable Design, Manufacturing, and Engineering Workforce Education for a Green Future Conference, https://getinfo.de/app/Green-photonics-the-role-of-photonics-in-sustainable/id/BLCP% 3ACN079692009*

***43. Electrical Power Research Institute.** Review of Photovoltaic System Reliability Challenges and Opportunities. 05 Dec. 2012, Product ID: 1024002.*

***44. Jornet J. M., Akyildiz I. F.** Joint Energy Harvesting and Communication Analysis for Perpetual Wireless Nanosensor Networks in the Terahertz Band. IEEE Transactions On Nanotechnology, Vol. 11(2012), No. 3, pp. 570-580.*

***45. Akyildiz I.F., Jornet J.M.** Electromagnetic wireless nanosensor networks. www.elsevier.com/ locate/ nanocomnet.*

***46. Jornet J. M., Akyildiz I. F.** Graphene-Based Nano-Antennas for Electromagnetic Nanonetworks in the Terahertz Band. In Proc. of 4th European Conference on Antennas and Propagation, Barcelona, Spain, April 2010.*

***47. Gangopadhyay Utpal, et al.** State of Art of Solar Photovoltaic Technology. Conference Papers in Energy, Volume 2013, Article ID 764132, 9 pages, http://dx.doi.org/10.1155/2013/764132*

***48. Razykov T. M. et al.** Solar Photovoltaic Electricity: Current Status and Future Prospects. Solar Energy 85(2011), pp. 1580–1608.*

***49. IEA International Energy Agency.** Trends 2015 in Photovoltaic Applications, http://www.iea-pvps.org/ fileadmin/ dam/public/report/national/ IEA-PVPS_-_Trends_2015_-_MedRes.pdf*

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