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**Review Article**

# A review of solar energy conversion Technologies

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**Abstract**

**The solar energy flux reaching the Earth's surface represents a few thousand times the current use of primary energy by humans. The potential of this resource is enormous and makes solar energy a crucial component of a renewable energy aimed at reducing the global emissions of greenhouse gasses into the atmosphere. Nevertheless, the current use of this energy resource represents less than 1% of the total electricity production from renewable sources. Even though the deployment of photovoltaic systems has been increasing steadily, the solar technologies still suffer from some setbacks that make them poorly competitive on an energy market dominated by fossil fuels: high capital cost, modest conversion efficiency, and intermittency. From a scientific and technical viewpoint, the development of new technologies with higher conversion efficiencies and low production costs is a key requirement for enabling the deployment of solar energy at a large scale. This paper summarizes the state of the research in solar technologies with high potential for large-scale energy production.**

**Keywords:** Solar energy, photovoltaic, greenhouse, technology

## INTRODUCTION

Solar radiation represents the largest energy flow entering the terrestrial ecosystem. After reflection and absorption in the atmosphere, some 100,000TW hit the surface of earth and undergo conversion to all forms of energy used by humans, with the exception of nuclear, geothermal, and tidal energy. This resource is enormous and corresponds to almost 6,000 fold the current global consumption of primary energy (13.7TW [IEA, "World Energy Outlook 2004",]). Thus, solar energy has the potential of becoming a major component of a sustainable energy portfolio with constrained greenhouse gas emissions

Solar radiation is a renewable energy resource that has been used by humanity in all ages. Passive solar technologies were already used by ancient civilizations for warming and/or cooling habitations and for water heating; in the Renaissance, concentration of solar radiation was extensively studied and in the 19th century the first solar-based mechanical engines were built ( Butti and Perlin,1980). The discovery of photovoltaic effect by Becquerel in 1839 and the creation of the first photovoltaic cell in the early 1950s opened entirely new perspectives on the use of solar energy for the production of electricity. Since then, the evolution of solar technologies continues at an unprecedented rate. Nowadays, there exist an extremely large variety of solar technologies, and photovoltaic's have been gaining an increasing market share for the last 20 years. Nevertheless, global generation of solar electricity is still small compared to the potential of this resource (http://archive.greenpeace.org/climate/climatecountdown/solargeneration/). The current cost of solar technologies and their intermittent nature make them hardly competitive on an energy market still dominated by cheap fossil fuels. From a scientific and technological viewpoint, the great challenge is finding new solutions for solar energy systems to become less capital intensive and more efficient. Many research efforts are addressing these problems. Low-cost and/or high-efficiency photovoltaic device concepts are being developed.

Solar thermal technologies are reaching a mature stage of development and have the potential of becoming competitive for large energy supply. Intermittency is being addressed with extended research efforts in energy storage devices, such as batteries and other electric storage systems, thermal storage, and the direct production of solar fuels (typically hydrogen). All these are valuable routes for enhancing the competitiveness and performance of solar technologies. The aim of this paper is to evaluate the potential of solar energy for low-carbon intensive and large-scale energy production and to provide a picture of the state of research in the most significant solar technologies. More than a comprehensive review, this paper is intended to be an attempt at identifying interdisciplinary and fundamental research topics with high breakthrough potential for the improvement of the performance, the reliability, and the competitiveness of solar technologies. For this reason this analysis is a bottom-up approach; solar technologies are organized by energy conversion paths and the discussion focuses, when possible, on the fundamental processes and the related technical challenges.

## Solar radiation

Solar radiation is an electromagnetic wave emitted by the Sun's surface that originates in the bulk of the Sun where fusion reactions convert hydrogen atoms into helium. Every second 3.89.1026J of nuclear energy is released by the Sun's core. This nuclear energy flux is rapidly converted into thermal energy and transported toward the surface of the star where it is released in the form of electromagnetic radiation. The power density emitted by the Sun is of the order of 64MW/m$^2$ of which ~1370W/m$^2$ reach the top of the Earth's atmosphere with no significant absorption in the space. The latter quantity is called the *solar constant*.

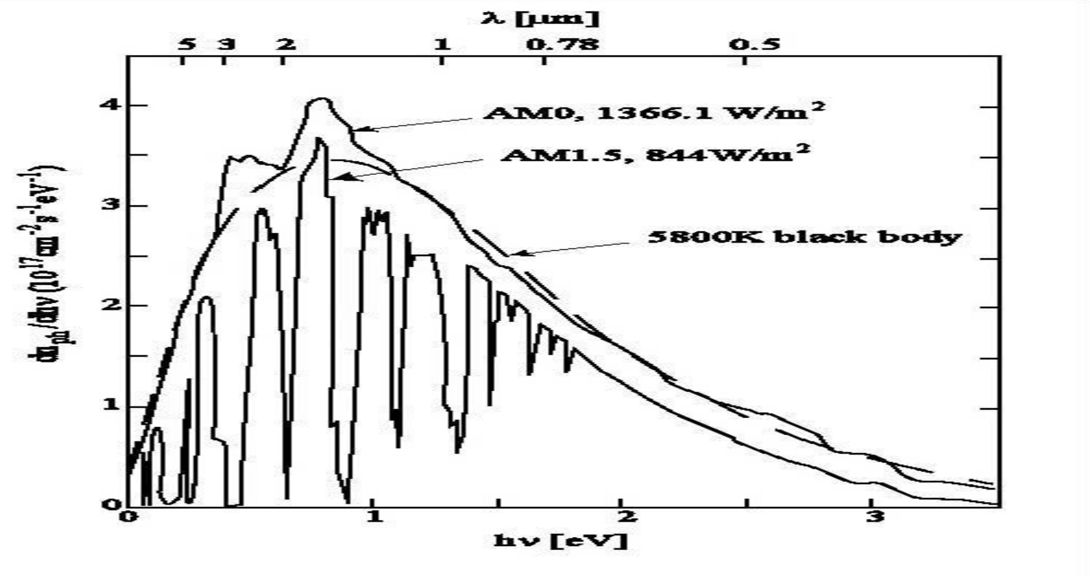

**Fig. 1.** Extraterrestrial (AM0) and ground-level (AM1.5) spectra of the solar radiation [5]. The dashed line represents the emission spectrum of a black body at 5800K.

The spectral range of the solar radiation is very large and encompasses nanometric wavelengths of gamma and X-rays through metric wavelengths of radio waves. The energy flux is divided unevenly among the three large spectral categories. Ultraviolet (UV) radiation (λ<400nm) accounts for less than 9% of the total; visible light (VIS) (400nm<λ<700nm) for 39%; and infrared (IR) for about 52%. As shown in Figure 1, the pattern of the solar spectrum resembles closely the radiation of a perfect black body at 5800K. In the figure, AM0 indicates the *Air Mass Zero* reference spectrum measured and partially modeled outside the terrestrial atmosphere (http://rredc.nrel.gov/). Radiation reaching the Earth's surface is altered by a number of factors, namely the inclination of the Earth's axis and the atmosphere that causes both absorption and reflection (*albedo*) of part of the incoming radiation. The influence of all these elements on solar radiation is visible in the ground-level spectrum, labeled AM1.51 in Figure 1, where the light absorption by the molecular elements of the atmosphere is particularly evident.

Accounting for absorption by the atmosphere, reflection from cloud tops, oceans, and terrestrial surfaces, and rotation of the Earth (day/night cycles), the annual mean of the solar radiation reaching the surface is 170W/m$^2$ for the oceans and 180W/m$^2$ for the continents. Of this, about 75% is direct light, the balance of which is scattered by air molecules, water vapor, and clouds.

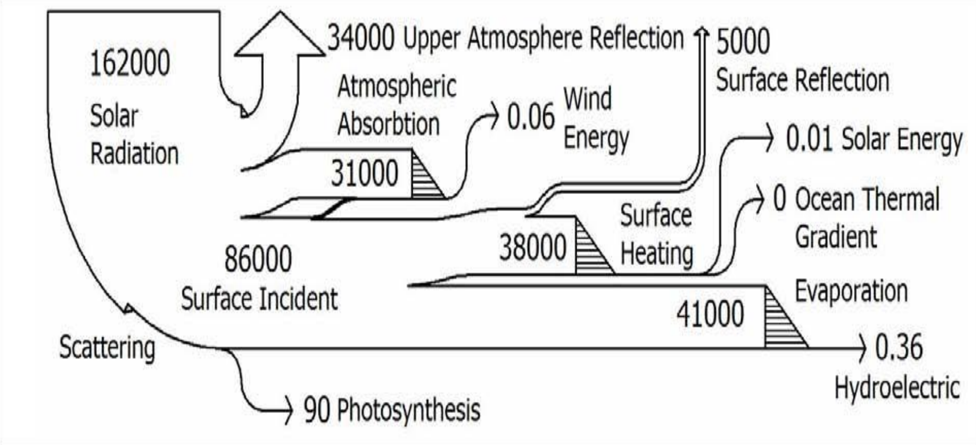

**Fig. 2.** Solar radiation exergy flow diagram (units in TW) [6]. Shaded surfaces represent natural exergy destruction; arrows represent human use for energy services.

The diagram in Figure 2 illustrates the flow of the work potential, or energy, of the solar energy into the atmosphere and the terrestrial ecosystem. This quantity represents the upper limit to the work obtainable from solar radiation conversion, a limit that is imposed by the 2nd law of thermodynamics and is independent of any conceptual device. Of the 162PW of solar radiation reaching the Earth, 86PW hit its surface in the form of direct (75%) and diffused light (25%). The energy quality of diffused radiation is lower (75.2% of energy content instead of 93.2% for direct light (Shafey and Ismail, 1999), with consequences on the amount of work that can be extracted from it. 38PW hit the continents and a total energy of 0.01TW is estimated to be destroyed during the collection and use of solar radiation for energy services. This estimation includes the use of photovoltaic and solar thermal plants for the production of electricity and hot water. Similar estimates are shown for wind energy (0.06TW), ocean thermal gradient (not yet exploited for energy production), and hydroelectric energy (0.36TW).

## Potential of solar energy

The global solar energy potential ranges from 2.5 to 80TW .The lowest estimate represents around 18% of the total current primary energy consumption (13.7TW ,IEA "World Energy Outlook 2004), and exceeds 10% of the estimated primary energy demand by 2030 (21.84TW ,IEA World Energy Outlook 2004). More optimistic assumptions give a potential for solar energy exceeding 5 fold the current global energy consumption. Despite the relatively low power density of the solar flux, solar energy has the potential of supplying a non-negligible fraction of our energy needs. In the case of the US for example, the total electricity demand (418GW in 2002) could be satisfied by covering a land surface of 180km square with photovoltaics. This surface represents 0.35% of the total land area and roughly corresponds to the surface covered by roads in the country (3.6.1010$m^2$ [Sims, 2003]).

If we want solar energy to significantly contribute to the world's energy supply, massive increases in manufacturing capacity are needed. From the research standpoint, more effort has to be put into improving efficiencies while reducing the manufacturing costs. This is a great technological challenge that requires investment of larger financial and intellectual resources to find innovative solutions.

## Environmental aspects of solar energy

Solar energy is promoted as a sustainable energy supply technology because of the renewable nature of solar radiation and the ability of solar energy conversion systems to generate greenhouse gas-free electricity during their lifetime. However, the energy requirement and the environmental impact of PV module manufacture can be further reduced, even though recent analysis of the energy and carbon cycles for PV technologies recognized that strong improvements were made both in terms of energy.

## Photon absorption and carrier generation

One of the most critical requirements for a single junction cell is that the band gap energy must be optimized to transfer maximum energy from the incident light to the photo generated electron-hole pairs. The simultaneous optimization of the cell voltage, proportional to Ebandgap, the photo generated current density, decreasing with bandgap and of the fill factor, increasing with Ebandgap (Green,1982) gives an optimal value of E bandgap~1.1- 1.4eV.

The bandgap energy of silicon (1.12eV) is almost ideal and allows absorption of photons in the near-infrared (NIR), visible, and ultraviolet spectrum. However, the indirect bandgap of crystalline silicon causes relatively poor light absorption (<104cm$^{-1}$) for photons with energies below 3.4eV, which is the silicon direct bandgap energy. Therefore, typical sc-Si wafers must be 100-300μm thick for achieving efficient light absorption.

Thin-film photovoltaic materials have a major advantage over silicon, since most of them have direct bandgap, resulting in higher optical absorption. This allows typical thin film PV devices to use very thin layers of active material (~1μm) that can thus be of lower quality. Today's most successful materials for thin-film photovoltaics are α-Si, where the optical absorption is increased by impurity scattering, Cd, Te, with a bandgap of 1.48eV, and CIGS, whose bandgap can be tuned around the nominal value of 1.04eV by controlling its composition and that has the highest absorption constant (3-6.105cm-1) reported for any semiconductor. More effort is required to find new semiconductor materials combining optimal bandgap, inactive grain boundaries, stability properties, and processing ease.

Spectrum splitting through *multijunction cells* with bandgap energies designed to match the solar spectrum is a very effective route to increasing efficiency, since this method reduces the energy loss driven by the thermalization of hot electrons generated by the absorption of photons with energy >Ebandgap. Many configurations and materials have been investigated for tandem and multijunction cell concepts. Among the most interesting approaches using silicon, are:

(i) The amorphous silicon-germanium alloys (a-Si, Ge:H) where the bandgap can be varied from 1.75eV down to below 1.3eV;

(ii) The microcrystalline and amorphous silicon tandem cells (μc-Si:H (1.12eV)/α-Si:H (1.75eV), also called *micromorph* (35) with enhanced stability properties against light-induced degradation and with maximal and stable efficiencies of 14.7% and 10.7%, respectively;

(iii) multijunctions incorporating material alloys such as amorphous or polycrystalline silicon carbide (α-Si:C) and silicon germanium (α-Si:Ge). III-V materials have ideal bandgap energies for highly efficient photon absorption (*e.g.* 1.0-1.1eV for InGaAsN, 1.4eV for GaAs). In addition, fine-tuning of both lattice constant and bandgap can be achieved by modifying the alloy composition, resulting in a large flexibility that is exploited for growing multijunction cells. Lattice-matched and metamorphic 3-junction GaInP/GaInAs/Ge cells currently hold the efficiency records under concentrated sunlight (39% efficiency at 236 suns and ~37% efficiency at 310 suns, respectively). The cost of growing processes such as molecular beam epitaxy and metal-organic vapor phase epitaxy directed these technologies to space applications, but their inclusion in *concentrator systems* together with manufacturing scale-up might have a sensible impact on their cost for terrestrial applications. To achieve this goal, however, concentrating technologies will require more technical development.

Nanoscale features are widely used in solar technologies to increase light absorption. In particular, *quantum dot sensitization* has large potential for matching the absorption spectrum of a photovoltaic cell to the solar spectrum. Nanoparticles can be built from a large variety of semiconductor materials and their bandgap can be tuned by changing the particle size and shape. Additionally, recent experimental results have demonstrated the feasibility of multiple (2 or more) carrier generation through *impact ionization* in PbSe nanocrystals for photon energies 3 fold larger than the nanocrystals bandgap energy, Ebandgap. Impact ionization can potentially increase the power conversion efficiency of a solar cell based on PbSe nanocrystals by 35-40% ( Schaller and Klimov, 2000)

*Extremely Thin Absorber 10* devices are another example of systems taking advantage of nanoscale structures (Lenzmann, 2004). The interest of this design is the tolerance to higher levels of defects and impurities than in flat thin-films devices, because photo induced charge separation occurs on a length scale of a few nanometers. On the other hand, making PN junctions (p-type semi-conductor/insulator/n-type semiconductor) with such high contact area is difficult and this has hampered the performance of these cells.

Multi-junction cells and multiple electron-hole pair generation are two among a set of novel approaches that could be denoted as "*3rd generation PVs*" that aim at increasing the thermodynamic efficiency limit of solar cell devices Research efforts in these technologies are increasing and the feasibility of some of them has still to be proven experimentally.

*Up/down converters*, converting respectively high energy photons (>2Ebandgap) into two lower-energy photons with energy >Ebandgap, and vice versa. The thermodynamic efficiency limit for a solar cell with a band gap energy of 2eV and with an optimised up-converter attached to its rear surface is 50.7% for a non-concentrated AM1.5 spectrum;

M*ultiband cells* where one or more electronic energy levels are created in the forbidden band of the bulk semiconductor material through super lattice structures based on a periodic structure of alternating layers of semiconductor materials with wide and narrow band gaps, high concentration impurities such as rare-earths in wide bandgap semiconductors, or by using semiconductors with multiple narrow bands such as I-VII and I3-VI compounds;

*Thermophotovoltaic* devices involving the photovoltaic conversion by a receiver cell of radiation from an emitter, which could be heated by various sources including sunlight. A prime difference from normal solar photovoltaics is that emitted energy unable to be used by the receiver can, in principle, be recycled, allowing high conversion efficiency (up to ~54%);

*surface plasmon* on metal nano particles used to enhance the light absorption of thin semiconductor layers by coupling the light with the waveguide modes of the semiconductor layer;

*solar antenna* (or "rectenna") *arrays* use a micro-scale antenna to convert broadband electromagnetic radiation into an AC field and optical frequency rectifiers to provide a DC electric output; theoretical efficiency limit is >85% under direct sunlight.

One of the key advantages of *organic photovoltaics* (OPVs) is that organic small molecules and polymer materials have very high absorption coefficients, exceeding 105cm-1, that permit the use of films with thicknesses of only several hundred nanometers. Current OPV devices exhibit high (>70%) quantum efficiency. However obtaining absorption in the NIR spectral range has proven to be challenging. Bandgaps of the active organic materials must be reduced to approach the nominally optimal value of 1.4eV while retaining good charge carrier mobility, open-circuit voltage, and the efficiency of charge separation. Conjugated polymers with band gaps ~1.6eV have been reported in the literature (Brabec and Winder, 2002) and various Ruthenium complex dyes absorbing up to 900nm ("blackdye"11) have been used in photo electrochemical cells (Grätzel, 2000).

Combinations of active donor and acceptor materials in organic heterojunctions and of different dyes in photo electrochemical cells can be used to broaden the absorption spectrum. In this context, light-harvesting antennae are an interesting alternative sensitizer. For example, the chromophore loaded zeolites developed by G. Calzaferri's group have demonstrated the ability to incorporate high densities of various dye molecules, complementing each other in their spectral features Calzaferri and Brühwiler, 2000). These systems also increase the dye stability by preventing their aggregation and display very efficient Föster energy transfer processes (Gfeller and Calzaferri, 1997).

## CONCLUSION

The deployment of solar technologies for energy production at a large scale requires the involvement of both political and economical players, but also further improvements in the conversion efficiency and reduction of manufacturing cost. A large ongoing research effort aims to find innovative solutions to overcome these barriers. In the last decade, photovoltaic technologies have experienced an astonishing evolution that led to the increase of the efficiency of crystal-silicon solar cells up to 25% and of thin-film devices up to 19%. Recently, nano-technology, innovative deposition and growth techniques, and novel materials opened routes for reaching higher performances (multi-junction devices and other 3rd generation photovoltaics) and for developing very low-cost devices such as organic-based PVs. All these technologies face comparable fundamental issues related to the steps involved in the conversion of photon energy into electricity: photon absorption, charge carrier generation, charge separation, and charge transport. Both fundamental research and technical development are critical requirements for these technologies to become more efficient, stable, and reliable. Solar thermal systems are at the demonstration stage and some installations are already operational. Their ability to overcome the intermittency problem using hybridization and thermal storage renders these technologies particularly suitable for large-scale electricity production. Direct production of chemicals fuels, and particularly hydrogen, from solar energy is a promising alternative to using fossil fuels for the development of a sustainable carbon-free fuel economy. Thermochemical and biological conversion processes are promising technologies with potential for high efficiency. However, only a few thermo-chemical processes have been investigated to date and biological systems require more understating of genetics and biological conversion to become efficient and stable. Solar energy has a large potential to be a major fraction of a future carbon-free energy portfolio, but technological advances and breakthroughs are necessary to overcome low conversion efficiency and high cost of presently available systems.

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