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Renewable energy technologies and its adaptation in an urban environment

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Abstract. This general article is based on the inaugural talk delivered at the opening of OMTAT 2013 conference. It notes that the integration of renewable energy sources into living and transport sectors presents a daunting task, still. In spite of the fact that the earth and its atmosphere continually receive 1.7×10^{17} watts of radiation from the sun, in the portfolio of sustainable and environment friendly energy options, which is about 16% of the world's energy consumption and mostly met by biomass, only a paltry 0.04% is accredited to solar. First and second generation solar cells offer mature technologies for applications. The most important difficulty with regards to integration with structures is not only the additional cost, but also the lack of sufficient knowledge in managing the available energy smartly and efficiently. The incorporation of PV as a part of building fabric greatly reduces the overall costs compared with retrofitting. BIPV (Building Integrated photovoltaic) is a critical technology for establishing aesthetically pleasing solar structures. Infusing PV and building elements is greatly simplified with some of the second generation thin film technologies now manufactured as flexible panels. The same holds true for 3rd generation technologies under development such as, and *dye- and quantum dot- sensitized solar cells*. Additionally, these technologies offer transparent or translucent solar cells for incorporation into windows and skylights. This review deals with the present state of solar cell technologies suitable for BIPV and the status of BIPV applications and its future prospects.

Keywords: Renewable energy; integrated photovoltaic; Solar cells.

INTRODUCTION

Fossil fuels and other non-renewable energy sources are currently relied upon to meet the world's energy demand. Emission from the power industry alone was reported as 10.9 Giga tons of carbon dioxide equivalents ($GtCO_2e$) per year in 2005, which is about 24% of the global greenhouse gas (GHG) emissions. This is estimated to reach 18.7 $GtCO_2e$ per year by 2030[1]. In principle, renewable energy sources are more than enough to meet the entire world's energy demands without causing large CO_2 production and emission. Though all the available renewable energy cannot be harvested for use, technical estimates show that the scope is enormous based on the following capacities: Wind 14 TW, Tide/Ocean Currents 0.7 TW, Geothermal 1.9 TW, Hydroelectric 1.2 TW, biomass 5-7 TW and Solar 10^5 TW at earth's surface. Of this, solar energy is the most abundant, vast and nonpolluting renewable energy resource. There are three solar energy conversion options available: 1) solar thermal: converting photons to heat, 2) solar photovoltaic (PV): converting photons to electrons and 3) solar fuels: using photons chemically for example, water splitting, to store light energy in the form of clean fuels.

Presently, 16 % of the world's energy consumption is met by burning biomass in a traditional manner and only 2.8 % by modern renewable technologies (small hydro, biofuels, modern biomass, wave, wind, solar and geothermal) with only 0.04 % by modern solar energy conversion methods. PV is the most promising eco-friendly technology to convert solar energy to electricity. With a solar flux of 1.1×10^5 TW, one hour of terrestrial incident irradiation is enough for a year of total energy consumption requirement[2]. Even if unusable areas such as large ocean masses are discounted, the true solar potential at the earth's surface is ~ 600 TW, which is ~ 42 times more energy available than the next most abundant renewable energy source, wind (14 TW).

The world's cumulative PV capacity surpassed 100-gigawatt (GW) installed electrical power mark, to reach just over 102 GW in 2012. This is capable of producing as much annual electrical energy as 16 coal or nuclear power plants of 1 GW each. Every year these PV installations save more than 53 million tons of CO_2. Globally, 31.1 GW of PV systems were newly installed in 2012, up from 30.4 GW in 2011. Currently, PV remains, after hydro and wind power, the third most important renewable energy source in terms of globally installed capacity. In fact, 17.2 GW of PV capacity were connected to the

grid in Europe alone in 2012, which still accounts for the predominant share of the global PV market, with 55% of all new capacity in 2012. In Europe, Germany remains as the top market with 7.6 GW of newly connected systems; followed by China with an estimated 5 GW; Italy with 3.4 GW; the USA with 3.3 GW; and Japan with an estimated 2 GW. The importance of PV in green energy conscious Europe is highlighted by the fact that for the second year in a row, PV was the number-one new source of electricity generation installed in Europe. The global annual market could reach anywhere between 48-84 GW in 2017, depending on various economic and policy factors governing the industry[3]. The scope for increasing the penetration of PV in different walks of life is enormous.

PV modules integrated into the building design e.g. as in roofs, walls, windows etc., known as building integrated photovoltaics (BIPV), perform as a functional part of the building to produce energy. The replacement of traditional building parts with PV systems reduce the cost compared to non-integrated PV installation, because it does not need further space for stand alone PV systems. BIPV can be considered in terms of PV foils, tiles, modules and glazings[1]. BIPV foil products are very important, as they are light and flexible. They are good to adapt to the weight constraints, which most roofs have and hence ideal for retro-installation. BIPV tile products can be part of roofs or form the entire roof itself. BIPV glazing products are now manufactured industrially to provide options for windows, roof or facades[1]. Over 40 % of total primary energy consumption worldwide is utilized in buildings causing around 24% of total green house gas emissions (when powered by conventional energy sources). These building related emissions can be reduced by up to 90% by 2050 by using more renewable energy applications for powering buildings, and both BIPV and solar thermal energy integrated BIPVT will have a predominant position in meeting this objective. Installations of building integrated energy systems, such as BIPV, BIPVT and total thermal energy management control systems, offer a green building concept, which minimises the energy requirement of buildings and reduces its operating cost. The entire or a substantial part of energy requirements in buildings such as electricity, heating and cooling can be fulfilled by these built-in renewable energy conversion and management systems. Installation can be by either partial or full by substituting some of the conventional building parts such as roofs, windows or facades. Tiles and glazing BIPV products may be used in opaque form as walls or roofs or in semi-transparent forms in walls, roofs or windows. Generally, BIPV should be installed on sloped or flat roofs and facades where most of the sunlight is available. The global market for BIPV is expected to grow from $\$1.8x10^9$ in 2009 to $\$8.7x10^9$ in 2016, according to consulting firm Nano Markets, NewYork[1]. For BIPV to succeed in large market scale they need to be significantly improved in terms of meeting low cost, high efficiency and physical flexibility in large area modules. Dye- and Q-dot-sensitized solar cells as well as organic photovoltaics (OPV) and other emerging technologies have the potential to adapt to the BIPV market. These technologies, which are still in research and developmental phase tending to semi-pilot level production stages are expected to create their own niche markets in the coming years, at a very low level compared to the global PV market. The European Photovoltaic Industry Association (EPIA) expects such technologies to make a stronger presence by the second half of this decade, assuming that current R&D effort will push down the costs, around 10 times higher today than conventional PV, and adapt them better to new customer needs to be served, possibly BIPV or totally new uses such as the automotive industry[3]. The use of polymers with superior properties and development of cheap processing techniques can be an asset in this regard. Though the emerging technologies such as organic photovoltaics (OPV), sensitized solar cells and the various hybrid nano-architectured based PV devices show promising energy conversion efficiencies reaching 10 – 15% with small area laboratory cells and have the potential to produce highly efficient modules, translating those efficiency figures to stable large areas at module production levels is yet to be successfully demonstrated. Various weathering parameters must also be considered when new materials for BIPV are developed. Some examples are, but not limited to, are continuous temperature variations, wind and humidity factors, pollution levels, physical and mechanical strains due to loads, varying solar radiation intensities, shades and heating caused by infra-red (IR) radiations. Equally important is that the PV raw materials continue to be cheap and readily available with low environmental impact, backed up through a life cycle analysis (LCA) study and low energy payback time. Presently, the energy payback for PV systems in Germany is reported to be in the range of 5.6-6.2 years (mono-crystalline silicon), 4.2-4.75 years (poly-crystalline silicon), 3.6-4.1 years (CIS), 3.0-3.75 years (amorphous silicon) and 2.7-3.3 years (CdTe)[1]. Such figures backed up by experience is yet to be ascertained for the new and emerging PV technologies such as OPV and sensitised solar cells, as these are untested in large scale commercial applications in sufficient numbers.

DEFINITIONS OF ZEB

There are different terminologies used for describing or rating energy and resources sustainability factors pertaining to buildings. The ultimate objective of a zero energy building or zero emission building is based on its energy and resources consumption and GHG emissions behaviour. A building, which is optimally energy efficient and satisfies its energy demand on site through renewable resources to a great extent is considered as a zero energy building (ZEB). If a building is such that it does not release CO_2 or any green house gas to the environment because of consumption or utilization of energy in it, then it is a zero emission or zero net CO_2 emission or zero net carbon building. Other terms used in the same context are zero impact buildings and net zero energy buildings. Table 1 summarises these definitions. Presently, the economic viability mostly allows to design only Near ZEBs (NZEB) in practice.

TABLE 1. Definitions of Energy efficient buildings.

Term	Definition
Zero-energy building	Optimally energy efficient and satisfy the remaining energy demands to a greatest extent with on-site renewable sources
Zero emission building/ zero net CO2 emissions/ zero net carbon	Does not produce or release any CO_2 or other greenhouse gases to the atmosphere as a direct or indirect result of the consumption and utilisation of energy in the building or on the site
Zero impact building	No net environmental impact, based on a particular definition of environmental impact
Net zero energy emissions/ net zero energy building	Produces at least as much emissions-free renewable energy as it uses from emission-producing energy sources

RATING SYSTEMS FOR BUILDINGS

Different countries provide different levels of certification for buildings by assessment based on a set of key aspects (Table 2) such as its management, energy and water consumption, use of materials, site ecology, pollution factors, transport, land consumption etc. Some other aspects considered are indoor air quality, innovation and design, emission etc. The buildings certified are usually offices, schools, industrial and retails buildings.

PV TYPES

The main PV cell types available for use in BIPV are listed in Figure 1. Semiconductor based PV technology such as Si, CdTe, CIS and GaAs have the optimal bandgap energies ranging between 1.1 and 1.4 eV and ensuring the absorbance of a significant portion of higher energy fraction of the terrestrial solar spectrum. In these conventional inorganic semiconductor based solid state solar cells, electrical current generation is driven by the electric-field created in a depletion region, when the incoming photons with energies greater than or equal to the bandgap of the semiconductor are absorbed within the cell and consequently generating an electron-hole pair. The upper theoretical limit of efficiency, i.e., the thermodynamic limiting efficiency, for *p-n* junction solar energy converters has been calculated for ideal cases in which the only recombination mechanism of hole-electron pairs is radiative or for the case in which radiative recombination is only a fixed fraction f_c of the total recombination, the rest being non-radiative, with the sun and cell being assumed to be blackbodies with temperatures of 6000°K and 300°K, respectively. This Shockley-Queisser thermodynamic limit of energy conversion efficiency for single junction solar cells with a band gap of 1.1 eV (i.e., silicon, typically) works out to be 30%[4] and increased to 40 % for concentrator PV systems[5]. For tandem multi-junction devices, this thermodynamic limit tends to be higher depending on the number of multi-junctions.

Silicon (Si) based PV cells

Silicon (Si) is the most commonly used material for fabricating commercial PV modules. They are made from either mono-crystalline, polycrystalline, amorphous or ribbon cast polycrystalline Si. It is a matured technology and no major changes should be expected as far as the main products are concerned in the short to medium term. Mono-crystalline silicon cells have the highest efficiency among all Si commercial cells, reaching 20-25% power conversion efficiency range under direct AM1.5G standard sunlight irradiation conditions. They require high purity materials and quite large amounts of material with thicknesses of few hundred micrometres (200 microns, generally) needed to be effective absorbers of the incoming sunlight. This heavy usage of costly pure Si increases their module cost. The challenge here is to bring down the wafer thickness to 40 or 50 micrometers and thus reduce the cost considerably. The most efficient mono-crystalline PV module to date is reported to have 22.9 % efficiency for a 778 cm^2 area[6]. Polycrystalline cells are less expensive due to their easier manufacturing process, but are less efficient having only around 14-18 % efficiency[1].

TABLE 2. Rating systems adopted for buildings in different countries.

System (Country of origin)	DGNB (Germany)	BREEAM (Great Britain)	LEED (USA)	Green Star (Australia)	CASBEE (Japan)	Minergie (Switzerland)
Initiation	2007	1990	1998	2003	2001	1998
Key Aspects of Assessment & Versions	-Ecological Quality -Economical Quality -Social Quality -Technical Quality -Process Quality -Site Quality Purpose of the DGNB certificate: Application for building of any kind (Office high-rises, detached residential homes, Infrastructure building etc.) DGNB for: - Offices - Existing Buildings - Retail - Industrial - Portfolios - Schools	-Management -Health & Well-being -Energy -Water -Material -Site Ecology -Pollution -Transport -Land Consumption BREEAM for: - Courts - EcoHomes - Education - Industrial - Health care - Multi-Residential - Offices - Prisons - Retail	-Sustainable Sites -Water Efficiency -Energy & Atmosphere -Material & Resources -Indoor Air Quality -Innovation & Design LEED for: - New Construction - Existing Buildings - Commercial Interiors - Core & Shell - Homes - Neighbourhood Development - School - Retail	- Management - Indoor Comfort - Energy - Transport - Water - Material - Land Consumption & Ecology - Emissions - Innovations Green Star for: - Office-Existing - Buildings - Office-Interior Design - Office-Design	Certification on the basis of "building environment efficiency factor" BEE-Q/L Q...Quality (Ecological Quality of buildings) Q1-Interior space Q2- Operation Q3-Environment L...Loadings (Ecological Effects on buildings) L1-Energy L2-Resources L3-Material Main Criteria (1) Energy Efficiency (2) Resource Consumption Efficiency (3) Building Environment (4)Building Interior	4 Building standards are available (1) Minergie - Dense building envelop - Efficient heating system - Comfort ventilation (2) Minergie-P additional criteria to (1): -Airtightness of building envelop -Efficiency of household applicances (3) Minergie-Eco additional criteria to (1): - Healthy ecological manner of construction (optimized day light conditions, low emissions of noise and pollutants) (4) Minergie-P-Eco Adherence to criteria of Minergie-P and Minergie-Eco
Level of Certification	Bronze Silver Gold	Pass Good Very Good Excellent Outstanding	LEED Certified LEED Silver LEED Gold LEED Platinum	4 Stars: Best Practice 5 Stars: Australian Excellence 6 Stars: World Leadership	C (poor) B B+ A S (excellent)	Minergie Minergie-P Minergie-Eco Minergie-P-Eco

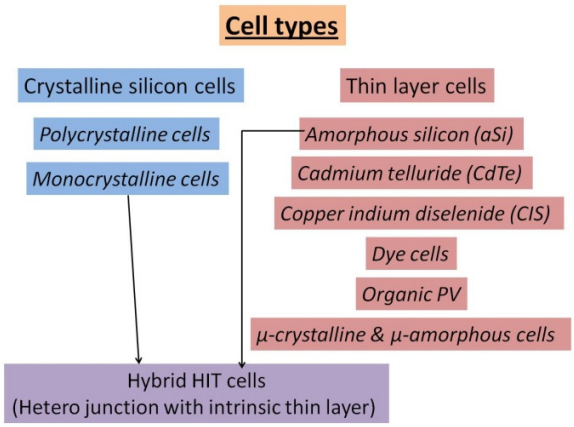


FIGURE 1: Types of photovoltaic cells.

Amorphous silicon (a-Si) cells falling under the thin film solar cells category are made up of a very thin layer of amorphous silicon deposited over a suitable glass or polymer substrate. They show efficiencies in the range of 4-13% in small cells, with record modules reaching over 10.0 %[6]. The power for mono and polycrystalline modules is in the range of 75-155 $Wp.cm^{-2}$ and for thin film modules it is 40-65 $Wp.cm^{-2}$ [1]. a-Si PV offers several advantages; it is a relatively simple technology, it is inexpensive with a high manufacturing output rate and for a given layer thickness a-Si:H, it absorbs much more energy than crystalline silicon (~2.5 times) and only much less material is required to manufacture cells (use approx 1% of the silicon needed for typical crystalline silicon cells, when materials wastage is also taken into account for the entire wafer technology production chain). This technology in fact yields lighter weight and less expensive PV modules. a-Si can be deposited on a wide range of substrates including flexible, curved and roll-to-roll types, which can not be done for crystalline silicon cases. However, the main disadvantages include lower energy conversion efficiency than crystalline silicon and high investment costs of manufacture involving a multi-layer approach. Serious light induced degradation of an a-Si device is often noticed. In a typical amorphous silicon solar cell the efficiency is reduced by up to 30% in the first 6 months as a result of the much studied Staebler–Wronski effect caused by metastable changes in a-Si:H material[7]. The observed changes were found to be reversible by annealing of a-Si:H samples at elevated temperatures (150 °C), and were attributed to a reversible increase in density of gap states acting as recombination centres for photoexcited carriers and leading to a shift of the dark Fermi level toward the midgap region[7]. To counter this effect, remedial solutions have been proposed, which includes using nanocrystalline Si, instead of amorphous material, integrating the solar panel with a photovoltaic thermal hybrid solar collector (PVT), which can be operated at high temperatures than standard PV and can be used to 'spike an anneal', and decreasing the lost performance considerably[8]. The near term target of a-Si solar cells is to attain 15% energy conversion efficiency, which will create a major boost to BIPV and BIPVT applications.

A combination of both crystalline and amorphous silicon layers can give a different output. A typical example and suitable for BIPV applications is the HIT (Hetero junction with Intrinsic Thin layer) solar cells, which consist of a mono-thin crystalline silicon wafer surrounded by ultra-thin amorphous silicon layers. The typical p-n junction of crystalline silicon is replaced with p-i-n junction by forming impurity free i-type a-Si layers between the crystalline base and p and n type a-Si layers to reduce the power generation loss and improve the performance. These HIT solar cells maintain higher efficiency than the conventional crystalline silicon solar cell. An efficiency of 18.3 % (183 kW from 780 panels in 1000 m^2) and 24.7 % for a 102 cm^2 cell is reported[9] (Figure 2). This is the highest efficiency recorded for a mono-crystalline silicon PV cell under sunlight at an area greater than 100 cm^2. The manufacturer also claim this solar cell maintains higher efficiencies than conventional crystalline silicon solar cells at high temperatures, with up to 10% more power output reported at 75°C.

Non-silicon based PV cells

The non-silicon based PV materials suitable for BIPV applications are cadmium telluride (CdTe), copper indium diselenide (CIS) and copper indium gallium selenide (CIGS). CdTe and CIGS/CIS can be fabricated as thin film and have more scalable processing capabilities than crystalline silicon. They can be deposited on low cost substrates. CdTe is one of the most promising thin film PV devices, because of its 1.45eV bandgap energy matching optimally with a major fraction of the terrestrial solar spectrum and has the lowest manufacturing costs among the thin film solar cell technologies to date. CdTe solar cells are prepared on a conductive substrate, generally fluorine doped tin oxide (FTO) or indium doped tin oxide (ITO) coated glass sheets. The conductive substrate is first coated with an n-type cadmium sulfide (CdS) window layer and secondly with the p-type CdTe absorber layer. The record for cadmium-telluride (CdTe) photovoltaic solar cell conversion efficiency is 19.6%[9]. However, CdTe

disadvantages include unfavourable CdS-CdTe junction formation, poor back contact between CdTe and metal foil on glass. Their fabrication on glass makes the device thick and heavy, fragile and rigid. There are also much debated issues with the toxicity of cadmium and the scarcity of tellurium. However, the industry offers materials recycling programmes to ward off this criticism. Also, the formation and use of CdTe, which itself is a very stable compound with no volatility or leaching behaviour in nature, has been justified by the fact that Cd is a by-product of Zn mining and the produced stocks as a result of mining may be more environmentally hazardous. Whereas, the CdTe technology offers the lowest cost among thin film modules, with typical cell efficiency values around 9.5 - 14.0 %, CIS (Copper indium diselenide) and CIGS (copper indium gallium diselenide) cell types are the most effective thin film cell types giving typically 11-19 % efficiency values. CIS and CIGS are promising materials for large-scale fabrication production lines: they attain higher energy conversion efficiencies with the formation of reliable thin films. These materials are also endowed with an advantage of tunable bandgaps ranging from 1 to 2 eV, making it attractive for tailored product applications and tandem device fabrication. Although they perform very well in laboratory they are proving difficult to commercialise[1]. Improved protection and stability towards moisture, perhaps through high quality barrier layers, is required to circumvent the problems associated with CIGS technology. Otherwise, CIGS has particular relevance for BIPV applications. Recently Swiss Federal Laboratories for Materials Science and Technology (Empa, Zürich, Switzerland) has achieved 20.4% efficiency with a lab scale CIGS PV cell on a flexible substrate[10]. This efficiency is the highest report to date for a CIGS solar cell[11]**.** Disadvantages with the CIGS PV film include: its complex nature (involving 5 elements), cadmium is considered toxic, indium is scarce and there are issues with durability. All CdTe, CIGS and CIS contain rare, expensive and/or toxic elements but recently a semiconducting compound, copper zinc tin sulfide (CZTS), which can be made as thin films, has achieved promising efficiencies. It has advantages over the other semiconducting technologies in that its materials are not rare, expensive or toxic. Hydrazine solution based processed CZTSSe devices with large grains, which yielded less opportunity for recombination at grain boundaries, achieved 11.1 % efficiency[12] on an area of 0.45 cm^2. This is not only a very interesting material to be considered for future BIPV applications, but also the solution processing method offers greater versatility in low cost flexible cell manufacturing.

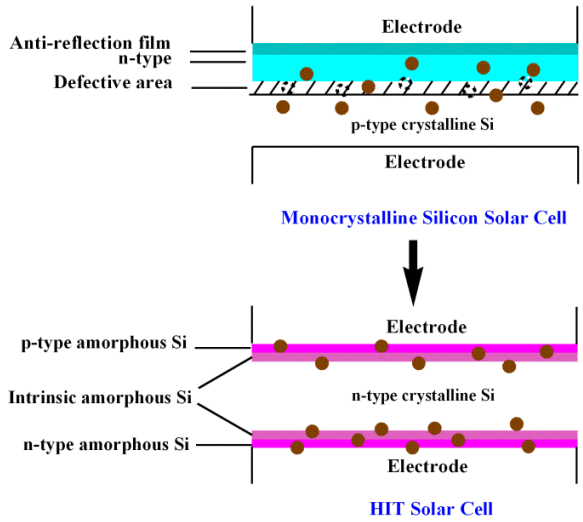


FIGURE 2. Scheme of a HIT solar cell[13]

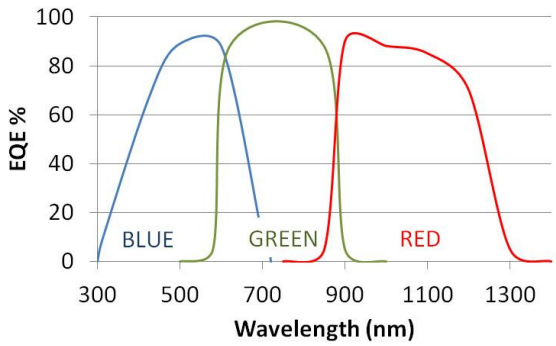


FIGURE 3. Representative spectral response for a multi-junction cell.

Two or more different PV technologies can also be incorporated to work together in tandem cells or multi-junction cells achieving better utilisation of the solar spectrum (Figure 3). The Shockley-Queisser limit of a tandem structure using two cells is 42%, and three cells is 49%[5]. Under light concentration this can be improved to 55% and 63%, respectively. An infinite number of stacked tandem cells is predicted to have a Shockley-Queisser limit of 68% (86% concentrated)[5]. One PV producer recently developed a triple junction cell to set a new record for energy conversion efficiency for any PV convertor (not using sunlight concentration). For a 1 cm^2 multi-junction InGaP/GaAs/InGaAs device they achieved an efficiency[9] of 37.9 %. These values are approaching the Shockley-Queisser thermodynamic limit of efficiency for triple junction cells (49%). Further notable advancements include a silicon cell architecture able to achieve 20.2% efficiency at lower manufacturing costs (up to 30 % less silver

required) by utilising Czochralski-grown silicon materials[14]. Recently[15] a "black-silicon" solar cell achieved 18.2% efficiency through control of carrier recombination in nanostructures, showing the promise of efficient high-surface-area solar cells with nano- and microstructured semiconductor absorbers. The cell did not require the antireflection coating layer(s) normally required to reach comparable performance levels. All these developments are particularly encouraging for PV applications in a wider scale, including BIPV.

3rd generation PV

Third generation PV includes sensitized solar cells (SSC) and organic PV (OPV). OPV use conductive organic polymers and suitable small organic molecules for its fabrication. One species absorbs incoming light and the other transports charge. The organic materials generally have a large molar extinction coefficient and only require small amounts of materials but, in practise they have low efficiencies and poor stability. The excitons based functioning principle and the electric field resulting from the difference in work functions between the two conductive species lead to significant electron-hole recombinations in most cell architectures. Bulk hetero junction (BHT) plastic solar cell architectures solved this problem considerably and are relatively easy in fabrication and of low cost but, complex in device physics[2]. The BHT device is prepared with two electrodes and a thin film casted between them. The thin film is synthesized of a solution prepared by mixing a polymeric electron donor and a fullerene based electron accepter, for example. Lately, the improvement in energy conversion efficiency is phenomenal in this area of research and development. In 2013, OPV technology achieved 12.0% conversion efficiency record cell on a small size of 1.1 cm^2 using two different absorber materials that convert light of different wavelengths to electricity. The use of two different absorber materials creates a stronger absorption of photons and improves energetic utilization through a higher photovoltage, according to researchers. Barely 9 months ago, the prior record set by the same group was only 10.7%[16]. A target of 15% efficiency is likely to be achieved by 2015 leading to roll-to-roll produced OPVs. However, the first roll-to-roll commercial products may have only lower conversion efficiencies, but the hardest part of marketing and sales will be decided by the long-term stability guaranteed through product warranties. If that is achieved, even with 10% light to electricity conversion efficiencies, the building and construction material industry as well as automotive, lighting and street and indoor furniture industries will start to integrate OPV films as energy harvesting components to increase the functionality of their products. This will significantly impact the BIPV, ZEB and interior design concepts in the near future.

Sensitized solar cells (SSC) comprising dyes, quantum dots (Q-dots) and lately Pb-containing organic-inorganic perovskite type materials, are one of the promising alternatives to conventional inorganic p-n junction solar cells and offers similar opportunities in applications described for OPV. The SSC operation principle mimics photosynthesis as it is kinetically controlled rather than field dependent. A SSC device consists of a semiconductor, preferably TiO_2, coated electrode with a monolayer of dye molecules or other sensitizers like quantum dots[17] adsorbed to the TiO_2 surface. The sensitizer absorbs photons from incoming sunlight and gets energetically excited. The excited electron is transferred to the semiconductor and then directed through an external circuit offering electrical work to arrive at a counter electrode. The electron is finally transferred back to the sensitizer for regeneration through an electrolyte medium. The photoreceptor and charge carrier elements are realized by two separate media rather than a singular p-n junction negating the need for high material purity required in inorganic PV as this cell functioning mechanism differs greatly from inorganic based PVs such as silicon and CdTe since electron diffusion is driven kinetically rather than assisted by an electric field. SSC have expected advantages in that they work even in low light conditions so as to have widespread applications in indoor environments and are reported to perform much better than poly-crystalline silicon in diffuse light conditions[18] under cloudy skies/indirect sunlight. They can be manufactured with varying degrees of opacity in different colours and aesthetics. Disadvantages include unattractiveness for large scale use, difficulty transferring lab performance to larger area cells, short life cycle and involve liquid electrolytes leading to issues with sealing/leakage and moisture ingress. Efforts to develop liquid free SSCs, using solid hole conductors and gel electrolytes were successful in lab scale but are yet to be proven successfully in commercial scale solar cells.

A record of 12.3% efficient dye-SSC device has been reported using porphyrin based dyes and $Co^{(II/III)}$tris(bipyridyl) tetracyanoborate complex as the redox couple in acetonitrile solvent under standard illumination conditions. >11.1 % efficiency is achieved with ruthenium based dyes and an iodide/triiodide redox couple (Table 3), too. A lot of research work is currently going on to improve the different challenges facing the field of SSC. Recently a new class of perovskite based sensitizers[19-26] has

achieved double digit efficiencies and record performances greater than 15% in small lab scale SSC devices. The perovskite sensitizers aim to completely replace dye sensitizers and with ongoing developments in the area efficiencies up to 20% are expected[27].

As stated earlier, one major problem in practical application of SSC is caused by liquid electrolyte leakage and improper sealing. Furthermore, freezing at low temperatures with water based electrolytes and sealant failure due to the large vapour pressures exerted by volatile organic solvents are also problems. To resolve these issues, various solvent free, gel/quasi-solid and solid state electrolytes have been tested for use in SSC (Table 3[28]). However, many of these materials offer disadvantages such as the presence of volatile organic solvents [eg PVDF and PAN-VA gels], difficult handling conditions, spin-coating techniques which involve significant material losses/waste [eg spiro-MeOTAD hole conductors], extra process steps (additional electrode treatment [eg $CsSnI_{3-x}F_x$[29] and CuI[30]]), and improper pore filling of the mesoporous TiO_2 layers. The stability of some of these compounds under air and moisture is also a concern as the mechanism of the degradation of many of these novel materials is still to be correctly understood.

The benefits and drawbacks of the discussed PV technologies are compared in Table 4. Thin film Si, CdTe and CIS are found to have advantages over crystalline silicon in terms of cost, required material and maintenance but they are still quite low in efficiency with up to twice the surface area needed to produce 1kWp compared to crystalline silicon. Their current records and a time line of the best reported research cell efficiencies can be found in Figure 4.

DESIGN REQUIREMENTS OF PVs

Transparent and semi-transparent solar cell panels are highly useful and attractive for BIPV applications with the option to replace windows and glazing materials. They also serve as replacements of conventional building parts, thus offering some cost advantage. The possibility to create PVs in a range of colours makes them aesthetically pleasing and offers the option for coloured designs/logos on the PV active materials as shown in Figure 5(a). A variety of advanced manufacturing and materials deposition methods are utilized for manufacturing transparent PV window panels. Both inorganic materials based as well as the SSC and OPV based technologies are competing to gain an upper hand in this technology. Although solar cells based on organics, nanocrystals, nanowires and other new materials hold significant promise towards fabricating transparent or translucent PV panels, many opportunities continue to exist for research into unconventional means of exploiting silicon in advanced photovoltaic systems achieving varying degrees of opacities. For example, researchers from the University of Illinois[31] have produced a manufacturing technique that could enable the production of monocrystalline silicon based transparent solar modules printed onto flexible substrates, potentially paving the way for energy harvesting windows capable of reaching energy conversion efficiencies of 15-20%, through anti-reflection coatings and light-trapping structures. They showed that by introducing practical means to create and manipulate monocrystalline Si solar cells that are much thinner (down to 100 nm, or limited only by junction depth) and smaller (down to a few micrometres) than those possible with other process technologies, the advantages offered by crystalline Si PV technology could be translated to create a new generation of stable transparent PV panels with low consumption of highly pure and expensive semiconducting materials. The technology however needs substantial development to reduce the costs and rejection rates in production in order to make it commercially viable.

Japanese PV companies have unveiled a semi-transparent PV panel for the Japanese market. With an energy conversion efficiency at 6.8 %, its glass like properties make it a useful construction material. It can be used as see-through solar cell and architectural glass and also acts as a heat shield in buildings[32]. A range of opaque and transparent, thin-film amorphous silicon (a-Si) glazing panels, for BIPV applications are available in the European market as well. They offer a direct alternative to conventional glazing and cladding materials, performing all the functions of glass such as: weatherproofing, thermal control, sound protection, light control and structural design. Companies already provide PV glass produced through various technologies including crystalline silicon, CIS/CIGS and micro-amorphous silicon, available in a range of colours and transparencies. The PV modules are designed specially as safety glass for buildings in different thicknesses, sizes and transparencies and can be used to replace standard building glass. Similarly, CIGS modules in various colours and a range of transparencies in both either stripe or dot design are also available.

One company produces a translucent green product that can be glued to windows, producing only 20% electricity of traditional silicon cells but expected to cost half as much. The film absorbs 80% of visible light and up to 90% of IR. A square meter can generate about 5 volts at 7 watts in peak conditions, and operates under far less sunlight than it takes to power a conventional panel[33].

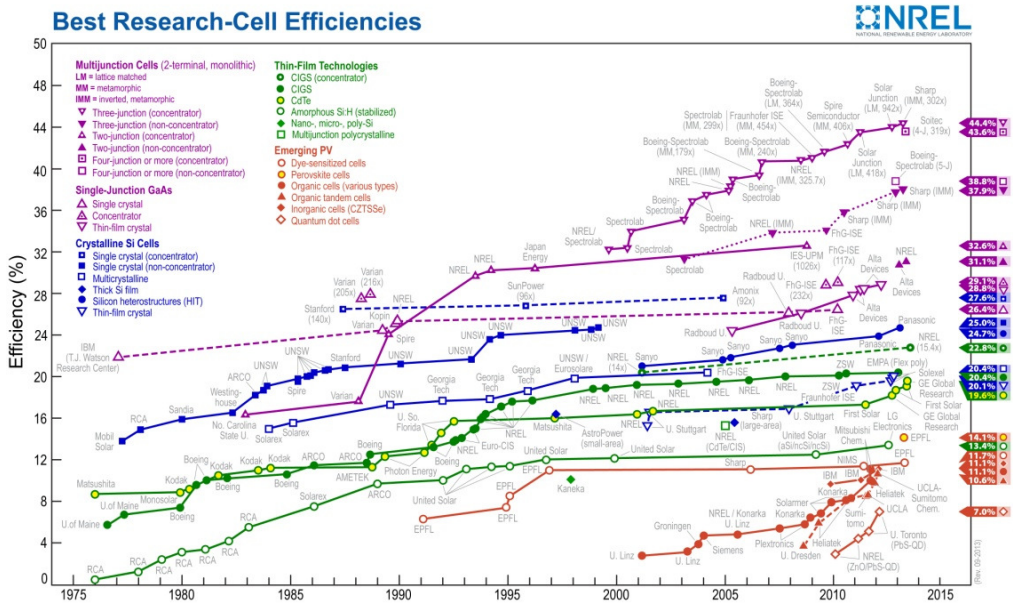
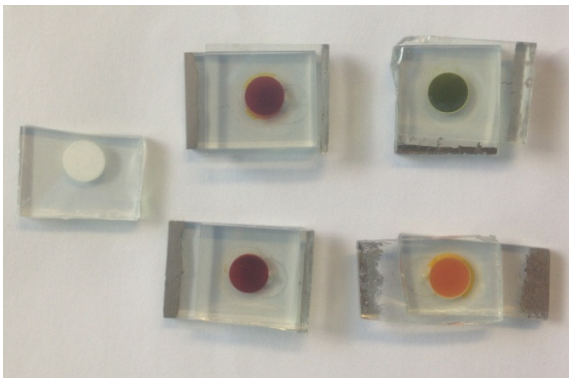
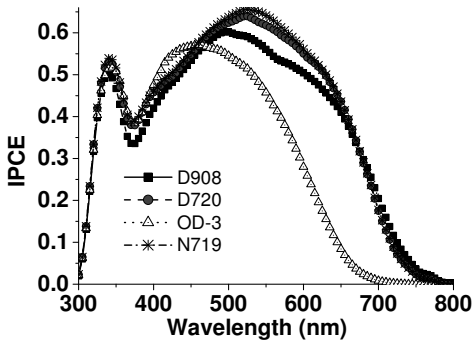


FIGURE 4. Time line of the best reported research cell efficiencies for various PV technologies[34].

(a)



(b)



(c)

	D720	D908	OD-3	N719
Appearance (powder)	Dark purple	Dark purple	Dark red -black	Maroon
Absorbance λmax (nm)	532 in DMF	523 in DMF	427 in DMF	533 in EtOH
D720, D908, OD-3 from Eversolar, Everlight Ltd, Taiwan. N719 from Dyesol Ltd.				

(d)

FIGURE 5. a) SSC can be produced in various colours and transparencies allowing company logos to be incorporated. b) Lab scale DSSC samples fabricated with different coloured dye molecules. c) the spectral response (IPCE) of several commercial dyes d) characteristics of some commercially available dye molecules.

TABLE 3. Some of the best DSSC performances reported for cells containing liquid, solid and quasi-solid phase electrolytes*.

	Electrolyte	Dye	η (%)	Voc (mV)	Jsc (mA/cm^2)	FF	ref
Liquid	**AY1**:$[Co^{II}(bpy)_3](B(CN)_4)_2$ (0.165 M), $[Co^{III}(bpy)_3](B(CN)_4)_3$ (0.045M), TBP (0.8M), $LiClO_4$ (0.1M) in ACN solvent	YD2-*o*-C8+Y123	**12.3**	935	17.66	74	35
	DMPII (0.6 M), LiI (0.1 M), I_2 (0.05 M), TBP (0.5 M) in ACN	Black dye	**11.1**	736	20.9	72.2	36
	E1: BMII (0.6 M), I_2 (0.03 M), GSCN (0.1 M), TBP (0.5 M) in ACN:valeronitrile (vol ratio: 85:15)) *[no mask]*	N719	**9.82** ***12.2***	820 *832*	16.0 *20.1*	74.5 *73.1*	37
	Solvent Free: DMII/EMII/EMITCB/I_2/NBB/GSCN (Molar ratio: 12;12;16;1.67;3.33;0.67)	Z907Na	**8.2**	741	14.26	77.4	38
Gel/ quasi-solid	LiI (0.1 M), I_2 (0.05 M), TBP (0.5 M), DMPII (0.5 M) in ACN + **Poly(acrylonitrile-*co*-vinyl acetate)** (PAN-VA)	N719	**9.03**	797	15.44	73	39
	LiI (0.1 M), I_2 (0.05 M), TBP (0.5 M), DMPII (0.5 M) in ACN + (PAN-VA) + TiO_2 filler (10 wt%)	N719	**9.46**	794	16.23	73	39
	PMII (0.6 M), I_2 (0.1 M), NMBI (0.45 M) in MPN + **PVDF-HFP** (5 wt%)	Z907	**6.7**	749	13.1	68.1	40
Solid	$P_{1,4}I/I_2$/**Succinonitrile** (5:1:100) (Plasma treated TiO_2 electrode)	N719	**9.37**	763	17.1	71.4	41
	$CsSnI_{2.95}F_{0.05}$ doped with 5% SnF_2 (Plasma treated TiO_2 electrode)	N719	**9.28**	730	17.4	72.9	29
	PEDOT + Li salt/propylene carbonate solution	D149	**6.1**	860	9.3	75	42
	PEDOT doped with LiTFSI, MPII, TBP	N719	**5.4**	640	14.2	60	43
	Spiro-MeOTAD (0.17 M), TBP (0.11 mM), $LiN(CF_3SO_2)_2$ (0.21 mM) in chlorobenzene	C220	**6.08**	860	10.90	69	44
	Spiro-OMeTAD	Z907	**4**	860	9.1	51	45
	CuI (MgO coated TiO_2 electrode)	N3	**4.7**	620	13.0	58	30

**See references for explanation of abbreviations.*

TABLE 4. Table comparing benefits (+) and drawbacks (−) of various PV technologies.

	Crys. Si	Thin film Si	CdTe	CIGS	SSC	OPV
Low material use	−	+	+	+	+	+
Low cost	−	+	+	+	−	+
High eff.	+	−	−	−	−	−
Low maintenance	−	+	+	+	+	−
Module efficiency[46]	13-19 (mono-crys.)	5-8	9-11	10-12	-	-
Surface area needed for 1kWp(m^2) [46]	5-9	13-20	9-11	8-10	-	-

OPV lab scale cells offer an efficiency of 7 % at a light transmission level of 23.5 %[47]. Currently, a transparency level of up to 40 % is produced by in laboratories in Dresden, Germany[47]. The cell efficiency remains constant with rising temperatures in contrast to traditional solar technologies.Recently a startup spun off from MIT has created a solar cell that is around 60 % transparent with an efficiency of 2 %. This solar cell absorbs IR and UV radiation while letting the visible pass through. It consists of organic layers on glass or a flexible film[48].

While, Si based transparent solar cell products rely on advanced manipulations and manufacturing techniques, the SSCs can be fabricated with a transparency of 10~30% transmittance of visible light and in various colours by utilising different dyes as displayed in (Figure 5) through relatively less sophisticated solution processing techniques. Organic

Dyes for SSC need to have the general structure: donor-linker-acceptor-anchoring group (pi electron rich donor, pi linker, electron poor acceptor) and are available in different colors (Figure 5c,d).

PV substrates (flexible, rigid)

PVs that can be fabricated in flexible designs offer building integration advantages, including potential for new applications due to their flexible and light weight nature and adaptation to surfaces of any shape or contour. Flexible manufacturing also allows for low cost, roll to roll production advantages with lower energy and faster capital payback. Flexible PV possibilities extend beyond even building integration towards consumer products with energy independence (e.g., laptop, mobile phone). However, disadvantages exist as most PV fabrication techniques involve some high temperature processing steps which are not appropriate for most flexible polymer substrates. Metal foil substrates can be used instead but ideally low temperature techniques are required which will allow ready processing on any substrate and the advantage of reduced manufacturing energy costs.

Silicon is most commonly found in flexible form as amorphous silicon cells as it can be deposited as a thin layer by sputtering or other methods on flexible substrates. Crystalline silicon which generally require thicker layers or wafers is not widely found in flexible form due to its rigidity and fragile nature. Producers have achieved 18.1% energy conversion efficiency in flexible, 100µm-thin polycrystalline lab scale PV cells by applying new methods such as the silicon wafer purification treatment technology, honeycomb structure and back surface reflection structure to increase conversion efficiency of the 100 µm-thin polycrystalline silicon wafer. This is the world's highest conversion-efficiency rating attained in a flexible 15cm x 15cm PV cell[49].

As of November 2011, the highest reported efficiency[50] in flexible CdTe solar cells of 13.8 % was achieved by EMPA Switzerland leapfrogging their previous world record of 12.6 % and nearing that of glass utilising a superstrate structure using thin polyimide. The highest efficiency in substrate form on polyimide is 7.3% and on metallic foils 7.8% has been achieved[50].

In January 2013 Swiss Federal Laboratories for Materials Science and Technology (EMPA, Zürich, Switzerland) also achieved a record 20.4% efficiency with a copper indium gallium diselenide (CIGS) solar photovoltaic (PV) cell on a flexible substrate[10]. Work is already underway on the challenging scale-up for large-area solar modules and adapting the complex processes for industrial manufacturability. The production technology aims to be roll-to-roll manufacturing of flexible solar modules, involving deposition of CIGS thin films onto polymer foil. A leading manufacturer of copper indium gallium selenide (CIGS) thin-film photovoltaic solar panels, announced a promising 15.7 percent aperture area (9703 cm^2) efficiency on commercial size flexible PV modules[9].

Even though SSC has become a highly active area of research and development as evidenced by the fast growth of scientific publications and patent applications over the last 15-20 years[51], manufacturing of small laboratory cells is commonly performed by hand without any concern for time or cost optimization. Simple procedures such as sensitizing and electrolyte filling are time consuming at the cell manufacturing level. All these steps must be done rapidly and efficiently for producing SSC modules at commercial scales[52]. In order for SSC to compete commercially with other PV technologies, manufacturing line speeds of 2 to >20 m/min are thought to be necessary[52]. Presently DSSC fabrication processes involve high temperature (500°C) sintering steps, so the possibility of polymer based substrates is not yet sufficiently mastered to be transferred to manufacturing lines. Some companies offer flexible DSSC products using metal foil substrates but require back side illumination causing a decrease in achieved energy conversion efficiency.

With the development of flexible and lightweight PVs, uses will extend beyond building integration to areas such as consumer devices and automotives. For example, the EU funded FP7 SMARTOP project aims to develop a prototype involving novel batteries, thermoelectric and photovoltaic technologies combined with advanced engineering integration to produce an autonomous smart roof for powering the air conditioning, lighting and passenger comfort part of the cabin within electrical and internal combustion vehicles. Conventional silicon solar cells and emerging dye-sensitized solar cells (DSSC) technologies, have been tailored specifically to the SMARTOP applications. Novel battery types and auxiliaries with reduced energy consumption and efficient power management aims to drive down overall energy use required for the car (Figure 6).

OPERATING CONDITIONS

The incorporation of solar cells into buildings as BIPV parts and into vehicles as solar roofs require precise knowledge regarding the performance and functioning of each of the available PV technologies under transient conditions since the behaviour of a specific type of solar cell depends how the light is incident on the cell surface at any given time. In building integrated PV (BIPV) where the PV is

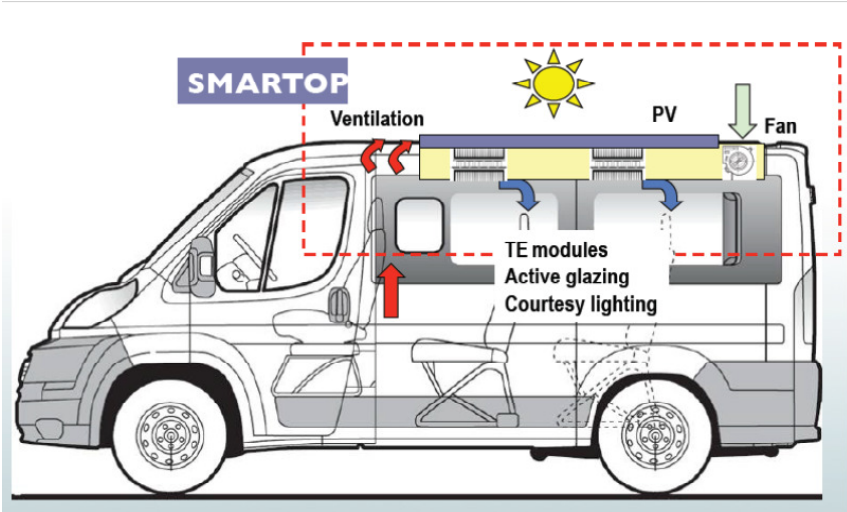


FIGURE 6. Conceptual drawing of the SMARTOP system.

stationary, the incident light will be constantly changing as the sun's position moves across the sky. The positioning of BIPV is not highly optimized as in roof top solar farms. Vehicle integrated PVs on the other hand will experience a continuous change of angle of incidences. Both will also experience frequently transient and moving shades, with relatively higher diffused light fractions to be harvested at times. It is therefore most important to know how the different solar cells operate under these continuously fluctuating conditions and the type that most effectively meets the restrictions imposed by the design and application requirements

Façades with an equator facing orientation would likely to benefit from PVs that respond efficiently to direct beam irradiation such as crystalline silicon. Walls on the other hand are best suited for a more economical or flexible option such as thin-films. Thin-film PVs are far cheaper than crystalline silicon PVs but they usually require twice the area of crystalline silicon for the same electrical output. Flat roofs by comparison should aim to operate efficiently with the 100 % of diffuse radiation available on the horizontal plane. The angular performance of a PV can be described by the Cosine Law which states that the signal output of an irradiance-sensitive device, illuminated with a collimated beam on its active surface, will decrease with the cosine of the angle of incidence (measured from the normal to the surface)[53] and can be described by

$$E_\theta = E_0 Cos(\theta)$$

where E_0 is the irradiance when light is normal to the PV surface. At θ = 0 degrees, irradiance E = 100%. At θ = 30°, E = 87%; θ = 60°, E = 50% and θ = 85°, E = 9%. This is plotted in Figure 7. PV short circuit current (Isc) follows the same trend as cell power and the Voc generally is predicted to be least affected by incident light angle changes. Methods to increase light capture and reduce the cosine dependency are commonly employed including solar tracking devices, anti-reflective films, light scattering[54-58] or reflecting particles and photonic crystals. The performance of PV at various intensities show the intensity dependence is dominated by the current response, which is linearly related to the light intensity (Figure 7).

It can be said that incident angle follows the cosine law (approx) and current changes are linearly related to light intensities. In both cases, voltage is least effected by lighting conditions changes and the observed PV power decreases are mainly caused by photocurrent contribution as the voltage output is governed logarithmically to light intensity, whereas the photocurrent is proportional to the flux of photons of > bandgap energy. This is important for considering power supply to buildings; the voltage supply to battery or appliances can be considered quite constant in a range of different lighting conditions. Cell current is the parameter which alters decisively at acute angles and directly effects cell power output and for BIPV architectural applications it is therefore an important criteria. Spherical silicon technology has been suggested to be a solution to the poor angular performance of classical planar PV at acute angles. Spherical silicon solar cell products, which are expected to yield better angular performance and better performance in conditions of

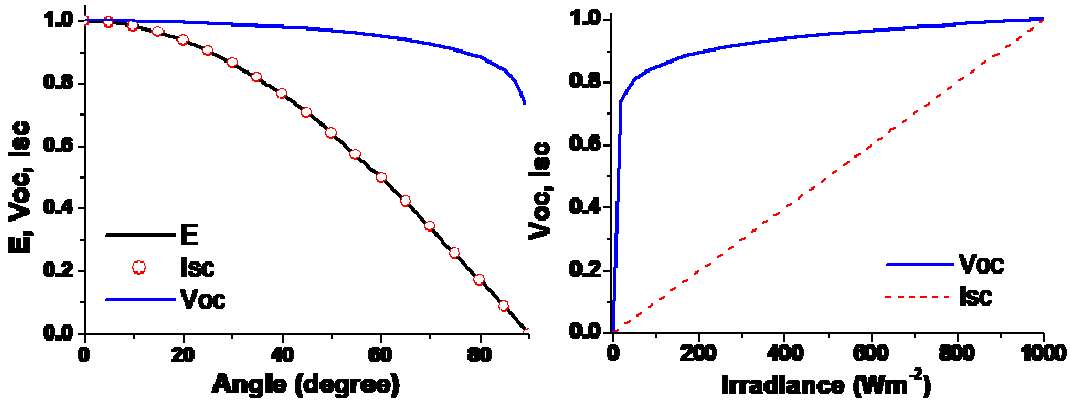
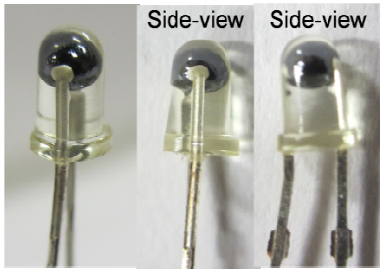


FIGURE 7. Left: Variation of PV short circuit current (Isc), open circuit voltage (Voc) and cell irradiance (E) as predicted by the Cosine Law **Right:** Predicted effect of intensity changes on PV Isc and Voc.



Single spherical (Sphelar) solar cell in 3 mm diameter plastic mold
Kyosemi Ltd (SphelarPower Corp.)
Product: KSP-OC1830MR-ER-X03

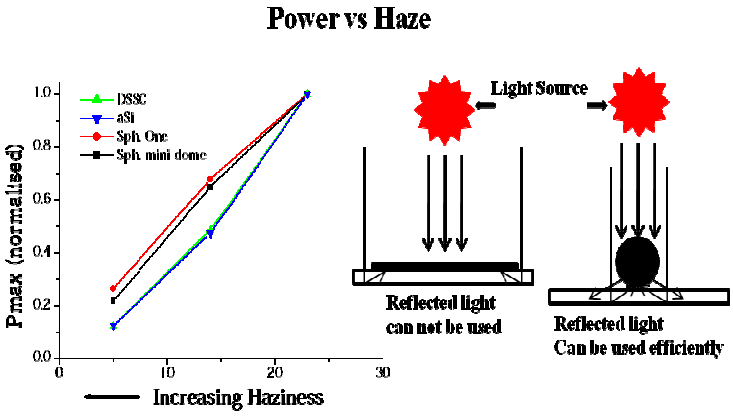


FIGURE 8. Left: Photo of a spherical solar cell, Sphelar One product. Centre: effect of hazing on PV performance (hazing produced by placing materials of varying degree of haziness between light source and sample). Right: Schematic of increased light capture in spherical solar cell.

increased haziness[59,60]. They may acquire importance in BIPV product lines in future as they are now under small levels of production and development.

Compared to a planar DSSC and a-Si sample, spherical silicon is observed to perform slightly better in hazy conditions (Figure 8). Although this spherical technology is still in an emerging phase and presently quite expensive, it has the option of being produced encapsulated in transparent flexible plastics to create transparent window glass, which could capture light from all angles and both sides for building integration. The opportunities are significant for developing products using such technologies, if the price factor is favourable.

TEMPERATURE EFFECT/PV-THERMAL HYBRID SYSTEM

BIPV panels are usually installed as sloped roofs or slanted facades because of the favorable angle with the sun for most part of the day. But, the performance of solar cells, especially mono and polycrystalline modules, are highly dependent on temperature. The efficiency of solar cells decrease at elevated temperatures and the decline is most noted for crystalline Si solar cells[61]. In order to limit this problem, panel fixing is designed with an air gap underneath the module to minimize heat entrapment. Semiconductor performance losses are due mainly to increased electron-hole recombination, with typical losses of 0.5% for every 1°C in temperature increase[62]. On the other hand, thin film modules are

less affected by the temperature, partly due to the differences in heat capacities of panels, with DSSC found to actually improve slightly at moderately elevated temperatures[61] due to decreased viscosities of their liquid electrolytes.

Photons with energies less than or exceeding the band-gap of the PV cells can heat up the PV panel causing decreased cell performance. A practical method to overcome this problem, and beneficially capture the generated thermal energy, is a photovoltaic thermal hybrid system (PVT), which combines a PV and a thermal absorber in one single unit. The thermal absorber is used to collect and transfer excess heat away from the PV, producing both useful heat and electricity as well as increasing the performance of PV through its cooling. Roof placement of BIPVT systems offer advantages as hot water storage units are usually placed on building tops and lead to not only short transfer distances between the thermal absorber and the thermal storage unit, but also increased water supply pressure. Conversely, BIPVT will generally be opaque so they can not be used in windows or glazing and do not offer the architectural flexibility of transparent and semi-transparent BIPV. The thermal collectors are generally flat so integration into curved surfaces will be challenging but their combination allows collection of both 1) solar thermal energy, converting unused photons to heat and 2) solar photovoltaic (PV), converting higher energy photons to electrons, maximising solar energy harvesting with the added advantage of minimising PV performance decreases caused by panel surface temperature rises.

TABLE 5. Comparison of various lighting technologies

	LEDs	**CFLs**	**Incandescents**
Frequent On/Off cycling	No effect	Shortens lifespan	Some effect
Turns on instantly	Yes	Slight delay	yes
Durability	Durable	Fragile	Fragile
Heat Emitted	Low (3 btu's/hr)	Medium (30 btu's/hr)	High (80 btu's/hr)
Sensitivity to temperature	No	Yes	Some
Sensitivity to humidity	No	Yes	Some
Hazardous materials	less and fastly being replaced with newer green materials	5 mg mercury/bulb	None
Replacement frequency (over 50k hours)	1	5	40+

COMPARISON BETWEEN LED, CFL AND INCANDESCENT

Another important factor for BIPV and creating zero energy buildings is how the captured solar energy is utilised. Recent advances in light sources such as light emitting diodes (LEDs) have dramatically improved building lighting energy requirements. An LED is a semiconductor light source. A typical example is Aluminium–Gallium-Arsenide (AlGaAs or $Al_xGa_{1-x}As$). Organic molecule based Organic LEDs also are under research and development and they are produced relatively in smaller numbers at present. A fair comparison of LED with CFL and Incandescent light is required to apply them beneficially[63]. Though the capital cost of LED lighting systems are higher and the available spectral ranges of LEDs are not the same as conventional light sources at present, with the remaining factors such as lumens per watt, LED's higher life span, reduced cost of electricity, etc., LED lighting systems are much superior technically. This technology is rapidly developing and the spectral gap with traditional lighting systems are narrowing fast. Based on these parameters the estimated cost of a LED bulb producing equivalent to 60 watts for 50000 hours is $85.75 which is better than CFL's $89.75 and incandescent bulb's $352.50. Assuming a household having 25 bulbs, it is estimated to save $6668.75 over the period of 50000 hours if all incandescent bulbs are replaced by LED[63]. Furthermore, LED performs much better than CFL and incandescent on other parameters as well such as, the frequent on/off cycling, durability, heat emission, sensitivity to temperature and humidity (Table 5).

CONCLUSIONS

In conclusion, we have reviewed the advantages and disadvantages associated with photovoltaics use in urban environments, particularly in building integrated PV. The leading PV technologies, record efficiencies and uses as flexible and/or transparent design components for buildings are discussed. The effect of incident lighting conditions and heating on PV performance is also presented.

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