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Solar energy: principles and possibilities

CHRISTOPHER J. RHODES

ABSTRACT

As the world faces an impending dearth of fossil fuels, most immediately oil, alternative sources of energy must be found. 174 PW worth of energy falls onto the top of the Earth's atmosphere in the form of sunlight which is almost 10,000 times the total amount of energy used by humans on Earth, as taken from all sources, oil, coal, natural gas, nuclear and hydroelectric power combined. If even a fraction of this could be harvested efficiently, the energy crunch could in principle be averted. Various means for garnering energy from the Sun are presented, including photovoltaics (PV), thin film solar cells, quantum dot cells, concentrating PV and thermal solar power stations, which are more efficient in practical terms. Finally the prospects of space based (satellite) solar power are considered. The caveat is that even if the entire world electricity budget could be met using solar energy, the remaining 80% of energy which is not used as electricity but thermal power (heat) still needs to be found in the absence of fossil fuels. Most pressingly, the decline of cheap plentiful crude oil (peak oil) will not find a substitution via solar unless a mainly electrified transportation system is devised and it is debatable that there is sufficient time and conventional energy remaining to accomplish this. The inevitable contraction of transportation will default a deconstruction of the globalised world economy into that of a system of localised communities.

Keywords: *photovoltaics, Grätzel cells, dye-sensitized solar cells, solar energy, solar power, quantum dots, thin film cells, satellites, peak oil, concentrating solar power, thermal solar power, space-based solar power*



Professor Chris Rhodes has a visiting position at the University of Reading and is Director of Fresh-lands Environmental Actions, PO Box 2074, Reading RG4 5ZQ, UK; E-mail: cjrhodes@fresh-lands.com. He was awarded a DPhil from the University of Sussex in 1985 and a DSc in 2003. He has catholic scientific interests (www.fresh-lands.com) which cover radiation chemistry, catalysis, zeolites, radioisotopes, free radicals and electron spin resonance spectroscopy, which more recently have developed into aspects of environmental decontamination

and the sustainable production of energy and fuels. He has published more than 200 peer reviewed articles and five books, and is also a published novelist, journalist and poet.

1. Introduction

1.1 *The problem of energy*

The world now uses a grand total of 18 TW (18 terawatts) of energy which amounts to 568 EJ (568 exajoules = 5.6×10^{20} J) over the period of a year, as provided from all fossil fuels combined (oil, gas and coal), plus nuclear and hydro (hydroelectric) power along with the meagre fraction of the total that is provided by renewables¹. The breakdown² of these various contributions is given in Table 1, and is presented more visually in Figure 1 as a bar chart. One sees immediately that almost two-fifths of total energy is derived from crude oil, and about one quarter each from coal and natural gas. Nuclear and hydro-power each contribute around 6%, while renewable energy from all sources, wind, wave, geothermal, wood, solar, *etc.* amount to less than 1%. These figures refer specifically to the year 2004, when the world got through 471 EJ of energy, and while

Table 1 Fuel type and average power in TW (10^{12} W) and energy/year in EJ (10^{18} J) (2004 figures)*

Fuel type	Average power	Energy/year
Oil	5.6 TW	180 EJ
Gas	3.5 TW	110 EJ
Coal	3.8 TW	120 EJ
Hydroelectric	0.9 TW	30 EJ
Nuclear	0.9 TW	30 EJ
Geothermal, wind, solar, wood	0.13 TW	4 EJ
Total	15.0 TW	471 EJ

*Data from ref. 2.

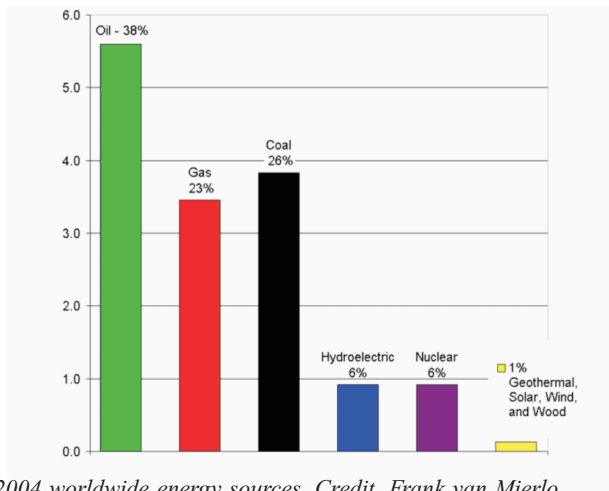


Fig. 1. 2004 worldwide energy sources. Credit, Frank van Mierlo.
http://commons.wikimedia.org/wiki/File:2004_Worldwide_Energy_Sources_graph.png

the relative proportion of each contributing energy source has remained fairly constant, it is clear that at a current 568 EJ, the demand placed on these energy sources by humans rises relentlessly (Figure 2). There are two aspects to be considered: firstly, the fossil fuels and uranium too (used for nuclear power) are in finite supply, since they were laid down by the forces of geology millions of years ago, and evidence is that their production will peak within the near future. Crude oil in particular is predicted to peak at some

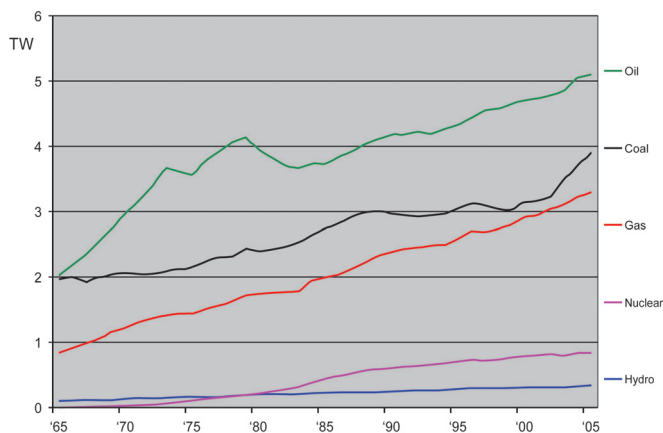


Fig. 2. Increase in use of energy sources over the period 1965–2005. Credit, Frank van Mierlo.
http://upload.wikimedia.org/wikipedia/commons/a/a0/World_Energy_consumption.png

point during the next 5 years. According to Figure 3, we are at the peak of oil production now—“peak oil”, beyond which world supplies of oil will decline forever³. The “oil-age” is coming to an end. There is much debate over just how much coal and gas there is left to be garnered, but the evidence is that the easily-extracted forms of both will plateau in production within this century. Secondly, the CO₂ produced by burning fossil fuels is thought to contribute to global-warming and climate-change^{4,5}. Thus both on grounds of resource-limitation and carbon emissions, alternative, ideally renewable sources of energy are needed.

2. Solar energy

Figure 4 summarises the quantity and fate of solar radiation striking the top of the Earth’s atmosphere^{1,2}. We see that 52 PW (10^{15} W) is reflected back into space (or 30% of the total). Thus, in outer space, there is more solar energy available to be collected, which has prompted potential schemes to launch photovoltaic arrays into space as satellites, with which to capture the Sun’s energy which is then beamed back to Earth in the form of microwaves for terrestrial applications. At the top of the atmosphere, with the Sun directly overhead, the radiation flux provides around 1.4 kW/m² of energy, the “solar constant”⁶. Since the total amount of energy (oil, gas, coal, nuclear, hydro, everything) used on Earth by humans amounts to a power of 18 TW, at 174 PW, the amount of radiation striking the exposed hemisphere of the Earth amounts to around 10,000 times that. So if we could capture even a small amount of that, the imminent energy crunch would thus be averted.

2.1 Means for capturing solar energy^{1,2}

- (1) Direct heating systems→on roof water heating systems; solar furnaces; concentrating solar thermal power (CSTP) plants, *etc.*
- (2) Photosynthesis (PS)→creates biomass, total of 200 EJ of fuel (Shell estimate) could be produced by hydrothermal conversion. PS is 12% efficient as a theoretical maximum, but most plants give 0.1–6%⁷. Growing biofuel crops also suffers from competition with food crops for fertile land, hence if we used all the available arable land in the UK (*i.e.* grew no food at all but turned each acre over to biofuel crops) we could only match around 10% of our fuel as is currently made from crude oil⁷.
- (3) Photovoltaics⁸.

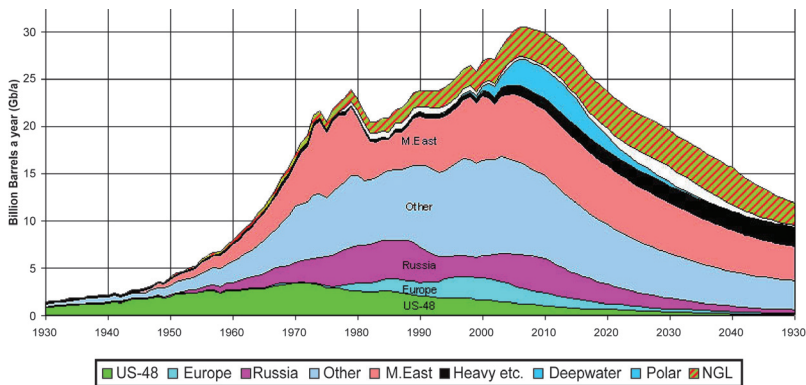


Fig. 3. The peak in oil production followed by its decline, according to the Association for the Study of Peak Oil.

http://www.exitmundi.nl/oilproblem_2004Scenariovan_deaspoassociation_for_the_study_of_peak_oil.jpg

In essence, light photons knock electrons into higher energy states in semi-conductor materials such as silicon and cause conduction (electron diffusion), generating electricity. The photo-active material needs a band-gap of $<3.2\text{ eV}$ (*i.e.* at the edge of the visible spectrum, 400 nm), and ideally down to around 1.0 eV (1250 nm)–which is the “near” IR region. The actual recovered efficiencies for single-junction silicon cells are now approaching the theoretical efficiency of 33%, which is way ahead of that for photosynthesis (6%).

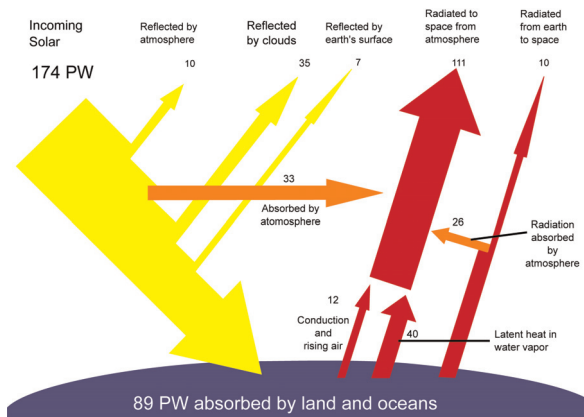


Fig. 4. Breakdown of the incoming solar energy. Credit, Frank van Mierlo.

http://upload.wikimedia.org/wikipedia/commons/5/50/Breakdown_of_the_incoming_solar_energy.svg

3. The solar spectrum in detail⁶

As noted, the energy of the Sun received at the top of the Earth's atmosphere amounts to 174 PW (petawatts = 10^{15} Watts). The "solar constant" is not really constant since the intensity of the energy received from the Sun varies somewhat according to the position of the Earth in its orbital cycle, and with the longitude of a given point on the Earth's surface, but it averages at 1366 Wm^{-2} as the amount of energy hitting the top of the Earth's atmosphere when the Sun is directly overhead. Broadly speaking, sunlight is the entirety of the electromagnetic radiation emitted by the Sun. The Earth's surface receives only around 70% of the overall radiation which is filtered by the atmosphere and around 30% of it is reflected back into space.

To calculate the amount of sunlight reaching the ground, both the elliptical nature of the Earth's orbit and the attenuation of the radiation by the Earth's atmosphere have to be accounted for. The extraterrestrial solar illuminance (E_{ext}), corrected for the elliptical orbit by using the day number of the year (dn), is given by Eqn (1):

$$E_{\text{ext}} = E_{\text{sc}} \left[1 + 0.034 \cdot \cos \left(2\pi \frac{\text{dn} - 3}{365} \right) \right] \quad (1)$$

where dn = 1 on 1 January; dn = 2 on 2 January; dn = 32 on February 1, *etc.* In this formula dn - 3 is used, because the closest approach of the Earth to the Sun and therefore the maximum E_{ext} , occurs around 3 January each year.

The solar illuminance constant (E_{sc}), is equal to $128 \times 10^3 \text{ lx}$ (lux). The direct normal illuminance (E_{dn}), corrected for the attenuating effects of the atmosphere is given by Eqn (2):

$$E_{\text{dn}} = E_{\text{ext}} e^{-cm} \quad (2)$$

where c is the atmospheric extinction coefficient and m is the relative optical airmass⁶.

The Earth receives a total amount of radiation determined by its cross section ($\pi \cdot R_{\text{E}}^2$) if account is taken of the angle θ at which the rays strike the Earth (using the Lambert cosine Law, and integrating $\cos \theta$ over the surface of the hemisphere)⁷, and noting that at any one moment half the planet is in darkness, which amounts to one quarter of the solar constant and is roughly 342 W/m^2 . The Earth captures around a mere one two billionth of the total amount of radiation that is emitted by the Sun⁶.

Table 2 Comparison of light received by planets in the Solar System*

Planet	Perihelion–aphelion distance (AU)	Solar radiation maximum–minimum (W/m ²)
Mercury	0.3075–0.4667	14,446–6,272
Venus	0.7184–0.7282	2,647–2,576
Earth	0.9833–1.017	1,413–1,321
Mars	1.382 –1.666	715–492
Jupiter	4.950 –5.458	55.8 –45.9
Saturn	9.048 –10.12	16.7 –13.4
Uranus	18.38 –20.08	4.04 –3.39
Neptune	29.77 –30.44	1.54 –1.47

*Data from ref. 6.

3.1 Sunlight intensity in the Solar System

The different planets in the Earth's Solar System vary in the intensity of the energy they receive from the Sun, since this is inversely proportional to the square of their distance from Sun. The difference between the maximum and minimum values further reflects the degree to which the particular planetary orbit deviates from the circular to the elliptical. A rough comparison of the amount of light received by each planet on the Solar System is given in Table 2.

3.2 Energy composition of the solar spectrum

The spectrum of the Sun's radiation approximates closely that of a black body at a temperature of about 5,800 K. Roughly 50% lies in the visible part of the electromagnetic spectrum and the other half mostly in the near-infrared region. There are also ultraviolet wavelengths present (Figure 5). The wavelengths of electromagnetic radiation striking the Earth's atmosphere lie in the range of 100–10⁶ nanometres (nm). For convenience, this can be divided into five regions in increasing order of wavelengths⁶:

- **Ultraviolet C** or (UVC) range: 100–280 nm. Ultraviolet radiation is of higher frequency than violet light and is invisible to the human eye; very little of it passes through the atmosphere to reach the Earth's surface since it is absorbed by photochemical reactions that occur within the ozone layer. This type of radiation has germicidal properties.

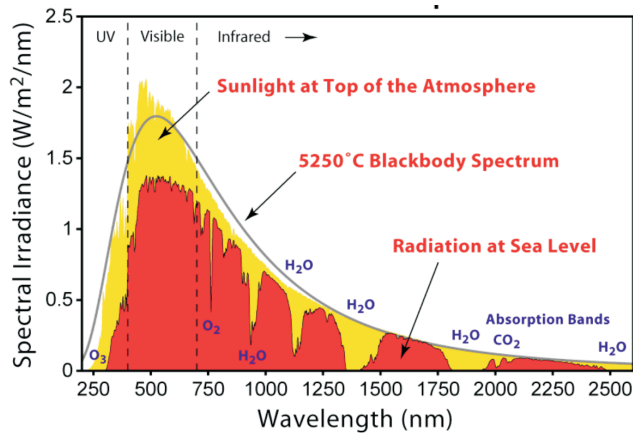


Fig. 5. The solar radiation spectrum for direct light at both the top of the Earth's atmosphere and at sea level. Credit, Robert A. Rohde, as part of the *Global Warming Art* project.

http://upload.wikimedia.org/wikipedia/commons/4/4c/Solar_Spectrum.png

- **Ultraviolet B** or (UVB) range: 280–315 nm. This is also absorbed by the atmosphere to a large extent, and along with UVC is responsible for the photochemical reactions that produce and maintain the ozone layer.
- **Ultraviolet A** or (UVA): 315–400 nm. This radiation range is traditionally thought of as being less damaging to the DNA, and is used to get a suntan and in PUVA therapy to treat psoriasis.
- **Visible light:** 400–700 nm. This range is visible to the naked eye.
- **Infrared radiation:** 700 nm– 10^6 nm. It is this region that is largely responsible for the heating effect of the sunlight. This may be furthermore divided into three types on the basis of wavelength:
 - Infrared A: 700–1,400 nm
 - Infrared B: 1,400–3,000 nm
 - Infrared C: 3,000– 10^6 nm (*i.e.* 1 mm).

4. Solar energy technologies

Solar energy technologies are broadly classified as being either passive or active according to the way they capture, convert and distribute sunlight. Among their applications are space heating and cooling through solar architecture, providing potable water by distillation and disinfection, lighting, hot water generation, heat for cooking, and heat for industrial processes. Active solar techniques

include the use of photovoltaic panels, or solar thermal collectors, which use either electrical or mechanical equipment, to convert sunlight into useful power outputs. Passive solar techniques include orienting the construction of a building toward the Sun, selecting materials with favourable thermal mass or light dispersing properties, and designing spaces that circulate air naturally. Active solar technologies increase the amount of energy produced and are considered supply side technologies, while passive solar technologies reduce the need for alternative energy sources and are generally considered demand side technologies⁹. Methods that specifically generate electricity (using either photovoltaic cells or thermal solar methods which use the Sun's energy to effectively boil water and drive a steam turbine) are normally described as solar power technologies.

About 70% of the incoming solar energy reaches the Earth's surface and is absorbed by land, the oceans and the atmosphere which raises their temperature. The circulation of the atmosphere is driven by warm, moist air rising from the oceans. At high altitudes, where it is sufficiently cold, water vapour condenses from the air forming clouds, from which rain falls onto the Earth's surface, thus driving the hydrological (water) cycle. As water condenses, its latent heat amplifies the convection process causing the winds, cyclones and anti-cyclones, while the Earth's surface is sustained at a mean 14°C by the absorption of sunlight by the oceans and land masses⁶. Light absorbed by green plants drives the process of photosynthesis⁷ which converts solar energy into chemical energy by the photochemical reaction between H₂O and CO₂ and is the source of all crop-plants and plant-based biomass.

The total solar energy absorbed by Earth's atmosphere, oceans and land masses amounts to approximately 3,850,000 EJ per year, and is more energy provided in a single hour than humanity uses in a whole year. Photosynthesis captures approximately 3,000 EJ per year in biomass.

From the data in Table 3, it might be deduced that any one of solar, wind or biomass would each be sufficient to provide for our entire human energy requirements, however, the increased use of biomass has resulted in deforestation *e.g.* to grow palm-oil, and has dramatically increased food prices by turning over arable land from food to biofuel production⁷. Since solar and wind are intermittent resources there are attendant problems of energy storage and providing a constant supply of energy from them. Thus none of them provide a complete solution, though they may each find application as part of a final energy mix.

Table 3 Yearly solar fluxes and human energy consumption*

Solar	3,850,000 EJ
Wind	2,250 EJ
Biomass	3,000 EJ
Primary energy use (2005)	487 EJ
Electricity (2005)	56.7 EJ

*Data from ref. 6.

5. Photovoltaic power generation¹⁰

The term “photovoltaic” derives from the Greek *φῶς* (*phos*) meaning “light”, and “voltaic”, meaning electric, to honour the name of the Italian physicist Volta after whom the volt is named. The photovoltaic effect was first recognized in 1839 by French physicist A.E. Becquerel. In 1883 Charles Fritts coated selenium with with an extremely thin layer of gold, thus creating a PV device which was only around 1% efficient. Russel Ohl patented the modern junction semiconductor solar cell in 1946, which was discovered while working on the series of advances that would eventually lead to the development of the transistor. In 1954, workers at Bell Laboratories accidentally found that silicon doped with certain impurities was very sensitive to light, and Daryl Chapin, along with Bell Labs colleagues Calvin Fuller and Gerald Pearson, invented the first practical device for converting sunlight into useful electrical power, with a sunlight energy conversion efficiency of around 6%. The first spacecraft to use solar panels was the US satellite Vanguard 1, launched in March 1958 and fitted with solar cells made by Hoffman Electronics. This milestone advance created interest in producing and launching a *geostationary communications satellite*, in which solar energy would provide a viable power supply. This was a crucial development which stimulated funding from several governments into research for improved solar cells. Today, the majority of photovoltaic modules are used for grid-connected power generation.

5.1 Resources for photovoltaics

There is plenty of silicon on Earth (sand, *etc.*), but if all the world’s electricity were to be made using conventional silicon-wafers of thickness 180–300 μm (first generation cells), we would need to multiply the present number of factories to make them by 100 and it would take more than 20 years¹¹ (Section 6.3). Silicon cells are

expensive with a pay-back time of 15–20 years for a typical house. Other materials, such as indium (in CIGS—*i.e.* copper indium gallium selenide) are literally in short supply and we will run out of indium in 5–10 years, unless wide-scale recycling programmes are introduced (Section 6.2). Thin-film (second generation) cells use around 1/100th the amount of material that first generation cells do. The material is applied to a surface such as glass or a ceramic or a plastic-film as a supporting substrate, *e.g.* CdTe, amorphous Si, CIGS and “micromorphous” (*microcrystalline* and *amorphous* in combination) silicon. Amorphous silicon (a-Si) has a higher bandgap (1.7 eV) than crystalline silicon (c-Si) (1.1 eV), which means it absorbs the visible part of the solar spectrum more strongly than the infrared portion of the spectrum. As nanocrystalline-Si (nc-Si) has about the same bandgap as c-Si, the nc-Si and a-Si can be combined in thin layers, creating a layered cell called a *tandem cell*. The top cell in a-Si absorbs the visible light and leaves the infrared part of the spectrum for the bottom cell in nanocrystalline Si. These are much cheaper but their efficiencies are lower at around 6–8% (*c.f.* 15% in practice for Si-cells). They are also less quickly degraded by radiation than are first-generation cells. The level of PV electricity production has increased by an average of 48% each year since 2002, making it the world’s fastest-growing energy technology. At the end of 2008, cumulative global production was 14,200 megawatts (MW)¹⁰. Around 90% of this generating capacity is tied into electrical grid-systems, rather than stand-alone installations. Figure 6 shows land area (small black dots) required to replace the world primary energy supply with solar electricity. The word “insolation” is used to define the amount of energy from the Sun which falls onto a given surface area and over most of the Earth this ranges from 150 to 300 W/m² or 3.5 to 7.0 kWh/m²/day⁶. Photovoltaic systems usually consist of solar cells packaged in photovoltaic modules (panels) which often are wired in multiples as solar PV arrays. In essence, photons from sunlight are absorbed by the solar panel and some of the electrons are energised so they can flow through the material thus creating an electric current. The word photovoltaic refers to the unbiased operating mode of a photodiode in that the current flowing through the device is driven entirely by the transduced light energy. Virtually all photovoltaic devices use a photodiode of some description.

Solar cells produce direct current (DC) electricity which can be used to power equipment or to charge a battery, say, which thus stores the energy. Since PV is mainly used to feed into electrical

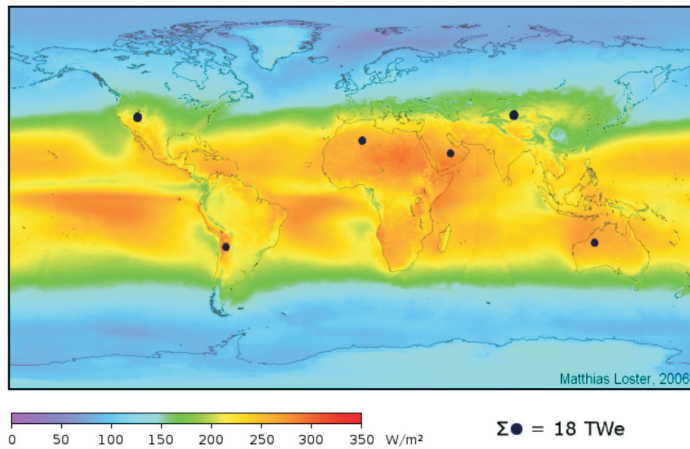


Fig. 6. Average insolation showing land area (small black dots) required to replace the world primary energy supply with solar electricity. 18 TW is 568 Exajoules (EJ) per year. Insolation for most people is from 150 to 300 W/m² or 3.5 to 7.0 kWh/m²/day. Credit, Mlino76.

grids, an inverter is introduced to convert the DC to AC. We see later in the context of space-applications where radiation damage is a particular problem for PV cells in the environment of outer space, but protection from the environment is nevertheless required even under terrestrial conditions, and so they are usually protected by a glass sheet. A single module (panel) is enough, e.g. in order to power an emergency telephone, but to power an entire a house and certainly a power plant the panels are arranged in arrays. There are financial incentives in Japan and Germany which have ushered-in an enormous growth in demand, which has been met by increased production.

5.2 Worldwide installed photovoltaic totals⁸

A record of 2.8 gigawatts peak (GWp) was achieved in 2007 worldwide of which the three leading countries (Germany, Japan and the USA) represent nearly 89% of the total PV installed world capacity. Germany was the fastest growing major PV market in the world during 2006 and 2007, with more than 1.3 GWp of PV installed in the latter year. The German PV industry supports over 10,000 jobs across the areas of production, distribution and installation. Photovoltaic power capacity is measured as maximum power output under standardized test conditions (STC) in “Wp” (Watts peak). However, the actual power output at a particular point in time may be lower or greater than this “rated”, value, depending

on geographical location, time of day, weather conditions, and other factors. Solar PV array capacity factors (efficiencies) are normally less than 25%, which is lower than that for most other commercial sources of electricity. Power stations fuelled by coal, gas, oil or nuclear generally run at the Carnot cycle efficiency of around 36% at their temperature differential employed. Hence, the 2006 installed base peak output would have provided an average output of 1.2 GW (assuming a capacity factor of $20\% \times 5,862 \text{ MWp}$), which represented 0.06% of the prevailing global demand.

5.3 Photovoltaic power stations

A summary¹² of the world's major PV power plants is given in Table 4, several of which were completed in Spain during 2008. As of April 2009, the largest PV power plants in the world are the Olmedilla Photovoltaic Park (Spain, 60 MW), the Puertollano Photovoltaic Park (Spain, 50 MW), the Moura photovoltaic power station (Portugal, 46 MW), and the Waldpolenz Solar Park (Germany, 40 MW). Many of these plants are integrated with agriculture and some of them use innovative tracking systems to follow the Sun's daily path across the sky to harvest more sunlight than is possible using conventional fixed-mounted systems. The 14 MW Nellis Solar Power Plant is located within the Nellis Air Force base in Clark County, Nevada, on the northeast side of Las Vegas. It is the largest solar PV system in North America and will generate in excess of 25 million kWh of electricity annually and supply more than 25% of the power used at the base (Figure 7).

5.4 Building-integrated photovoltaics¹³

Building-integrated photovoltaics (BIPV) are increasingly incorporated into new domestic and industrial buildings (*e.g.* Figure 8) as a principal or ancillary source of electrical power, and are one of the fastest growing segments of the photovoltaic industry. Typically, a PV-array is incorporated into the roof or walls of a building, and roof tiles with integrated PV cells are currently available. Arrays can also be retrofitted into existing buildings, usually on top of the prevailing roof structure. However, an integrated "designed-in" arrangement is cheaper and more pleasing to the eye. Where a building is located some distance from the general electricity supply, *e.g.* in remote or mountainous areas, PV may be the preferred possibility for generating electricity, or PV may be used together with wind, diesel generators and/or hydroelectric power. In

Table 4 *World major photovoltaic power plants*¹²

Name of PV power plant	Country	DC Peak Power (MW)	GWh/year	Capacity factor	Notes
(a) World's largest photovoltaic (PV) power plants (12 MW or larger)					
Olmedilla Photovoltaic Park	Spain	60	85	0.16	Completed September 2008
Lieberose Photovoltaic Park	Germany	53			2009
Puertollano Photovoltaic Park	Spain	50			Completed December 2008
Moura photovoltaic power station	Portugal	46	93	0.16	550,000 First solar thin-film CdTe modules.
Waldpolenz Solar Park	Germany	40	40	0.11	Completed December 2008
Amedo Solar Plant	Spain	34			Completed October 2008
Merida/Don Alvaro Solar Park	Spain	30			Completed September 2008
Planta Solar La Magascona & La Magasquilla	Spain	30			
Planta Solar Ose de la Vega	Spain	30			
Planta Fotovoltaico Casas de Los Pinos	Spain	28			
SinAn power plant	Korea	24	33		Completed October 2008
Planta fotovoltaica de Lucainena de las Torres	Spain	23.2			Completed August 2008
Parque Fotovoltaico Abertura Solar	Spain	23.1	47	0.23	
Parque Solar Hoya de Los Vincentes	Spain	23	41	0.20	
Huerta Solar Almaraz	Spain	22.1			Completed September 2008
Parque Solar El Coronil 1	Spain	21.4			
Solarpark Calveron	Spain	21.2	40	0.22	
Huerta Solar Almaraz	Spain	20			Completed September 2008
Planta solar fotovoltaico Calasparra	Spain	20			
Beneixama photovoltaic power plant	Spain	20	30	0.17	Tenesol, Aleo and Solon solar modules with Q-Cells

Table 4 World major photovoltaic power plants¹² (continued)

Name of PV power plant	Country	DC Peak Power (MW)	GWh/year	Capacity factor	Notes
(a) World's largest photovoltaic (PV) power plants (12 MW or larger) (continued)					
Parque Solar Olivenza	Spain	18			Completed October 2008
Parque Solar Bomillo	Spain	18			
Planta Solar Calzada de Oropesa	Spain	15			
Gochang power plant	Korea	15	23		Completed October 2008
Planta de energía solar Mahora	Spain	15			Completed September 2008
Koethen	Germany	14.75	13		200,000 First Solar thin-film CdTe modules. Completed December 2008
Nellis Solar Power Plant	USA	14.02	30	0.24	70,000 solar panels
Planta Solar de Salamanca	Spain	13.8	n.a.		70,000 Kyocera panels
Parque Solar Guadarranque	Spain	13.6	20	0.17	
Parque Solar El Realengo	Spain	13.2			
Parque Fotovoltaico Solten 1	Spain	13			
Lobosillo Solar Park	Spain	12.7	n.a.		Chaori and YingLi modules
Semptra Generation PV Plant	USA	12.6			Completed December 2008
Parque Solar Hinojosa del Valle	Spain	12			
Parque Solar Fotovoltaico Villafranca	Spain	12			High concentration PV technology
Erlasee Solar Park	Germany	12	14	0.13	1,408 Solon mover

Table 4 *World major photovoltaic power plants*¹² (continued)

Name of PV power plant	Country	DC Peak Power (MW)	GWh/year	Capacity factor	Notes
(b) Important selected smaller plants					
Serpa solar power plant ^[7]	Portugal	11	20	0.21	52,000 solar modules
Pocking Solar Park	Germany	10	11.5	0.13	57,912 solar modules
Monte Alto photovoltaic power plant	Spain	9.5	14	0.17	
Viana Solar Park	Spain	8.7	11	0.14	
Gottelborn Solar Park	Germany	8.4	8.4	0.11	
Alamosa photovoltaic power plant	USA	8.2	17	0.24	Completed December 2007
Bavaria Solar Park in Muhlhausen	Germany	6.3	6.7	0.12	57,600 solar modules
Huerta solar de Aldea del Conde	Spain	6.3			Completed October 2007
Huerta Solar Crevillent	Spain	6	8	0.15	Completed January 2008
Huerta Solar de Olmedilla	Spain	6			Completed November 2007
Rote Jahne Solar Park ^[10]	Germany	6	5.7	0.11	90,000 first solar thin-film modules
Darro Solar Park	Spain	5.8	11.6	0.23	Conergy and Sunpower modules
Kameyama	Japan	5.2	n.a.		47,000 square metres on Sharp LCD factory roof

To place these numbers into perspective, it may be noted that the largest non-photovoltaic solar plant, the solar thermal SEGS in California, has an installed capacity of 354 MW. The largest nuclear power stations generate more than 1,000 MW.



Fig. 7. Solar array at Nellis Air Force Base. These panels track the Sun in one axis.
Credit: U.S. Air Force photo by Senior Airman Larry E. Reid Jr.
http://upload.wikimedia.org/wikipedia/commons/d/de/Nellis_AFB_Solar_panels.jpg

such circumstances batteries are usually used to store the electric power. In locations near the grid, however, feeding the grid using PV panels is more practical. As a failsafe measure in case of power failure, some grid tied systems are arranged so they may be disconnected from the grid for local power generation. Building-Integrated Photovoltaic modules are available in several forms.

- Flat roofs
 - The most widely installed to date is a thin-film cell integrated to a flexible polymer roofing membrane.
- Pitched roofs
 - Modules shaped like multiple roof tiles
 - Solar shingles are modules designed to look and act like regular shingles, while incorporating a flexible thin film cell.
- Facades
 - Modules mounted on exterior faces of buildings can provide additional weatherproofing or simply be used as a style element.
- Glazing
 - (Semi)transparent modules can be used to replace a number of architectural elements commonly made with glass or similar materials, e.g. windows and skylights.



Fig. 8. The CIS Tower, Manchester, England, was clad in PV panels at a cost of £5.5 million. It started feeding electricity to the national grid in November 2005. Credit, Pit-yacker.

http://upload.wikimedia.org/wikipedia/commons/6/6e/CIS_Tower.jpg

5.5 Power costs⁸

The PV industry is beginning to adopt a “levelized cost of energy” (LCOE) as the unit of cost. Table 5 is a purely mathematical construct, and illustrates the calculated total cost in US cents per kilowatt-hour of electricity generated by a photovoltaic system as a function of the investment cost and of the efficiency, assuming some accounting parameters such as cost of capital and depreciation period. The row headings on the left show the total cost per peak kilowatt (kWp) of a PV installation, while the column headings across the top express the annual energy output in kilowatt-hours

expected from each installed peak kilowatt. Logically, this varies according to geographic region because the average insolation depends precisely on the latitude in respect to the Sun's rays and their angle with respect to the surface of the Earth. Using solar tracking, still more perpendicular sunlight may be garnered, hence increasing the total energy output. The calculated values in the table reflect the total cost in cents per kilowatt-hour generated, assuming a 10% total capital cost (for instance 4% interest rate, 1% operating and maintenance cost, and depreciation of the capital outlay over 20 years).

6. Environmental impacts¹⁴

In some ways, similar to arguments made in favour of nuclear power, there are no harmful emissions during the generation of power using PV. That said, when the devices are produced there are costs both in terms of pollution and input energy. This is often referred to as the energy input to output ratio or more generally energy returned on energy invested (EROEI). If more energy is needed to produce the system than is ultimately produced by it the strategy is overall inefficient. Also, placement of photovoltaics affects the environment. If they are located where photosynthesizing plants would normally grow, they simply substitute one potentially renewable resource (biomass) for another. Even though the biomass cycle converts *solar radiation energy to chemical energy* with significantly less efficiency than photovoltaic cells alone, it is much simpler to simply plant seeds than it is to mine and process materials and to fabricate solar cells from them. In the latter case, there are energy costs too, mainly derived from fossil sources and the issue (as we see later) that many metals are in very short supply, especially indium and gallium as are used to make electronic devices including PV.

One analysis¹⁴ indicates that PV causes 25–32 g of CO₂/kWh over its working lifetime but this could be reduced to 15 g/kWh. This can be compared¹⁰ with around 915 g/kWh for a coal-fired power station, and 6–25 g/kWh for nuclear and 11 g/kWh for wind power. Since cadmium is a toxic element with a tendency to accumulate in food chains, there is some concern over its use in cadmium telluride solar cells. However, the amount used in thin-film modules is around only 5–10 g/m² and within the scope of current technologies, the emissions of cadmium amount to around 0.3–0.9 micrograms/kWh over the whole life-cycle of the CdTe cell¹⁴. Interestingly, the emissions from the cell itself are practi-

Table 5 Average cost in cents/kWh over 20 years for solar power panels.*

Cost	Insolation									
	2400 kWh/kW p·yr	2200 kWh/kW p·yr	2000 kWh/kW p·yr	1800 kWh/kW p·yr	1600 kWh/kW p·yr	1400M kWh/kW p·yr	1200 kWh/kW p·yr	1000 kWh/kW Wp·y	800 kWh/kW p·yr	
200\$/kWp	0.8	0.9	1.0	1.1	1.3	1.4	1.7	2.0	2.5	
600\$/kWp	2.5	2.7	3.0	3.3	3.8	4.3	5.0	6.0	7.5	
1000\$/kWp	4.2	4.5	5.0	5.6	6.3	7.1	8.3	10.0	12.5	
1400\$/kWp	5.8	6.4	7.0	7.8	8.8	10.0	11.7	14.0	17.5	
1800\$/kWp	7.5	8.2	9.0	10.0	11.3	12.9	15.0	18.0	22.5	
2200\$/kWp	9.2	10.0	11.0	12.2	13.8	15.7	18.3	22.0	27.5	
2600\$/kWp	10.8	11.8	13.0	14.4	16.3	18.6	21.7	26.0	32.5	
3000\$/kWp	12.5	13.6	15.0	16.7	18.8	21.4	25.0	30.0	37.5	
3400\$/kWp	14.2	15.5	17.0	18.9	21.3	24.3	28.3	34.0	42.5	
3800\$/kWp	15.8	17.3	19.0	21.1	23.8	27.1	31.7	38.0	47.5	
4200\$/kWp	17.5	19.1	21.0	23.3	26.3	30.0	35.0	42.0	52.5	
4600\$/kWp	19.2	20.9	23.0	25.6	28.8	32.9	38.3	46.0	57.5	
5000\$/kWp	20.8	22.7	25.0	27.8	31.3	35.7	41.7	50.0	62.5	

* Data from ref. 10.

cally zero and the figure refers mainly to the use of electricity derived from coal and lignite. Life-cycle cadmium emissions from coal is 3.1 microgram/kWh, lignite 6.2, and natural gas 0.2 microgram/kWh.

6.1 Energy payback time and energy returned on energy invested (EROEI)

The energy payback time is the time required to produce an amount of energy equal to that used during production and is arrived at via a life cycle analysis of the energy costs involved. The EROEI is another key indicator of environmental performance, tightly related to the energy payback time, and is the ratio of electricity generated divided by the energy required to build *and maintain* the equipment. Both figures seem to be improving. In 2000 the energy payback time was estimated as 8–11 years but more recent studies suggest that technological progress has reduced this to 1.5–3.5 years for crystalline silicon PV systems¹⁴. Thin film cells (which use far less semiconductor material, perhaps 1/100th that for a first generation cell), now have energy pay-back times in the range of 1–1.5 years, and given that they should operate for at least 30 years, the EROEI is in the range of 10–30.

6.2 Silicon processing¹⁰

Although silicon is a very common element in the Earth's crust, it is normally bound in silica or silica sand (SiO_2). Silicon is produced industrially by the reaction between carbon (charcoal) and silica at a temperature around 1700°C . The process is called carbothermic reduction, and for each tonne of silicon that is produced, around 1.5 tonnes of carbon dioxide is also formed. The bonds between silicon and oxygen are very strong and it is necessary to input considerable energy to make them undergo chemical reactions, and to place the amount of energy into context, it takes one to two years for a conventional solar cell to generate as much energy as was used to make the silicon it contains. Solid silica can also be reduced to pure silicon by direct electrolysis in a molten salt bath at a much lower temperature of 800 to 900°C . Interestingly, silicon produced by the electrolytic method is porous and easily converted to a fine powder, with a particle size of a few micrometres. Thus new solar cell technologies may arise from its use.

In order to reduce the amount of silicon needed, a silicon wafer, typically 1–2 mm thick is taken, and a multitude of parallel, transverse slices cut across the wafer, to make a large number of slivers of thickness of 50 microns and of width equal to the original wafer thickness. By rotating these slices through 90 degrees, the surfaces corresponding to the faces of the original wafer become the edges of the slivers. Thus, *e.g.* a 150 mm diameter, 2 mm-thick wafer with an exposed silicon surface area of about 175 cm² per side is transformed into about 1000 slivers having dimensions of 100 mm × 2 mm × 0.1 mm, exposing a silicon surface area of about 2,000 cm² per side. Using this technique, one silicon wafer is sufficient to produce a 140 watt panel, rather than nearer 60 wafers as are required to make a conventional module with the same power output.

6.2.1 *A slim chance for solar energy?*

Such is the explosive growth of the solar power industry that manufacturers of polysilicon, which is moulded into a long ingot and then sliced into thin wafers for solar cells, cannot keep up with demand for it. It appears that new supplies are not due to come on stream until 2010, and meanwhile the price of polysilicon has tripled in the past two years and could continue to rise. In the light of this circumstance, it is of interest to look over a few figures and facts about what might be extracted from sunlight, and on what scale this could be achieved. Indeed, is a solar economy possible? The solar radiation flux (sunlight intensity) at the top of the atmosphere is 1,400 W/m², but some of this energy is absorbed by the atmosphere as the radiation passes through it. At the equator, at sea level, and at noon on a clear day, the solar flux reaching the Earth is attenuated to 1,000 W/m². If the performance of the solar cell were perfect (*i.e.* 100% conversion of radiation to electricity) an electrical output of 1,000 W/m² (*i.e.* 1 kW/m²) would be obtained. However, the actual output is nearer 100 W, *i.e.* 10% efficiency. Undoubtedly, the technology will improve, and there are solar cells in research laboratories that can generate electricity with an efficiency of more than 30%, but 10% is a reasonable figure for a commercial solar cell at present, so we will work with this. In the UK, however, an average value for the received solar flux is nearer 150 W/m², which at 10% efficiency means 15 W/m².

This is, of course, only during the day. At night, the power output drops essentially to zero. In the early morning and late day, more of the Sun's energy is absorbed by the atmosphere; clouds also reduce the power, and so the actual output is highly dependent on the weather conditions and hence the emphasis on finding ways to "store" the electricity produced by photovoltaic technology.

To get some rough numbers and a scale of what is required, let us consider generating capacities for the UK, the USA, China and the world as a whole, and hence the area of photovoltaic solar panels required to meet these outputs.

According to "The CIA World Factbook (2003)": (available at <https://www.cia.gov/news-information/press-releases-statements/press-release-archive-2003/pr08122003>), in that year the UK generated 360.9 billion kWh of electricity. Dividing by the number of hours in the year, this amounts to a generating capacity of $360.9 \times 10^9 \text{ kWh} / 8760 \text{ h} = 41.2 \text{ GW}$ (41,200 MW). Hence, we would need:

$41.2 \times 10^9 \text{ W} / (15 \text{ W/m}^2) = 2.74 \times 10^9 \text{ m}^2$ of solar panel area to generate it.

Since 1 square kilometre (km^2) = 1 million m^2 , this amounts to 2,747 km^2 , which is only 1.2% of the total land area of the UK mainland (230,000 km^2). For the USA, the total is 3.717 trillion kWh = $3.717 \times 10^{12} \text{ kWh} / 8,760 \text{ h} = 425 \text{ GW}$. China generated $1.42 \times 10^{12} \text{ kWh} / 8,760 = 162 \text{ GW}$. For the entire world, a grand total of 14.85 trillion kWh was generated, which translates to a generating capacity of $14.85 \times 10^{12} / 8,760 = 1,695 \text{ GW}$.

The relative solar panel areas appear quite respectable. I leave the reader to work out the percentage of total area required for the U.S. and China, and confine myself to noting that for the whole world, $1,695 \times 10^9 \text{ W} / (15 \text{ W/m}^2) = 113,000 \text{ km}^2$ is needed.

This is worked out on the basis of the UK's sunshine and the area could be reduced considerably by placing the panels nearer to the equator, so probably, any solar-powered "local" electricity generating operation would be more efficient in the developing world, e.g. India, Africa, South America—China is more complex in terms of its climate. Given that 30% of the surface of the Earth is land (*i.e.* not presently covered by sea – a value that might change if sea levels rise; although they appear to be falling in the Arctic for reasons no one understands), and assuming the planet to be a perfect sphere, we have a land area of:

$$0.3 \times 4\pi \times r^2 = 0.3 \times 4\pi \times (6366)^2 = 153 \times 10^6 \text{ km}^2.$$

This is a rough estimate made on the basis of a circumference of 40,000 km for the Earth, and hence a radius (r) of $40,000/2\pi = 6,366$ km.

Hence, we need “only” cover the Earth to the extent of $113,000/153 \times 10^6 = 0.07\%$, which does not sound much. Indeed, it corresponds to an area of about 300 kilometres by 380 kilometres, or 235 miles by 300 miles, which is almost exactly half that of the UK mainland. Not that I am suggesting we host the whole world’s solar production capacity within these shores.

As noted, the Sun shines only during the day, and we can expect a sizable output for, say, only 8 hours per day (on average: more in the summer, less in the winter). Therefore, some other means for providing our electrical power is necessary during the dark (night) period. Alternatively and in principle, we might have around three times the area of solar panelling (3×8 hours = 24 hours) to meet the total demand required, and store the extra in the form of an “energy carrier”, either as electrons (batteries) or hydrogen. If we need this energy in the form of electricity, then “electrons” stored in batteries would be the better bet, as getting electricity “back” from hydrogen via fuel cells would be overall less efficient.

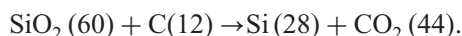
How much silicon would be required to make the required swathe of solar panels? To estimate this, I shall assume that a silicon layer with a thickness of 200 microns ($= 0.02$ cm) is to be used (this is toward the “thin” end of the 180–350 micron range quoted in Wikipedia for solar cells).

The total required solar panel area of $113,000 \text{ km}^2 = 113,000 \times 10^6 \text{ m}^2 = 113,000 \times 10^6 \times 10^4 \text{ cm}^2$. This corresponds to a volume of $1.13 \times 10^{15} \times 0.02 = 2.26 \times 10^{13} \text{ cm}^3 = 2.26 \times 10^7 \text{ m}^3$.

Assuming an average density of silicon of 2.3 tonnes/m^3 , this volume corresponds to:

$2.26 \times 10^7 \text{ m}^3 \times 2.3 \text{ tonnes/m}^3 = 51.98 \times 10^6 \text{ tonnes}$; *i.e.* about 52 million tonnes of pure silicon.

As noted, the manufacture of one tonne of silicon is reckoned to cause the release of 1.5 tonnes of carbon dioxide. This, presumably, is reckoned on the basis of an overall mass balance as:



From the ratio of molecular/atomic masses for CO_2 and Si, $44/28$, a value of 1.57 is obtained, in close agreement with the above estimate. However, since the reaction occurs at 1,700 degrees C, a considerable input of energy is required in the

form of electricity to make the reaction “go”, with an additional amount of CO₂ being unleashed skyward. Indeed, it is estimated that 13 MWh of electricity is used to make one tonne of pure silicon. To make the 52 million tonnes of silicon required for our global solar programme would demand 6.76×10^{11} kWh. We are not of course going to make it all in one year, and perhaps manufacture over 20 years would be more realistic. However, that still means making 2.6 million tonnes of silicon every year, a figure to be compared with the current 30,000 tonnes currently produced, and in factories that make up to 10,000 tonnes per year each (some are far smaller than this). Hence, for a start we need something like 100 times the number of silicon factories that we now have!

What about the power requirement for them? To arrive at a per annum estimate we divide the total 6.76×10^{11} kWh by 20 years, which gives us 3.38×10^{10} kWh, and is to be compared with the world total electricity production of 14.85×10^{12} kWh. Hence, for a 20-year silicon programme, we would need at this rate to increase the world’s annual electricity production by just 0.23%. Nonetheless, building the number of factories necessary to manufacture “pure” silicon on 100 times the scale of current production is simply breathtaking, especially given the difficulty of even meeting the existing demand. Taken with the acquisition of the silica “ore” and the production of charcoal at the necessary grade to make “solar grade silicon”, along with the fabrication of the solar panels themselves, the whole enterprise would be a stupendous undertaking. The message is clear that solar will never become a sole producer of the world’s electricity, although it will become increasingly important for stand-alone applications, particularly in the developing world. My considerations here are only made over current electricity production. If we try to factor in how much provision, *e.g.* by solar, would be required to produce electrons or hydrogen to run the world’s transport systems at their current and rising scale, we could easily multiply the above estimates by a factor of three or four: *i.e.* renewables offer us little comfort in the absence of energy efficiency, which must be our leading step forward; then we may be in with a slim chance. The best option for photovoltaic technology is through the development of thin-film technology, which uses perhaps 1/100th of the amount of semiconductor material, but the task is still monumental on the grand scale, while more localised applications are thus favoured. Other means to capture solar-energy are through roof-based water-heater systems.

6.3 *Metals shortages*¹⁵

Evidence of peaking is found for a number of minerals, *e.g.* mercury around 1962; lead in 1986; Zircon in 1990; selenium in 1994; gallium in 2000. The results for gallium are significant, both in that the peak occurred seven years ago and in the size of its total reserve, which when compared with the amount used worldwide by the electronics industry implies that we may run short of gallium in the near future. Tellurium and selenium are two other minerals that underpin the semiconductor industry and it appears that their decline in production may also impact negatively on future technologies that are entirely reliant upon them, since there are no obvious substitute materials with precisely equivalent properties. Probably there is only 5–10 years worth of indium left. These conclusions rest upon the case that the determined “peaks” represent actual global production maxima. Indeed, more reserves of all minerals may yet be found if we look assiduously enough for them; but herein lies the issue of underpinning costs, both in terms of finance and energy. It is the latter that may determine the real peaking and decline of minerals, which extend beyond the simple facts, say, of mining and refining a metal from its crude ore. There is also the cost-contribution from the energy needed to garner energy-materials such as oil, gas, coal and uranium, and thence to turn them into power and machinery.

The whole “extractive system” is interconnected through required underpinning supplies of fossil fuels, and it is perhaps this that explains why the production of so many minerals seems to be peaking during the period between the latter part of the 20th century and the start of the 21st, in a virtual mirror-image of the era when troubles in the production of fossil fuels (notably oil) were experienced across the globe. Hence, it may be the lack of fossil fuels which determines the real amount of all other minerals that can be brought onto the world markets¹⁵.

6.3.1 *The role of recycling*

In the face of resource depletion, recycling looks increasingly attractive. In this stage of development of the throw-away society, now might be the time to begin “mining” its refuse. A recent analysis has shown part-per-million (p.p.m.) quantities of platinum in road-side dust¹⁶, which is similar to the 3 p.p.m. concentration in South African platinum ore. It is suggested that extracting platinum from this dust, which originates in catalytic converters, might prove

lucrative and would expand the limited amount of platinum available, which even now does not meet demand for it. Discarded cell-phones too, might be a worthwhile source. For metals such as hafnium and Indium, recycling is the only way to extend the lifetime of critical sectors of the electronics industry. This is true also of gallium, tellurium and selenium, since all of them are past their production peak, which forewarns of imminent potential production shortages and escalating prices (Table 6). While recycling of base-metals from scrap is a mature part of an industry worth \$160 billion per year, current efforts to recover and recycle rare-metals are far less well advanced. However, in view of its present high-price, rhenium is now recovered from scrap bimetallic catalysts used in the oil refining industry. I expect to see an expansion of this top-end of the metals-market since rising demand for rare-metals will confer highly lucrative profits. It might be argued that we will never “run-out” of metals because their atoms remain intact, but the more dispersion that occurs in converting concentrated ores into final products, the more difficult and hence energy intensive it becomes to reclaim those metals in quantity (Table 7). In a sense, the problem is the same as deciding which quality of ore to mine in the first place: we now need to either find richer sources to recycle from or arrange how we use these materials in the first place to facilitate recycling. Ultimately, recycling needs to be deliberately designed into an integrated paradigm of extraction, use and reuse, rather than treating it as an unplanned consequence.

7. Solar cells¹⁰

Solar cells are classified into three generations which indicates the order in which each became important. At present, there is concurrent research into all three generations while the first generation technologies are most highly represented in commercial production, accounting for 89.6% of 2007 production (*e.g.* Figure 9). First-generation cells are large-area, high-quality single-junction devices. The technologies to produce them involve high inputs of both energy and labour which makes reducing costs of production practically impossible. For this reason, second generation (thin-film) approaches have been developed to minimise the costs and materials employed to make solar cells. The most successful materials used to make thin-films are cadmium telluride (CdTe), copper indium gallium selenide (CIGS), amorphous silicon and micromorphous silicon, which are coated onto a supporting

Table 6 *Metals under threat: the world total reserve of each, and the expected time of exhaustion based on current rates of production and their principal uses**

Aluminium, 32,350 million tonnes, 1027 years (transport, electrical, consumer-durables)
Arsenic, 1 million tonnes, 20 years (semiconductors, solar cells)
Antimony, 3.86 million tonnes, 30 years (some pharmaceuticals and catalysts)
Cadmium, 1.6 million tonnes, 70 years (Ni–Cd batteries)
Chromium, 779 million tonnes, 143 years (chrome plating)
Copper, 937 million tonnes, 61 years (wires, coins, plumbing)
Germanium, 500,000 tonnes (US reserve base), 5 years (semiconductors, solar-cells)
Gold, 89,700 tonnes, 45 years (jewellery, “gold-teeth”)
Hafnium, 1124 tonnes, 20 years (computer-chips, nuclear control-rods)
Indium, 6000 tonnes, 13 years (solar-cells and LCDs)
Lead, 144 million tonnes, 42 years (pipes and lead-acid batteries)
Nickel, 143 million tonnes, 90 years (batteries, turbine-blades)
Phosphorus, 49,750 million tonnes, 345 years (fertilizer, animal feed)
Platinum/rhodium, 79,840 tonnes, 360 years for Pt (jewellery, industrial catalysts, fuel cells, catalytic converters)
Selenium, 170,000 tonnes, 120 years (semiconductors, solar cells)
Silver, 569,000 tonnes, 29 years (jewellery, industrial catalysts)
Tantalum, 153,000 tonnes, 116 years, (cell phones, camera lenses)
Thallium, 650,000 tonnes, 65 years (high-temperature superconductors, organic reagents)
Tin, 11.2 million tonnes, 40 years, (cans, solder)
Uranium, 3.3 million tonnes, 59 years (nuclear power-stations and weapons)
Zinc, 460 million tonnes, 46 years (galvanizing)

*Data from ref. 15.

substrate such as glass or a ceramic. These second generation technologies hold the promise of higher light-conversion efficiencies, particularly CIGS-CIS, dye-sensitized cells (DSC) and CdTe which offers significantly lower production costs, although as noted these are toxic materials and there is the issue of how much of

Table 7 *Predicted effect of the growth in world population and new technologies on the lifetime of key metals**

Antimony, 15–20 years
Hafnium, 10 years
Indium, 5–10 years
Platinum, 15 years
Silver, 15–20 years
Tantalum, 20–30 years
Uranium, 30–40 years
Zinc, 20–30 years

*Data from ref. 15.



Fig. 9. A solar cell made from a monocrystalline silicon wafer. Credit, United States Department of Energy.
http://upload.wikimedia.org/wikipedia/commons/9/90/Solar_cell.png



Fig. 10. Polycrystalline PV cells laminated to backing materials in a PV module. Credit, Georg Slickers. http://upload.wikimedia.org/wikipedia/commons/1/15/Polycrystalline-silicon-wafer_20060626_568.jpg

them, especially indium, there is available. A series of third generation technologies, which include quantum dot cells, aims to enhance the relatively poor efficiencies of second generation (thin-film) technologies while keeping production costs down.

Solar cells are most often incorporated within a PV module in which they are connected in series, thus producing an additive voltage. The module is usually protected by a sheet of glass on the front (Sun up) side, which protects the semiconductor wafers from the elements while allowing light to pass through. Since connecting cells in parallel yields a higher current, the modules are further interconnected, in series or parallel, or both, to create an array (Figure 10) with the desired peak DC voltage and current.

7.1 An overview of the cell mechanism

1. Photons in sunlight hit the solar panel and are absorbed by a semiconducting material, such as silicon, which excites electrons from atoms, knocking them free.
2. The electrons then flow through the material producing electricity. The electrons are restricted to move in a single direction by the structure of the cells. Complementary positive charges are also created and are called “holes” which flow in the opposite direction to the electrons.
3. An array of multiple solar cells is able to convert solar energy into an amount of direct current (DC) electricity sufficient to power an electrical device of some kind.

When a photon hits a piece of silicon, one of three things can happen:

1. The photon can pass straight through the silicon—this happens for photons with less energy than the band gap.
2. The photon can be scattered from the surface.
3. If the photon has an energy greater than the silicon band gap, an electron-hole pair is produced and the excess energy usually ends up as heat.

A photon need only have an energy above that of the band gap in order to excite an electron from the valence band into the conduction band. Since, as noted (Section 3.2), the solar frequency spectrum approximates to a black body spectrum at $\sim 6,000$ K, much of the solar radiation reaching the Earth is composed of photons with energies greater than the band gap of silicon. These higher energy photons will still be absorbed by the solar cell, but the difference in energy between these photons and the silicon band

gap is converted into heat (via lattice vibrations—called phonons) rather than into usable electrical energy. It is thus an inefficient process in terms of light to electricity conversion since so much of the incident light energy (insolation) is wasted.

There are two main modes for charge carrier separation in a solar cell:

1. Drift of carriers, which is driven by an electrostatic field established across the device.
2. Diffusion of carriers from zones of high carrier concentration to zones of low carrier concentration (following a gradient of electrochemical potential).

In the widely used p–n junction solar cells, the dominant mode of charge carrier separation is by drift. However, in non-p–n-junction solar cells (typical of the third generation solar cells, e.g. dye and polymer solar cells), it is demonstrated that a general electrostatic field is absent, and the dominant mode of separation is through charge carrier diffusion.

7.1.1 The p–n junction

The usual solar cell is configured as a large-area p–n junction made from silicon. If a piece of p-type silicon is placed in intimate contact with a piece of n-type silicon, then a diffusion of electrons occurs from the region of high electron concentration (the n-type side of the junction) into the region of low electron concentration (p-type side of the junction). When the electrons diffuse across the p–n junction, they recombine with holes on the p-type side. The electric field established across the p–n junction creates a diode that permits the flow of current in just one direction across the junction. The region where electrons have diffused across the junction is called the depletion region because it no longer contains any mobile charge carriers. It is also described as the “space charge region”.

7.2 Solar cell efficiency factors

7.2.1 Energy conversion efficiency

A solar cell’s *energy conversion efficiency* (η), is the percentage of energy from absorbed light that is converted to electrical energy, when the cell is connected as part of an electrical circuit. It is calculated [Eqn (3)] using the ratio of the maximum power point, P_m , divided by the input light *irradiance* (E , in W/m^2) under

standard test conditions (STC) and the *surface area* of the solar cell (A_c in m^2).

$$\eta = \frac{P_m}{E \times A_c} \quad (3)$$

STC specifies a temperature of 25°C and an irradiance of 1000 W/m^2 with an air mass 1.5 (AM1.5) spectrum. These correspond to the irradiance and spectrum of sunlight incident on a clear day upon a Sun-facing 37° -tilted surface with the Sun at an angle of 41.81° above the horizon^{17,18}. This condition is chosen since it approximates to that prevailing at the solar noon at the spring and autumn equinoxes in the continental United States, if the cell surface is oriented directly toward the Sun. Under these conditions a solar cell of 12% efficiency with a 100 cm^2 (0.01 m^2) surface area can be expected to produce approximately 1.2 watts of power. In practice, the energy losses from a solar cell are a product of reflectance losses, the thermodynamic efficiency limit, electron-hole recombination losses and losses due to electrical resistance. However, since these parameters are not readily measured directly, other more tractable parameters are used instead: thermodynamic efficiency, quantum efficiency, v_{oc} ratio, and fill factor.

7.2.2 Comparison of energy conversion efficiencies

In space, where there is no atmosphere, the spectrum of the Sun is relatively unattenuated. At the Earth's surface, the received solar spectrum is modified by filtration through the atmosphere. In order to avoid confusion, a system was devised to calculate this filtering effect, and is accounted simply from Air Mass 0 (AM0) in space, to approximately Air Mass 1.5 on Earth. By multiplying the spectral differences by the quantum efficiency of a particular solar cell, the efficiency of the device is obtained. Hence, a silicon solar cell in space might have an efficiency of 14% at AM0, but have an efficiency of 16% on Earth at AM 1.5. It should be noted that terrestrial efficiencies are in general greater than space efficiencies.

Solar cell efficiencies vary from 6% for amorphous silicon-based solar cells to 40.7% with multiple-junction research lab cells and 42.8% with multiple dies assembled into a hybrid package¹⁹. Solar cell energy conversion efficiencies for commercially available *multi-crystalline Si* solar cells are around 14–19%²⁰. Indeed, the highest efficiency cells are not necessarily the most economical—as an example, a 30% efficient multijunction cell based on expensive materials such as gallium arsenide or indium selenide produced in

low volume, might cost perhaps 100 times as much as an 8% efficient amorphous silicon cell in mass production, while only delivering about four times the electrical power. Nonetheless, the intensity of solar power can be boosted using “concentrator systems”, and increasing the concentration of photogenerated carriers, so increasing the efficiency by up to 15%. These concentrator systems have only begun to become economic through the development of high efficiency GaAs cells. Typically, concentrating optics are used to achieve this effect, and a typical concentrator system may use a light of intensity 6-400 times the Sun, but increase the efficiency of a one Sun intensity GaAs cell from 31% at AM 1.5 to 35%¹⁰.

7.3 Concentrating photovoltaics²¹

In a concentrating photovoltaic (CPV) system, an array of lenses or mirrors covering a relatively large surface area is used to focus sunlight onto a much smaller area of photovoltaic cells, perhaps by a factor of a hundred. Nearly all concentration systems need a one axis or two axis tracking system, since most systems only use direct sunlight and need to be angled at the Sun with less than a 3 degree error. It is often claimed that the primary reason for using CPV is that less semiconductor material is required per kW of energy, but in reality the saving is slight especially given the envisaged huge expansion of PV solar power. There are three classifications for CPV systems: low concentration with a solar concentration of 2–100 Suns. For economic reasons, conventional or modified silicon solar cells are typically used, and, at these concentrations, the amount of attendant heat is sufficiently low that active cooling is unnecessary. Medium CPV means a concentration of say 100–300 Suns, and now cooling and more complex solar tracking devices are required. Finally, there are high concentration photovoltaics (HCPV) systems which use dish reflectors or Fresnel lenses that concentrate sunlight to intensities of above 200 Suns or more. In the latter case, highly efficient cooling is necessary both to avoid thermal disintegration of the cell material and to largely prevent performance loss at high temperatures. There are multijunction solar cells, more efficient than silicon cells and originally designed for non-concentrating space-based satellites, which have been re-engineered for use with CPV, to cope with the high-current densities encountered: typically 8 A/cm² at 500 Suns²¹. We shall discuss concentrating

thermal Solar Systems later, which collect heat and use it to drive a steam-turbine and produce electricity but meanwhile note that it is possible to use concentrating photovoltaics and thermal technology in combination (CPVT) to produce both electricity and thermal energy (heat) in the same module. CPVT systems can be used to power individual homes very effectively since there is an increase in total energy output to 40–50%, from ordinary solar panels which have an efficiency of 10–20% efficiency, the rest being “lost” as heat.

7.4 Materials for light absorption and different kinds of cells

The materials used in solar cells tend to have the property of preferentially absorbing those wavelengths of solar light that reach the Earth’s surface for terrestrial applications, while other solar cells are optimized to absorb light wavelengths above the Earth’s atmosphere too, for space applications, *e.g.* satellites. It is possible to configure several different band gap materials into an array to harvest more of the solar spectrum, and this can be structured to absorb more of the available light than is possible in a simple arrangement of flat panels. The majority of solar cells are made from bulk semiconductor materials (silicon being the most common) which are cut into wafers and fabricated through a “top-down” synthesis. Other materials such as inorganic layers, organic dyes and organic polymers are assembled as thin-films (second generation cells) by depositing the semiconductor onto supporting glass, ceramic or plastic substrates, and yet another class are fabricated in the form of nanocrystals to make “quantum dots” (Section 10), in which the electrons are confined in all three spatial dimensions, that are embedded in a supporting (often organic polymer) matrix in a “bottom-up” synthesis. Silicon is unique in that it has been thoroughly investigated both as a bulk and thin-film conductor. Developments to silicon photocells abound, but of particular interest and potential is nanoparticle silicon printing processes by which silicon can be printed reel-to-reel on stainless steel or other high temperature substrates²². Nonetheless, arriving at the next generation of photovoltaics is mostly directed toward printing onto cheap and flexible polymer films and ultimately onto such materials as are used commonly in packaging. The major focus is on CIGS, CdTe, DSSC and organic photovoltaics²².

7.4.1 Silicon thin films

Thin-film silicon cells are normally made by chemical vapour deposition using a mixture of silane (SiH_4) and H_2 gas. This is typically a plasma-enhanced process (PE-CVD) which can be adjusted to yield amorphous silicon (a-Si or a-Si:H), protocrystalline silicon or nanocrystalline silicon (nc-Si or nc-Si:H). In all cases, there are dangling and twisted bonds present, which form deep defects (energy levels within the bandgap) as well as a deformation of the valence and conduction bands (band tails). Defects in silicon have been extensively investigated using electron spin resonance (ESR) spectroscopy²³. Solar cells made from these materials tend to have a reduced light-to-electricity conversion efficiency than bulk silicon, but they are much cheaper and use far less material to produce. Thin film solar cells also demonstrate lower quantum efficiencies in consequence of the fewer charge carriers that are produced per incident photon. The bandgap for amorphous silicon is higher (1.7 eV) than that for crystalline silicon (c-Si) (1.1 eV), which allows it to absorb the visible part of the solar spectrum more strongly than the infrared wavelengths. In contrast, nc-Si and c-Si have roughly the same bandgap and hence the two materials can be combined in a tandem cell, where a-Si absorbs visible light in the top cell and leaves the infrared part of the spectrum to be absorbed by nc-Si in the bottom cell.

7.4.2 Nanocrystalline quantum dot solar cells

These structures utilise similar thin-film light absorbing materials but they are introduced as an overlay of an extremely thin absorber onto a supporting matrix of a conductive polymer or mesoporous metal oxide with a very high surface area in order to increase the number internal reflections and thus the probability of light absorption. By means of nanocrystals it is possible to construct architectures on a nanometre scale of dimensions, which is of the order of a typical exciton diffusion length. Single-nanocrystal ('channel') devices, with an array of single p-n junctions between the electrodes and separated by approximately the length of one diffusion length, promise a new generation of high efficiency solar cells. See Section 10.

7.4.3 *Polymer processing*

Alan Heeger, Alan G. MacDiarmid and Hideki Shirakawa were awarded the Nobel prize for chemistry in 2000 in recognition of their discovery of conductive polymers²⁴. As noted earlier in this article, there is a potential shortage of metals used in the electronics industry including photovoltaics, most notably indium, and thus if cheap solar cells could be made from organic materials, then this would ensure the future of the technology and of the industry, albeit noting that crude oil, which is the ultimate chemical feedstock, will begin to rise increasingly in price and eventually become scarce thus necessitating an alternative organic source, perhaps derived from coal or biomass. However, organic solar cells are far less robust than their inorganically derived analogues, and are degraded fairly rapidly by the action of UV light in the presence of oxygen and water, since the conjugated double bond systems in the polymers, which carry the charge, undergo photochemical reactions at these shorter wavelengths.

7.4.4 *Processing of nanoparticles*

Quantum heterostructures such as carbon nanotubes (Section 8) or quantum dots (Section 10), may be embedded in conductive polymers or mesoporous metal oxides. Conventional solar cells based on silicon may be enhanced by adding to them thin films of many of these materials which increases the optical coupling efficiency, hence improves the overall cell-efficiency. Since the size of the quantum dot particles can be tuned according to synthetic methods, so can the cells be tuned to absorb different wavelengths. Although commercial devices are not yet available, it is thought that quantum dot-modified PV may be able to achieve up to 42% light-to-electricity conversion efficiency as a result of multiple exciton generation (MEG)²⁵, although 65% has been claimed²⁶ as an attainable upper limit (Section 10).

7.4.5 *Infrared solar cells*¹⁰

Devices employing billions of heat collecting nanoantennas (“nantennas”) are also under development, which may eventually provide a solar energy collector that is amenable to mass-production using flexible sheets. It is not presently possible to convert the energy collected to electricity but it is envisaged that once this

hurdle is overcome, lightweight “skins” could be made to power all kinds of electrical devices from i-Pods to electric cars, at a higher efficiency than is possible with traditional PV cells. The nanoantennas also have the potential to cool buildings or electronics by collecting background Infrared (heat) energy which could be used to make electricity that could provide further cooling by powering air-conditioning units. Since they target mid-infrared rays, which the Earth continuously radiates as heat after absorbing energy from the Sun during the day, they could be used to produce electricity at night, in contrast with PV cells which are useless after dark. Infrared driven PV cells are another route to providing night time solar electricity.

A nanantenna^{27,28} is an electromagnetic collector designed to absorb specific wavelengths that are proportional to the size of the nanantenna. Currently, Idaho National Laboratories has designed a nanantenna to absorb wavelengths in the range of 3–15 μm ²⁷. Since around 85% of the solar radiation spectrum (Figure 5) contains light with shorter than infrared wavelengths, in the range 0.4–1.6 μm it would be ideal to make nanantennas of these dimensions to harvest more energy than is possible with PV. Nanantennas work in practically the same way as rectifying antennas: namely that incident light drags electrons in the antenna material back and forth at the same frequency as the incoming light, in consequence of the oscillating electric field component of the electromagnetic light wave. The refractive index of a material has a similar origin. The oscillating electrons generate an alternating current (AC) in the antenna circuit, which must be rectified to convert it into DC power usually with a diode device of some kind, and the DC current can then be used to power an external load. Since the wavelengths in the solar spectrum lie in the approximate range 0.3–2.0 μm , a rectifying antenna needs to be of the order of hundreds of nm in size to provide an efficient energy collector. Since the oscillating (AC) frequency from the nanantenna array is around 10 THz, converting it to the 50–60 Hz power used worldwide poses a challenge in terms of using the technology to generate real usable electricity. The main problem with rectifying diodes is that they have a finite recovery time which limits their operating frequency. Commercially available ultrafast diodes presently have an upper limit of the order of several GHz, and so they need to be made to work faster. This seems to be the principal obstacle to the success of generating electricity using nanantenna.

There have been many affirmations to the effect that the theoretical efficiency of nanantennas is >85%, which in comparison

with the theoretical efficiency of single junction solar cells (30%), looks very impressive. There is some ambiguity over this, however, depending on exactly how the efficiencies are calculated for the two kinds of device²⁷.

The most obvious advantage of nanennas over semiconductor photovoltaics is that the nanenna arrays can be scaled to absorb any frequency of light. Since the resonance frequency is in direct proportion to the size of the antenna, the array may be tuned by simply varying the size of the nanenna in the array to absorb specific light wavelengths. In the case of PV the frequency of absorbed light depends almost entirely on the band gap energy, and so the semiconductor material must be changed to vary the latter. Indeed, this aspect of dimensional engineering is in some ways reminiscent of nanotube (Section 8) and quantum dot (Section 9) devices. Although the latter work in quite different ways, the point is made that it is not only the chemical composition of the material but the size of its assembly that provides a tuning to the absorption of light that is possible by a device.

7.4.6 Ultraviolet solar cells¹⁰

While most conventional solar cells use visible and infrared light to generate electricity, Japanese workers have developed a solar cell that generates electricity from ultraviolet light but allows visible light to pass through it. It is thought that conventional window glass could be substituted by them, providing a very large installation surface area that could be incorporated within a combined strategy of power generation, lighting and temperature control. PEDOT : PSS or Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (Figure 11) is a mixed polymer made from two component ionomers. One component is sodium polystyrene sulfonate in which some of the sulfonyl groups are deprotonated and thus carry a negative charge. The other component is poly(3,4-ethylenedioxythiophene) or PEDOT which is a positively charged conjugated polymer; the two components mixed together provide electrical neutrality in the form of a polymer salt. PEDOT-PSS solar cells are (UV) light selective and are moreover easily manufactured.

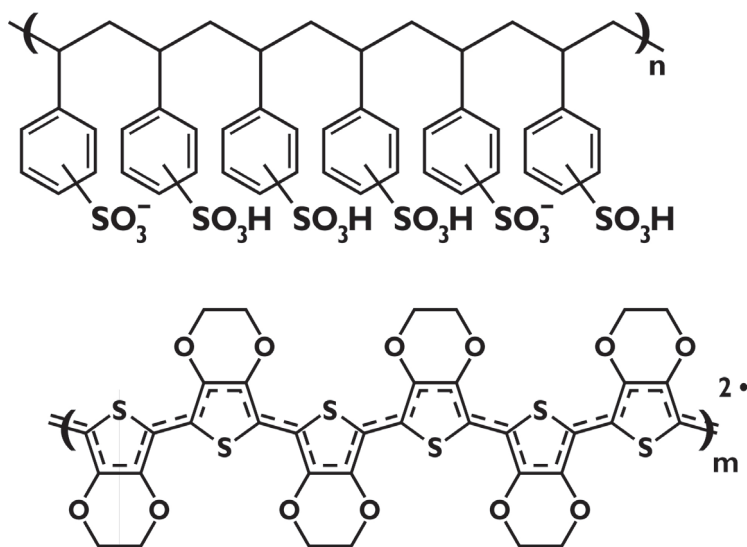


Fig. 11. PEDOT-PSS. Credit, Grimlock.

http://upload.wikimedia.org/wikipedia/commons/9/97/Polythiophenes_Pedotpss.png

8. Organic solar cells

8.1 Polymer solar cells^{29,30}

Solar cells were developed in the 1970s based upon conducting polymers. They are sometimes called plastic solar cells and are a type of organic solar or organic photovoltaic cell. In contrast with silicon cells, polymer solar cells are light, easily disposed of, less harsh on the environment, and cheap to manufacture, sometimes using printed electronics. They are also flexible and, on the molecular level, can be tuned toward particular optical and electronic properties, and have a potentially less negative environmental impact. A schematic device is sketched in Figure 12.

Unlike an inorganic PV material, with its band structure and delocalized electrons, excitons (electron–hole pairs) in organic photovoltaics are strongly bound with an energy between 0.1 and 1.4 eV, as a result of more localized wavefunctions in organic molecules, and a higher electrostatic attraction which holds the electron and hole together as an exciton. If an interface is present across which the chemical potential of electrons decreases then the electron and hole can dissociate. However, the electron and hole may still be present as a geminate pair so that an electric field is then required to separate them. After exciton dissociation, the

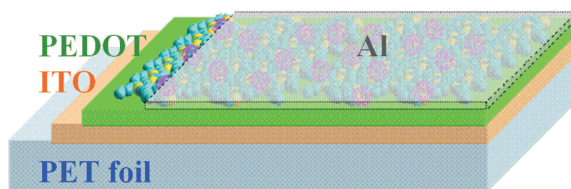


Fig. 12. The scheme of plastic solar cells. PET-Polyethylene terephthalate, ITO-Indium Tin Oxide, PEDOT:PSS-Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate), Active Layer (usually a polymer:fullerene blend), Al-Aluminium. Credit, Victor I. Krinichnyi.

<http://upload.wikimedia.org/wikipedia/en/8/87/Solarcells4.gif>

electron and hole must be collected at contacts. Charge carrier mobility is crucial, since if their mobility is not fast enough, the carriers will not reach the contacts, but will rather will recombine at trap sites or remain in the device as undesirable space charges which actually oppose the drift of new carriers. As an example, organic photovoltaics can be fabricated with an active polymer and a fullerene-based electron acceptor. The illumination of this system by visible light leads to electron transfer from the polymer chain to a fullerene molecule. As a result, a photoinduced quasiparticle, or polaron (P^+), is formed on the polymer chain and the fullerene becomes a radical anion C_{60}^- . The polarons can diffuse away as a result of their high mobility along the length of the polymer chain. Since both the polarons and radical anion have spin $S = 1/2$, the charge formation and separation processes can be monitored by ESR spectroscopy.

Currently, it is debatable as to what future polymer-based solar cells have, especially in competition with silicon and other thin-film cells. For the time being, the silicon cell industry works hand in glove infrastructurally with the computer industry. The efficiency of organic polymers cells is still only around 5% and as noted, organic conductors suffer from the disadvantage that they are not particularly environmentally robust, being sensitive to photochemical degradation in the presence of oxygen and moisture. The development of adequate protective coatings to preserve the organic conductor will be key to the future of such devices. That said, if it can be brought about, there is the prospect of fabricating very cheap solar PV cells, without which and in the absence of government subsidies as exist in Germany and Japan, future expansion of solar PV technology on the scale envisaged to significantly supplant fossil and nuclear fuel derived electricity will be severely hampered.

8.2 Dye-sensitized solar cells³¹

This type of cell was invented by Michael Grätzel and Brian O'Regan at the École Polytechnique Fédérale de Lausanne in 1991³² and DSC are hence also known as Grätzel cells. The main advantage of this approach is that (mostly) cheap materials are used which can be engineered into flexible sheets. The processing itself is far less stringent and elaborate than, say, making silicon cells, and the cells are tough in practical applications, meaning they do not have to be shielded from the elements. It is thought that DSC may provide a significant contribution to the European solar energy target for 2020. In a silicon cell, the silicon acts as the source of photoelectrons, and provides the necessary electric field to separate the electrons and holes in order to generate an electric current. In the DSC, the bulk of the semiconductor is used solely for charge transport, since a separate photoactive dye-layer acts as the source of the photoelectrons. The charges are separated at the surfaces between the dye-layer, semiconductor and electrolyte.

It is necessary to have a reasonable thickness of the dye-layer, in relation to the nanometre dimension of its individual molecules and for this purpose a nanomaterial (in fact the semiconductor itself) is used as a scaffold to hold large numbers of the dye molecules in a 3-D matrix, increasing the number of molecules for any given surface area of cell. The original Grätzel cell³² has three primary parts (Figure 13). At the very top is a transparent anode made of fluorine-doped tin oxide ($\text{SnO}_2:\text{F}$) deposited on the back of a conductive glass plate. On the back of the plate is a thin layer of titanium dioxide (TiO_2), which is highly porous and has an extremely high surface area. TiO_2 absorbs only a small fraction of the solar photons, in fact those in the UV region $<400\text{ nm}$. The plate is immersed in a solution of a photosensitive ruthenium-polypyridine dye which leaves a thin layer of the dye, bonded covalently to the TiO_2 surface. Finally, there is a separate backing with a thin layer of the iodide electrolyte spread over a conductive sheet, made typically of platinum metal. The front and back parts are then joined and sealed together to prevent the electrolyte from leaking. As noted earlier (Section 6.3) there is a problem potentially with the rate of recovery of platinum and of rhodium too since the two metals tend to occur in the same ore. Since both are necessary (for the fabrication of firstly the conductive sheet and secondly the rhodium-based dye) to make Grätzel cells, there is a potential resource limitation to the widescale manufacture of them, especially since there are competing demands for both Pt and Rh, in terms of

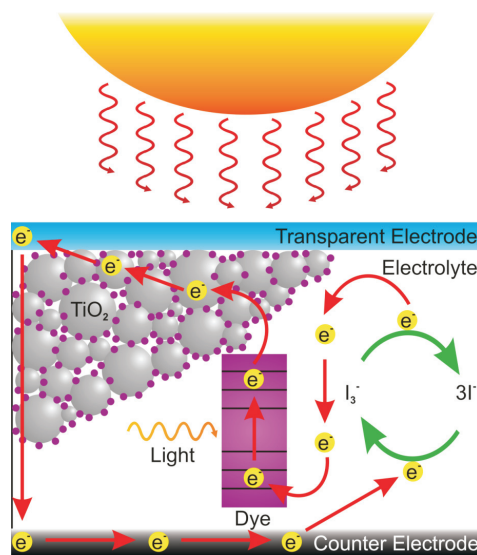


Fig. 13. Schematic working of a Dye Sensitized (Grätzel) Solar Cell. Credit, M.R. Jones.
http://upload.wikimedia.org/wikipedia/commons/f/fd/Dye_Sensitized_Solar_Cell_Scheme.png

catalytic convertors, fuel cells and industrial catalysts, which in total already exceed their current supply.

Figure 13 represents a schematic for the operation of the cell. First, sunlight enters the cell through the transparent $\text{SnO}_2\text{:F}$ contact and strikes the dye molecules on the surface of the TiO_2 . Photons that are energetic enough to be absorbed will create an excited state of the dye molecule, from which an electron can be “injected” directly into the conduction band of the TiO_2 , and from there it moves by diffusion (as a result of an electron concentration gradient) to the clear anode on top.

Since the dye molecule has lost an electron, the molecule will undergo degradative chemical reactions if another electron is not provided. The dye strips one from iodide in the electrolyte below the TiO_2 , oxidizing it into triiodide. The triiodide then recovers its missing electron by mechanically diffusing to the bottom of the cell, where the counter electrode re-introduces the electrons after flowing through the external circuit. Although the dye is highly efficient (90%) in turning photons into electrons, it is only those electrons with enough energy to cross the TiO_2 bandgap that will result in current being produced. The bandgap has a slightly greater energy than is the case for silicon, which means that fewer of the available solar photons can be absorbed, while the electrolyte limits the speed

at which the dye molecules can regain their electrons and become available for further photoexcitation. Thus the current generated by a DSC is only about 20 mA/cm², whereas a traditional silicon-based solar cell delivers about 35 mA/cm².

DSC are currently the most efficient second-generation solar technology available, at around 11%. Other thin-film technologies are typically around 8%, and traditional low-cost commercial silicon panels operate between 12% and 15%. DSC offer great promise in “low density” applications such as rooftop solar collectors, where the mechanical robustness and light weight of the glass-less collector is a major advantage. The cell’s mechanical and thermal robustness indirectly leads to higher efficiencies at higher temperatures, since in any semiconductor, increasing the temperature will promote some electrons into the conduction band. At low temperatures the liquid electrolyte may freeze, ending power production and potentially leading to physical damage, while the liquid may expand at higher temperatures, making sealing the panels a serious problem. Replacing the liquid electrolyte with a solid is a major research challenge. Michael Grätzel and his colleagues at the Chinese Academy of Sciences have measured cell efficiencies of 8.2% using a new all-solid electrolyte consisting of a melt of three salts, as an alternative to using organic solvents as an electrolyte solution, which they feel can be improved³³.

Dyes have been introduced with a far broader frequency response than those used in the original cells, notably “triscarboxy-terpyridine Ru-complex” [Ru(2,2',2''-(COOH)₃-terpy)(NCS)₃] (Figure 14), which absorbs light efficiently even down to the low-frequency range of red and Infrared light. In consequence of it absorbing such a broad range of wavelengths, the dye has a deep brown-black colour, and is referred to simply as “black dye”³⁴. Further gains in the efficiency of DSC are possible, for example by means of quantum

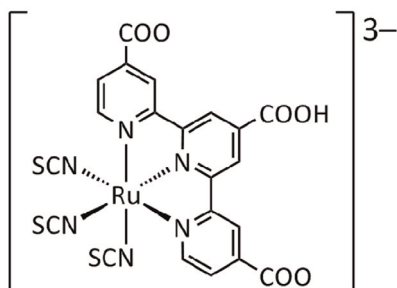


Fig. 14. “Black Dye”, an anionic Ru-terpyridine complex. Credit, Ph0987.
<http://upload.wikimedia.org/wikipedia/en/1/19/BlackDye.png>

dots for conversion of more energetic (higher frequency) light into multiple electrons (excitons), using solid-state electrolytes to achieve a better temperature response, and changing the doping of the TiO_2 to match it more closely with the particular electrolyte. Arrays of nanowires and a combination of nanowires and nanoparticles have been designed to provide a direct path to the electrode via the semiconductor conduction band. It is thought that structures of this kind may exhibit improved quantum efficiency of DSC in the red region of the spectrum, where their performance is currently limited³⁵. Organic dyes based on porphyrins have been found to show an efficiency of 7.1% using these low-cost dyes³⁶. Since these are very cheap, being the working component of the hemoproteins in animals and chlorophyll in plants, further cost reduction in making DSC might prove possible using them.

9. Carbon nanotubes in photovoltaics³⁷

As already noted, organic photovoltaic (OPV) cells offer the prospect of being made cheaply both in terms of the cost of raw materials for them and the manufacturing processes themselves. They are, however, limited in their light to electricity conversion efficiency (*ca* 5%) as compared with standard first generation silicon cells (*ca* 15%) and even with second generation thin-film cells (*ca* 8%). There is therefore a spur to improve the efficiency of such devices which are based around organic conductive polymers. Carbon nanotubes (CNTs) have a high conductivity along the tube axis and, if they are dispersed within an organic conductor (photoactive layer), they offer the potential to increase the efficiency of OPV devices, while retaining the advantages of the latter. Due to interpenetrating bulk donor-acceptor heterojunctions in such media, there is a bicontinuous network which allows the separation and collection of charges (electrons and holes), which can move toward their particular contacts. In this medium are polymer/nanotube junctions with high electric fields, strong enough to dissociate the exciton pairs while the electron capturing SWNT (single-walled nanotube) provides a conduit for the electrons. The latter effect is thought to result in an improvement in the overall photovoltaic efficiency.

Generally poly(3-hexylthiophene) (P3HT) or poly(3-octylthiophene) (P3OT) are used as the organic matrix, and are spin coated onto a transparent conductive electrode of thickness 60–120 nm. These electrodes are more often made of glass covered with indium tin oxide (ITO) coated with a 40 nm mixed underlayer

of (poly(3,4-ethylenedioxythiophene) (PEDOT) and poly(styrenesulfonate) (PSS) (Figure 11). The effect of the underlay is to smooth the ITO surface, decreasing the density of pinholes and stifling current leakage. A 20–70 nm layer of aluminium is deposited onto the photoactive material through thermal evaporation or sputter-coating and sometimes an intermediate layer of lithium fluoride is applied. Multiple research investigations^{38–44} with both multi-walled carbon nanotubes (MWCNTs) and single-walled carbon nanotubes (SWCNTs) integrated into the photoactive material have been completed. Nonetheless, although CNTs have shown potential in the photoactive layer, they have not resulted in a solar cell with a better power conversion efficiency than the maximum 6.5% obtained for tandem organic cells⁴⁵. A major problem in achieving these devices successfully is to obtain a uniform and controllable blending of the electron donating conjugated polymer and the electron accepting CNT in the mix. This, accordingly, is crucial to obtaining an efficient photocurrent in CNT-based OPV devices.

9.1 Carbon nanotubes in dye-sensitized solar cells

Section 8.2 describes the advantages of DSC in terms of the simplicity of their fabrication and low production costs. That noted, the efficiencies of DSC while better than most thin-film cells need to be improved before they can compete with other solar cell technologies. It is the marketplace that determines the viability and fate of new technologies including solar, rather than humanistic and altruistic concerns for the future of the Earth, its climate and resources, and for our fellow human and other animals. Thus for solar energy to arise on the grand scale, unless huge subsidies are to be bestowed worldwide, the cost of its installation has to be got down massively. Titanium dioxide nanoparticles have shown an efficiency of 11% (a record for any semiconductor⁴⁶), as the working electrode in DSC under air mass (AM) 1.5 and 100 mW/cm² irradiation conditions⁴⁷. However, all efforts to raise this further have thus far been unsuccessful⁴⁸. In these materials, the electrons encounter many grain boundaries during the transit and experience a random path. Thus the probability of their recombination with oxidized sensitizer is increased, which dampens the electronic flux over the particle network. This provides a significant obstacle to achieving higher photoconversion efficiency in nanostructured electrodes⁴⁹. Therefore, enlarging the oxide electrode surface area does not increase its efficiency due to the necessity

to avoid photo-generated charge recombination. It is possible that various CNT-based nanocomposites and nanostructures might be employed to direct the flow of photogenerated electrons and thereby to aid charge injection and extraction. Other kinds of semiconductor particles including CdSe and CdTe have been shown to induce charge-transfer processes under visible light irradiation when attached to CNTs⁵⁰. By incorporating photoactive donor polymers (that include porphyrins) and acceptor fullerenes onto electrode surfaces, a considerable improvement has been found in the photovoltaic efficiency of solar cells⁵¹. Thus it might be practical to facilitate electron transport and increase the photoconversion efficiency of DSC by means of the electron-accepting ability of semiconducting SWCNTs.

DSCs were also prepared by means of the sol-gel method to obtain titanium dioxide coated (multi-walled carbon nanotubes) MWCNTs for use as an electrode material⁴⁸. In their pristine state, MWCNTs have a hydrophobic surface, and are poorly dispersive. Hence they were pretreated with H₂O₂ in order to generate carboxylic acid groups by surface oxidation, thus rendering the surface hydrophilic and to carry a negatively charge, which improved the dispersion stability. The MWCNTs were finally surrounded completely with TiO₂ nanoparticles using the sol-gel method, which caused increase in the efficiency by about 50% over that for a conventional titanium dioxide cell. It is believed that there is an improvement in the short circuit current density via the enhanced interconnectivity between the titanium dioxide particles and the MWCNTs, leading to a more efficient electron transfer through the film.

9.2 Dye-coated titania nanotubes in dye-sensitized solar cells⁵²

Researchers at Penn State have used TiO₂ nanotubes to replace the particulate coatings in DSC, from which an initial 3% conversion efficiency has been reported⁵². In contrast with conventional solar cells which are made from blocks of slowly grown silicon boules that are sliced into wafers, in this approach a layer of titanium 500 nm thick is sputtered onto a piece of glass coated with a fluorine-doped tin oxide. The titanium layer is anodized in an acidic medium and titanium dioxide nanotube arrays grow to about 360 nm in length. On heating in oxygen, the tubes crystallize, which transforms the initially opaque coating of titanium into a transparent coating of titania nanotubes. The

nanotubular array is next coated with a commercially available dye. The dye-coated nanotubes form the cathodes and the anode, which contains an iodized electrolyte, seals the cell. When the Sun shines through the glass, the energy falls on the dye molecules and an electron is freed. The tube structure of the titanium dioxide increases the transport of electrons (over their loss by recombination with holes) by an order of magnitude. It is thought that a 15% efficiency is possible for these cells, if the thickness of the titania nanotube film is increased. If the initial titanium dioxide coatings are made thicker, longer nanotubes would result in more “free” electrons (*i.e.* that do not recombine with holes), producing more electricity.

10. Nanocrystal (quantum dot) solar cells⁵³

Nanocrystal solar cells are also called quantum dot (QD) solar cells, and are based on a silicon substrate with a coating of nanocrystals. Formerly, the creation of QDs required expensive molecular beam epitaxy methods, but they are now quite readily produced using methods of colloidal synthesis which is much cheaper since in effect it merely involves mixing appropriate reagents with *e.g.* surfactants (to control the particle size) under standard laboratory conditions. Thin films of QDs are produced by “spin-coating”, in which a quantity of a solution containing the QDs is placed on onto the surface of a flat substrate, which is then rotated very quickly, causing the solution to spread out uniformly. The spinning is maintained until the required thickness is achieved.

QD based photovoltaic cells based around dye-sensitized colloidal TiO₂ films were investigated in 1991⁵⁴ and were found to exhibit a promising efficiency for converting incident light energy to electrical energy, and appeared highly encouraging due to the low cost of materials in the search for more commercially viable/affordable renewable energy sources.

10.1 Quantum dots and ultra-efficient solar-cells⁵⁵?

The term “quantum dot” was coined by Mark Reed at Yale University. A quantum dot⁵⁶ is a semiconductor whose excitons are confined in all three spatial dimensions. Accordingly, they have properties that are between those of bulk semiconductors and those of discrete molecules. They were discovered by Louis E. Brus, who was then at Bell Labs. QDs are nanocrystalline materials (or

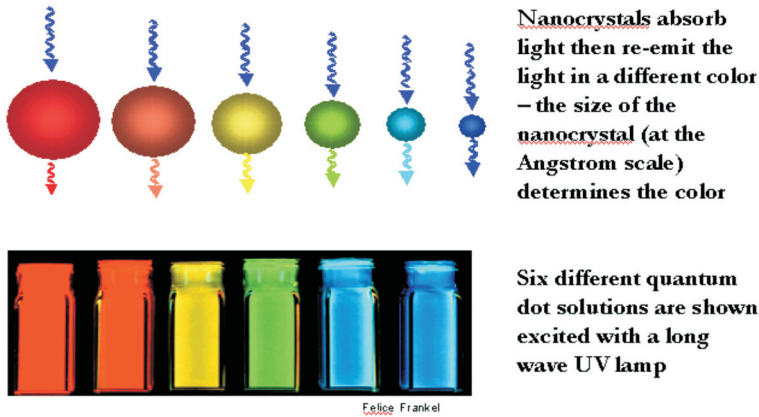


Fig. 15. © Quantum Dot Corporation (2003).
<http://www.nanotech-now.com/images/QDot-nanocrystal.jpg>

materials that contain nanocrystals) in which the dimension of the crystal is smaller (in all directions) than the Bohr exciton radius of the exciton pair ($M + \dots e^-$). This causes the energy levels to become quantised (*quantum confinement*), as in individual molecules, rather than coalescing into the “band structure” of bulk semiconductors. Traditional (bulk) semiconductors lack versatility, since their band-gap and hence optical and electronic properties cannot be easily changed, if at all. By *tuning* the size of the QD particle, the band-gap can be tailored for specific applications. The gap enlarges as the crystalline dimension decreases, so that the fluorescence wavelength shortens; conversely, as the crystal becomes bigger, the wavelength increases, so the fluorescence shifts toward the red end of the visible spectrum (Figure 15).

QDs range in size from 2 to 10 nanometres (10–50 atoms) in diameter and contain as few as 100 to 100,000 atoms. Nearly 3 million quantum dots could be lined up end to end and fit within the width of a human thumb. There are several ways to confine excitons in semiconductors, resulting in different methods to produce quantum dots. In general, quantum wires, wells and dots are grown by advanced epitaxial techniques in nanocrystals produced by chemical methods or by ion implantation, or in nanodevices made by state-of-the-art lithographic techniques. There are also colloidal methods to produce many different QD semiconductors, including cadmium selenide, cadmium sulfide, indium arsenide, and indium phosphide. Large quantities of quantum dots may be synthesized via colloidal synthesis, which can be done under benchtop conditions, *i.e.* mixing the appropriate precursor

compounds in a flask, usually in the presence of a surfactant to control the particle size, rather than complex and expensive molecular beam epitaxy techniques.

QDs are less rapidly damaged by radiation because ejected electrons and positive holes cannot escape from one another sufficiently to perform their own (non-radiative) chemical reactions (atomic displacements) as they do in the bulk phase. Thus they tend to recombine radiatively without causing molecular-level damage. There is a dimensional restriction on the normal reactivity of the bulk material, since the QD is smaller than the normal hole-electron pair separation distance, which limits the extent of chemical reactions normally induced in the bulk semiconductor, and in the absence of alternative routes, the holes and electrons are more likely simply to recombine. Quantum dots have up to 100 times the radiation resistance of thin-film cells and thus up to 1000 times the radiation hardness of conventional bulk materials. Thin-films too are relatively radiation-resistant, and one can invoke a simple geometric argument, in that the total concentration of active material is comparatively small, hence kinetically the relative rate of damage is lower.

QDs may improve the efficiency of solar cells by providing a broader range of band gaps so that more of the solar spectrum can be sampled and also by generating more excitons from a single photon. Since around half of the solar spectral wavelengths fall in the infrared region, if a PV cell responds to these thermal wavelengths—‘thermovoltaics’—then radiation can be harvested from sunlight or from a fuel-fired source with considerable efficiency. As an example, if a silicon cell of area 1 cm^2 placed in direct sunlight can generate about 0.01 W, then an efficient infrared photovoltaic cell of equal size can produce nearer 1 W in a fuel-fired system. QDs have a definite application here, when they are encased in conjugated polymers. The polymer poly(2-methoxy-5-(2'-ethylhexyloxy-*p*-phenylenevinylene)] (MEH-PPV) has an absorption spectrum in the range 400–600 nm, while QDs of lead sulphide (PbS) can be tuned to absorb in the range 800–2000 nm. If the PbS QDs are incorporated in a matrix of MEH-PPV the absorption spectrum of the polymer could be shifted into the infrared region. It is anticipated that this will become a commercial proposition within 3–5 years.

If the energy of the photon absorbed is much greater than the semiconductor band gap, multiple exciton formation is possible, although it is not normally observed in bulk semiconductor materials in which the excess energy is rapidly lost as heat. In a

QD, the excess energy is lost far more slowly and the charge carriers are confined in very close proximity to one another so making it more likely for multiple excitons to form. It is thought that the theoretical efficiency of a QD might be increased⁵⁵ from 31 to 42% although there is another claim that an efficiency of 65% might be possible²⁶. QDs do seem to offer remarkable potential in photovoltaic applications generally, but in space-applications particularly, in terms of radiation resistance, low payload weight, and light to electricity conversion efficiency in beamed-energy applications (Section 12).

11. Concentrating solar power generation⁵⁷

Concentrating solar power (CSP) systems employ lenses or mirrors coupled with tracking systems to concentrate a large area of sunlight into a small beam, rather in analogy with the simple and familiar burning-lens. The concentrated energy may be used to heat a central “boiler” to run a power plant fitted with a conventional steam-turbine from which electricity is generated in the usual manner. A quite broad range of methods may be used to accomplish this, *e.g.* the parabolic trough, the solar (parabolic) dish and the solar power tower. All such systems contain a working fluid which is heated by the concentrated sunlight, and then used to generate power or to store energy. In a parabolic trough (Figure 16) there is a linear parabolic reflector which concentrates sunlight onto a receiver oriented along its focal line. By means of a tracking system, the reflector follows the Sun during the daylight hours along a single axis. Trough systems are the most efficient of any solar technology in regard to the land area occupied by the plant. The SEGS plants in California and the Acciona Nevada Solar One near Boulder City, Nevada are based on trough systems. A parabolic (solar) dish system consists of a single parabolic reflector which concentrates light at the focal point of the reflector, which tracks the Sun along two axes. Of all the CSP technologies, parabolic dish systems are the most efficient. The 50 kW Big Dish in Canberra, Australia is an example of this technology. The Stirling solar dish combines a parabolic concentrating dish with a Stirling heat engine which drives an electric generator. (The term “Stirling” refers to the fact that the device operates on a simple heat-engine principle.) Stirling solar energy production is more efficient than photovoltaic cells and the technology has a longer working lifetime. A solar power tower consists of an array of dual-axis tracking reflectors (heliostats) that concentrate light on a central receiver at the top of a

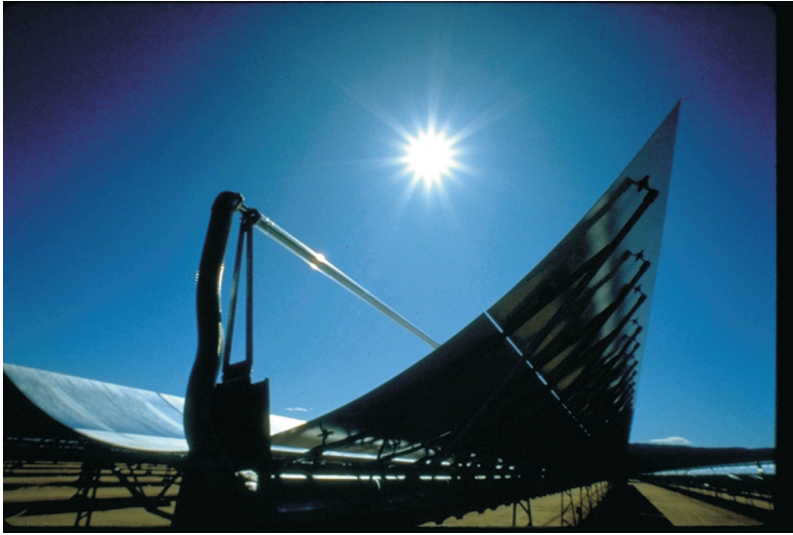


Fig. 16. Parabolic troughs are the most widely deployed and the most cost-effective CSP technology. Credit, Sandia National Laboratory.
<http://www.energylan.sandia.gov/photo/photos/1428/142821c.jpg>

tower (Figure 17). The receiver contains a working fluid to absorb the heat, which can be seawater. The working fluid in the receiver is heated to 500–1000°C and then used as a heat source to generate power or to store energy. As we see later, concentrating thermal



Fig. 17. The PS10 concentrates sunlight from a field of heliostats on a central tower. Credit, afloresm.
http://upload.wikimedia.org/wikipedia/commons/e/eb/PS10_solar_power_tower.jpg

power is the main technology proposed for a cooperation to produce electricity and desalinated water in the arid regions of North Africa and Southern Europe by the Trans-Mediterranean Renewable Energy Cooperation Desertec (Section 11.3).

11.1 The future of concentrated solar power

The potential and future of concentrated solar power was investigated and reported from a study by Greenpeace International, the European Solar Thermal Electricity Association, and the International Energy Agency's SolarPACES group. Remarkably, it was concluded that concentrated solar power could provide 25% of the world's energy needs by 2050. To achieve this, however, would require an increase in world investment from 2 billion euros to 92.5 billion euros over that same time period, although it further predicted that the price of electricity would drop from the present 0.15–0.23 euros currently per kilowatt, to 0.10–0.14 euros a kilowatt. We always hear this, however, in the inauguration of all new technologies, most notably (or notoriously) atomic power⁵⁸. As is clear from Section 11.2, Spain is the world leader in concentrated solar power technology, with more than 50 projects underway. As part of an overall intention to create “a new carbon-free network linking Europe, the Middle East and North Africa” the Desertec scheme has been devised (Section 11.3).

11.2 List of solar thermal power stations

Table 8 lists the currently operating STC power stations and those under construction are outlined in Table 9. Among the major players are the 354 MW Solar Energy Generating Systems power plant in the USA, Nevada Solar One (USA, 64 MW), Andasol 1 (Spain, 50 MW), PS20 solar power tower (Spain, 20 MW), and the PS10 solar power tower (Spain, 11 MW). The solar thermal power industry is experiencing rapid growth with 1.2 GW worth of generating capacity under construction as of April 2009 and another 13.9 GW anticipated worldwide by the year 2014. Spain is the world leader in regard to solar thermal power development with 22 projects totalling 1,037 MW under construction, all of which are projected to be producing electricity by the end of 2010. The United States has announced its intention to construct 5,600 MW worth of solar thermal power production.

Table 8 Operational solar thermal power stations

Capacity (MW)	Technology type	Name	Country	Location	Notes
354	Parabolic trough	Solar Energy Generating Systems	USA	Mojave Desert, California	Collection of 9 units
64	Parabolic trough	Nevada Solar One	USA	Las Vegas, Nevada	
50	Parabolic trough	Andasol solar power station	Spain	Granada	Andasol 1 (50 MW) completed November 2008
50	Parabolic trough	Energia Solar De Puertollano	Spain	Puertollano, Ciudad Real	Completed May 2009
50	Parabolic trough	Alvarado 1	Spain	Badajoz	Completed July 2009
20	Solar Power tower	PS20 solar power tower	Spain	Seville	Completed April 2009
11	Solar Power tower	PS10 solar power tower	Spain	Seville	Europe's first commercial solar tower
5	Fresnel reflector	Kimberlina Solar thermal energy plant	USA	Bakersfield, California	Ausra demonstration plant
5	Solar power tower	Sierra SunTower	USA	Lancaster, California	eSolar demonstration plant, USA's first commercial solar tower, completed August 2009
2	Fresnel reflector	Liddell power station solar steam generator	Australia	New South Wales	Electrical equivalent steam boost for coal station
1.5	Solar power tower	Jülich solar tower	Germany	Jülich	Completed December 2008
1.4	Solar power tower	THEMIS solar power tower	France	Pyrénées-Orientales	Hybrid solar/gas electric power, using solar energy to heat the air entering a gas turbine
1.4	Fresnel reflector	Puerto Errado 1	Spain	Murcia	Completed April 2009
1	Parabolic trough	Saguaro solar power station	USA	Red Rock Arizona	
1	Parabolic trough	Keahole solar power	USA	Hawaii	
0.1	Power tower	Kibbutz Samar Power Flower	Israel	Kibbutz Samar	
617.4	—	Overall operational capacity	—	—	—

Table 9 *Solar thermal power stations under construction*

Capacity (MW)	Technology type	Name	Country	Location	Notes
75	ISCC	Martin Next Generation Solar Energy Center	USA	Florida	Steam input into a combined cycle
150	parabolic trough	Andasol 2-4	Spain	Granada	With heat storage
100	parabolic trough	Palma del Rio 1, 2	Spain	Cordoba	
50	parabolic trough	Majadas de Tiétar	Spain	Cacares	
150	parabolic trough	Solnova 1, 3, 4	Spain	Seville	
150	parabolic trough	Extresol 1-3	Spain	Torre de Miguel Sesmero (Badajoz)	
100	parabolic trough	Helioenergy 1, 2	Spain	Ecija	With heat storage
100	parabolic trough	Solaben 1, 2	Spain	Logrosan	
100	parabolic trough	Valle solar power station	Spain	Cadiz	With heat storage
50	parabolic trough	Lebrija-1	Spain	Lebrija	
50	parabolic trough	Manchasol-1	Spain	Ciudad Real	With heat storage
50	parabolic trough	La Florida	Spain	Alvarado (Badajoz)	
50	parabolic trough	La Dehesa	Spain	La Garrovilla (Badajoz)	
100	parabolic trough	Aste 1A, 1B	Spain	Alcázar de San Juan (Ciudad Real)	
50	parabolic trough	Axtesol 2	Spain	Badajoz	
50	parabolic trough	Arenales PS	Spain	Moron de la Frontera (Seville)	

Table 9 Solar thermal power stations under construction (continued)

Capacity (MW)	Technology type	Name	Country	Location	Notes
50	parabolic trough	Serrezuela Solar 2	Spain	Talarrubias (Badajoz)	
50	parabolic trough	El Reboso 2	Spain	El Puebla del Rio (Seville)	
100	parabolic trough	Termosol 1 + 2	Spain	Navalvillar de Pela (Badajoz)	
100	parabolic trough	Helios 1 + 2	Spain	Ciudad Real	
20	ISCC	Kuraymat Plant	Egypt	Kuraymat	
25	ISCC	Hassi R'mel integrated solar combined cycle power station	Algeria	Hassi R'mel	
20	ISCC	Beni Mathar Plant	Morocco	Beni Mathar	
17	power tower	Gemasolar, former Solar Tres power tower	Spain	Fuentes de Andalucía (Seville)	
1757	-	Overall capacity under construction	-	-	-

11.3 Desertec Project^{59,60}

Desertec is a project officially launched on the 13 July 2009 by 12 European companies. It operates under the auspices of the Club of Rome and the Trans-Mediterranean Renewable Energy Cooperation⁶⁰. The project intends to install a network of concentrating solar power systems over an area of 6,500 square miles (17,000 km²) in the Sahara Desert, to produce electricity that would be transmitted to European and African countries by a super grid of high-voltage direct current cables. At a total cost of €400 billion, the scheme would provide continental Europe with 15% of its electricity, although the precise course of action and final costings will be presented in 2012. The location is logical, since the Saharan desert is virtually uninhabited and is close to Europe, and being close to the equator is well provided for by sunlight. It is voiced by its protagonists that the project will keep Europe “at the forefront of the fight against climate change and help North African and European economies to grow within greenhouse gas emission limits”; however, there are notes of criticism too. As usual, some opponents to the scheme point out that centralized solar energy plants and transmission lines could become a target of terrorist attacks, while others are of the opinion that generating so much of electricity consumed in Europe in Africa would create a geopolitical dependency on North African countries. There are further issues over the demand that will be imposed on local freshwater supplies, in terms of cleaning and cooling turbines, which may impact on drinking water supplies for local villagers. Undoubtedly, unprecedented cooperation will be required between nations of the EU and Northern Africa which may delay the project through red tape, especially over the expropriation of assets, the granting of licenses and so forth. There are environmental issues too, in that the Earth’s deserts act to cool the planet by reflecting heat energy, and if they are instead covered with heat-absorbing installations there may be a contribution to global warming. The integrated plan of Desertec is outlined in Figure 18.

12. Applications of photovoltaics in outer-space

The main application in which PV devices are relevant to applications in outer-space are: (1) satellites (Section 12.1), (2) space-exploration, and (3) satellite energy-beams to Earth (Section 12.2). Satellites are used for communications, weather measurements, *e.g.* the International Space Station, the Hubble Space Telescope, *etc.* In

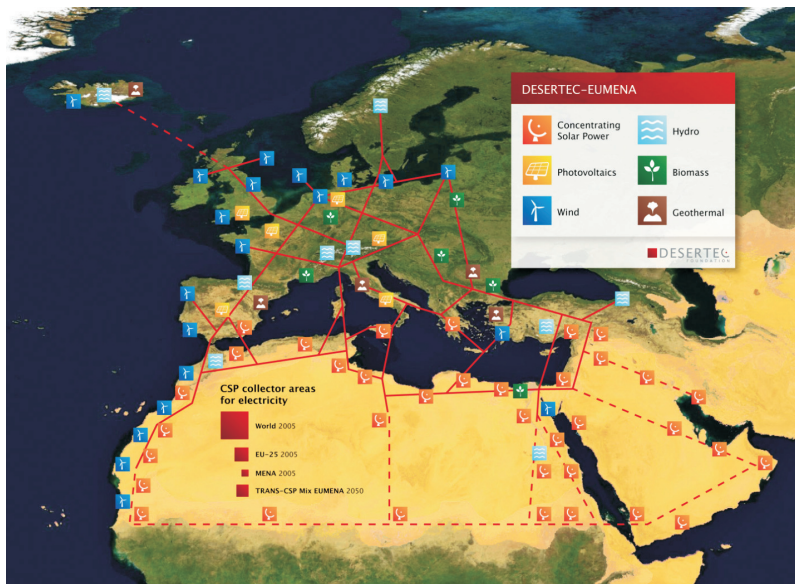


Fig. 18. Hypothetical infrastructure of HVDC power supply to Europe from the Middle East and North Africa (from a DLR study:

http://www.dlr.de/tt/desktopdefault.aspx/tabid-2885/4422_read-6575/).

Credit, TREC.

http://upload.wikimedia.org/wikipedia/commons/7/71/DESERTEC-Map_large.jpg

all of the above, deriving solar energy via PV cells is a key component of the strategy of obtaining power in outer-space. In order to obtain solar energy from above the Earth's atmosphere, the working PV arrays would be hosted on satellites. Since the particular craft must be "got up there" in the first place, and once there are subject to levels of radiation not encountered on Earth, the following issues arise:

- (1) Light-weight payload for easier launching: thin-film cells (TFCs) may be useful here because they contain less material than conventional silicon cells.
- (2) Although there is 30% more solar energy available above the atmosphere, the radiation damage is greater to solar-cells (and to electronics), without protection by the atmosphere.
- (3) Materials need to be "radiation-hard", *i.e.* resistant to radiation, but also give a good light to electricity conversion efficiency.

TFCs tend to have lower efficiencies (about half of conventional cells) but are more resistant to radiation damage (by an order of magnitude) than first generation cells are, and so their photovoltaic

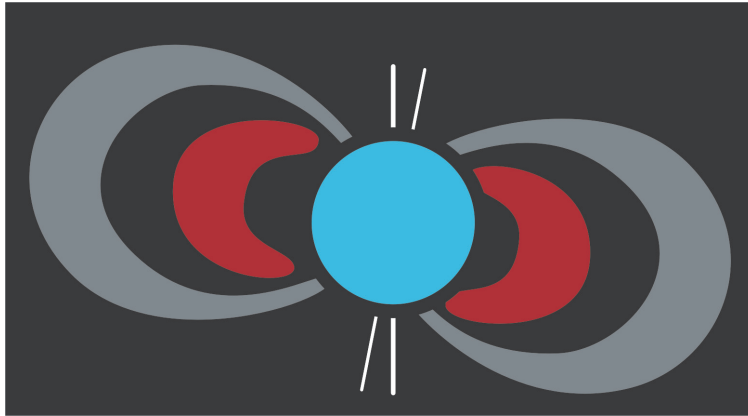


Fig. 19. Van Allen Radiation Belts.

http://upload.wikimedia.org/wikipedia/commons/0/02/Van_Allen_radiation_belt.svg

efficiencies decrease less rapidly over the working lifetime of the cell in outer-space. The degree of radiation exposure depends on the altitude of the satellite above the Earth's surface. The radiation tends to be concentrated in particular regions around the Earth in the Van Allen belts (Figure 19). The inner belt extends from about 700 to 10,000 km (0.1 to 1.5 Earth radii- R_E) above the Earth's surface and contains high concentrations of protons with energies greater than 100 MeV and electrons with energies of hundreds of keV. The outer belt is much larger and extends from 3 to 10 R_E , contains mostly electrons (0.1–10 MeV) and has its greatest intensity at around 4–5 R_E . There are energetic protons and other ions, *e.g.* α -particles and O^+ present too, similar to those in the ionosphere, but with far greater energies. At an altitude of 5.6 R_E , 35,786 km), where there is no atmosphere, a satellite in the geostationary orbit will experience a substantial accumulated radiation dose, and solar cells, integrated circuits and sensors can undergo considerable radiation damage over a working lifetime of perhaps 20 years or more. Geostationary orbits are useful because they cause a satellite to appear stationary with respect to a fixed point on the rotating Earth. As a result, an antenna can point in a fixed direction and maintain a link with the satellite. Most satellites are placed in much lower orbits, *e.g.* for use in navigation, telecommunications and other purposes, such as the Hubble Space Telescope (559 km) and the International Space Station (350 km), so the radiation damage is generally less severe. Thin-film cells offer the desired combination of low payload, reasonable light-to-electricity conversion efficiency, radiation hardness over working life

time, cheapness and relative ease of production. Quantum Dots are of considerable potential interest in this regard since QD cells show a yet greater resistance to radiation perhaps by a factor of a hundred or more (*i.e.* a thousand times greater than conventional silicon solar cells⁶¹).

12.1 Satellite distances and speeds

The following is derived from standard physics⁶². In order for a satellite to orbit the Earth continually, a stable stationary orbit must exist. We can express [according Newton's Law, Eqn(4)]:

$$F(\text{gravity}) = GMm/r^2, \quad (4)$$

where G is the gravitational constant, M is the Earth's mass and m is the mass of the satellite, with r being the distance between the centres of the two bodies. We can further express for a simple circular orbit, the centrifugal force [which acts in opposition to the gravitational force, Eqn (5)]:

$$F(\text{centrifugal}) = mv^2/r, \quad (5)$$

where v is the angular velocity of the satellite. For a stable stationary orbit to exist, the two forces must be equal and opposite, and so we can write that $F(\text{gravity}) = F(\text{centrifugal})$, and hence: $GMm/r^2 = mv^2/r$. By cancelling the terms, m , and rearranging, we get Eqn (6):

$$GM = v^2r. \quad (6)$$

Assuming a circular orbit, the mean angular velocity, v is the circumference of the orbit divided by the time (t) taken for the satellite to make that orbit, *i.e.* $v = 2\pi r/t$, and so if we substitute for v , we find Eqn (7):

$$t^2 = 4\pi^2r^3/GM. \quad (7)$$

A special case is the geostationary orbit, with a unique property which is very useful for communications and weather satellites. This is a geosynchronous orbit directly above the Earth's equator (latitude 0°), with a period equal to the Earth's rotational period and an orbital eccentricity of approximately zero. Due to the constant 0° latitude and circular nature of geostationary orbits, satellites in them differ in location only by longitude. In essence, from the point of view of an observer on the Earth's surface, the orbiting satellite stands still in the sky, because it moves through its orbital cycle at the same rate as the equatorial surface point below it moves round

with the Earth's rotation. Clearly the satellite must sweep through a greater distance than the equatorial surface point below it does in the same time interval and hence it moves at a greater speed, as we shall see.

To compute the size of the orbital radius (r), taken from the centre of mass (*i.e.* the centre of the Earth), we can rearrange the above to solve for r :

$$\begin{aligned} r &= (t^2 GM/4\pi^2)^{1/3} \\ &= [(24 \text{ h} \times 3600 \text{ s/h}) \times 6.6726 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} \times 6.0 \times 10^{24} \text{ kg}/4\pi^2]^{1/3} \\ &= (7.57 \times 10^{22})^{1/3} = 4.23 \times 10^7 \text{ m} = 42,300 \text{ km}. \end{aligned}$$

If we subtract the mean Earth radius of $6.4 \times 10^6 \text{ m}$, we obtain an altitude of $3.59 \times 10^7 \text{ m}$ (35,900 km).

To obtain an orbital speed, we note that the circumference of the orbit is $2\pi r = 2\pi \times 4.23 \times 10^7 \text{ m} = 2.66 \times 10^8 \text{ m}$.

The speed is thus:

$$\begin{aligned} 2.66 \times 10^8 \text{ m}/(24 \text{ h} \times 3600 \text{ s/h}) &= 3,079 \text{ m/s} = 3.08 \text{ km/s}; \\ &\times 3600 \text{ s/h} = 11,088 \text{ km/h} = 6,930 \text{ miles per hour}. \end{aligned}$$

[For comparison, an equatorial point at the Earth's surface rotates at

$$\begin{aligned} (2\pi \times 6 \times 10^6)/(24 \times 3600) &= 465 \text{ m/s} = 0.465 \text{ km/s}; \\ &\times 3600 \text{ s/h} = 1,676 \text{ km/h} = 1,047 \text{ mph}]. \end{aligned}$$

As noted, most satellites are launched at much lower orbits, *e.g.* 500 km in altitude, for use in navigation, telecommunications and other purposes, thus, the Hubble Space Telescope has an orbital altitude of 559 km.

In this case,

$$\begin{aligned} t^2 &= 4\pi^2 \times [(6.4 + 0.5) \times 10^6]^3 / (6.6726 \times 10^{-11} \times 6 \times 10^{24}) \\ &= 3.24 \times 10^7 \text{ s} \end{aligned}$$

Therefore the orbital period,

$$t = (3.24 \times 10^7 \text{ s})^{1/2} = 5692 \text{ s} = 94.9 \text{ minutes}.$$

Its orbital speed is

$$\begin{aligned} 2\pi \times (6.9 \times 10^6)/5692 &= 7.62 \text{ km/s} \\ &= 27,420 \text{ km/h} = 17,137 \text{ miles/h} \end{aligned}$$

The International Space Station has an orbital altitude of 350 km, and so its speed is nearly the same (27,725 km/h; 17,328 mph), according to an orbital period of 91.8 mins.

12.1.1 Escape speed for the Earth

The escape speed for the Earth is usually incorrectly called the “escape velocity” but is just a speed *i.e.* distance/time since there is no direction specified.

To get this quantity, which is the kinetic energy $(1/2)mv^2$, required to cancel the gravitational “pull” of the Earth, we can write Eqn (8):

$$(1/2)mv^2 = GMm/r \quad (8)$$

where r is the Earth’s radius, and M its mass, and by cancelling the terms m from both sides (which tells us that the mass of the satellite is unimportant and it is only that of the Earth which matters), we get:

$$\begin{aligned} v &= (2GM/r)^{1/2} = (2 \times 6.6726 \times 10^{-11} \times 6 \times 10^{24} / 6.4 \times 10^6)^{1/2} \\ &= 11,185 \text{ m/s (11.19 km/s)} \\ &= 40,267 \text{ km/h} = 25,167 \text{ mph.} \end{aligned}$$

Thus, this is about half as fast again as the speed required to maintain a 500 km orbit above the Earth. Satellites will never therefore simply fly-off into space and with the virtual absence of air-resistance above *ca* 100 km, there is no mechanism for efficient energy-loss so they cannot simply tumble back to Earth either.

12.2 Space-based, solar-power⁶³

In outer space there is around half as much radiation again per unit area as exists on Earth, but the practicalities of constructing and launching satellites carrying very large (of the order of thousands of km^2) arrays of photovoltaic panels would mean an engineering project of unparalleled dimension and difficulty. Indeed, to obtain power from outer space in this way has, in terms of cost, been compared with obtaining power from nuclear fusion⁶⁴. Although solar energy can be collected in space in principle for use on Earth, there is the problem of how to transmit energy from the collection point, in space, to the Earth’s surface where it is to be used. Clearly it is not practical to link the energy collecting orbiting satellite to the Earth using wires, and for this reason many SBSP (space based

solar power) designs have been proposed in which the energy would be converted to a beam of microwaves to transmit the power wirelessly using a microwave emitter or a laser. The collecting satellite would convert solar energy into electrical energy using PV, which would then be used to power a microwave emitter (Figure 20) or a laser directed at a collector on the Earth's surface (Figure 21). While it is true that the solar panels would be protected from corrosion and impact from prevailing weather conditions such as they suffer at the Earth's surface, and the resulting maintenance costs; in outer space they would be subject to high levels of radiation damage and impacts from micrometeorites. While the notion may sound like Star-Wars, in fact producing electricity from sunlight in space is a fairly well-established technology. Indeed, many space-faring craft, such as rovers and shuttles, are covered in solar cells, and hundreds of satellites actually in space use solar energy as their main source of power. What is totally new, however, is the transmission of the power back to Earth for terrestrial applications and, perhaps more daunting, to build such massive structures as would be required. Indeed, these are so large that it may be necessary to assemble them physically in space rather than trying to launch them from planet Earth. If it could be done, then it is an environmentalist's dream since a perfectly clean source of energy would be on-tap, solving certainly the problem of electricity production (noting that 80% of the energy used on Earth is not provided by electricity) and there are no by-products (greenhouse gases, *etc.*) although there would be environmental costs in terms of the actual production of the PV devices and the craft themselves. The timeline for SBSP technology has been outlined, and extends over 40 years⁶³.

12.2.1 Timeline for space-based, solar-power⁶³

- **1968:** Dr Peter Glaser introduces the concept of a large solar power satellite system [originally known as satellite solar power system (SSPS)] of square miles of solar collectors in high geosynchronous orbit (GEO is an orbit 36,000 km above the equator), for collection and conversion of the Sun's energy into an electromagnetic microwave beam to transmit usable energy to large receiving antennas (rectennas) on Earth for distribution on the national electric power grid.
- **1973:** Dr Peter Glaser was granted US patent number 3,781,647 for his method of transmitting power over long distances (*e.g.*, from an SPS to the Earth's surface) using microwaves from a very large (up

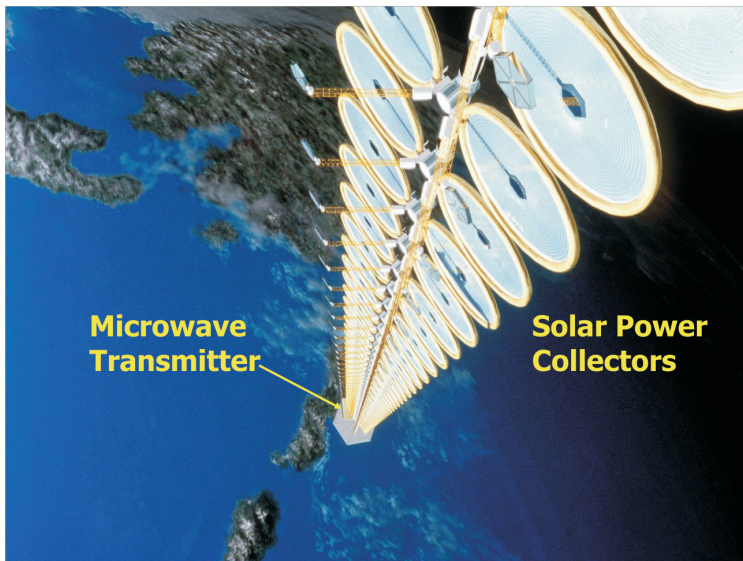


Fig. 20. Essentials of a space-based solar power system (SBPS), satellite collecting solar energy through photovoltaics to drive a microwave transmitter. With permission from Dr Neville Marzwell.

<http://spaceinvestmentsummit.com/sis3/2A-Marzwell.pdf> Page 7.

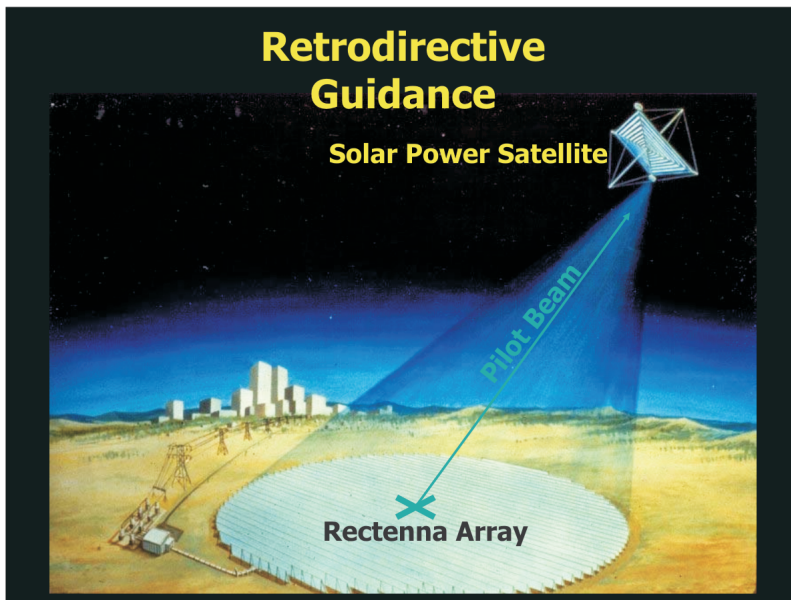


Fig. 21. Microwave beam from SBPS satellite (Figure 20) directed at rectenna array at the Earth's surface. With permission from Dr Neville Marzwell.

<http://spaceinvestmentsummit.com/sis3/2A-Marzwell.pdf> Page 8.

to one square kilometre) antenna on the satellite to a much larger one on the ground, now known as a rectenna.

- **1970s:** DOE and NASA examines the SPS concept extensively.
- **1994:** The United States Air Force conducts the Advanced Photovoltaic Experiment using a satellite launched into low Earth orbit by a Pegasus rocket.
- **1995–1997:** NASA conducts a “Fresh Look” study of SSP concepts and technologies.
- **1998:** Space Solar Power Concept Definition Study (CDS) identifies commercially viable SSP concepts which are credible, with technical and programmatic risks identified.
- **1999:** NASA’s Space Solar Power Exploratory Research and Technology program (SERT see section below) program initiated.
- **2000:** John Mankins of NASA testifies in the US House “Large-scale SSP is a very complex integrated system of systems that requires numerous significant advances in current technology and capabilities. A technology roadmap has been developed that lays out potential paths for achieving all needed advances—albeit over several decades.”
- **2001:** PowerSat Corporation founded by William Maness.
- **2001:** Dr Neville Marzwell of NASA states “We now have the technology to convert the Sun’s energy at the rate of 42 to 56 percent... We have made tremendous progress....If you can concentrate the Sun’s rays through the use of large mirrors or lenses you get more for your money because most of the cost is in the PV arrays... There is a risk element but you can reduce it... You can put these small receivers in the desert or in the mountains away from populated areas....We believe that in 15 to 25 years we can lower that cost to 7 to 10 cents per kilowatt hour....We offer an advantage. You do not need cables, pipes, gas or copper wires. We can send it to you like a cell phone call—where you want it and when you want it, in real time.”
- **2001:** NASDA (Japan’s national space agency) announced plans to perform additional research and prototyping by launching an experimental satellite of capacity between 10 kilowatts and 1 megawatt of power.
- **2007:** The Pentagon’s National Security Space Office (NSSO) issued a report on October 10, 2007 that states they intend to collect solar energy from space for use on Earth to help the United States’ ongoing relationship with the Middle East and the battle for oil. The International Space Station is most likely to be the first test ground for this new idea, even though it is in a low-Earth orbit.

- **2007:** In May 2007 a workshop was held at MIT to review the current state of the market and technology.
- **2009:** A new company, Space Energy, Inc., plans to provide space-based solar power commercially. They say they have developed a “rock-solid business platform” and should be able to provide space-based solar power within a decade.
- **2009:** Pacific Gas and Electric (PG&E) announces it is seeking regulatory approval for an agreement with Solaren to buy 200 MW of solar power, starting in 2016. PG&E spokesman Jonathan Marshall stated that “We’ve been very careful not to bear risk in this.”

12.2.2 SERT

In 1999 NASA’s Space Solar Power Exploratory Research and Technology program (SERT) was initiated for the following purpose⁶³:

- Perform design studies of selected flight demonstration concepts.
- Evaluate studies of the general feasibility, design, and requirements.
- Create conceptual designs of subsystems that make use of advanced SSP technologies to benefit future space or terrestrial applications.
- Formulate a preliminary plan of action for the U.S. (working with international partners) to undertake an aggressive technology initiative.
- Construct technology development and demonstration roadmaps for critical SSP elements.
- To develop a SPS concept for a future gigawatt space power systems to provide electrical power by converting the Sun’s energy and beaming it to the Earth’s surface.
- To provide a developmental path to solutions for current space power architectures. Subject to studies, it proposed an inflatable photovoltaic gossamer structure with concentrator lenses or solar dynamic engines to convert solar flux into electricity. Collection systems were assumed to be in Sun-synchronous orbit.

Some of SERT’s conclusions include the following:

- The increasing global energy demand is likely to continue for many decades resulting in new power plants of all sizes being built.
- The environmental impact of those plants and their impact on world energy supplies and geopolitical relationships can be problematic.
- Renewable energy is a compelling approach, both philosophically and in engineering terms.

- Many renewable energy sources are limited in their ability to affordably provide the base load power required for global industrial development and prosperity, because of inherent land and water requirements.
- Based on their Concept Definition Study, space solar power concepts may be ready to reenter the discussion.
- Solar power satellites should no longer be envisioned as requiring unimaginably large initial investments in fixed infrastructure before the emplacement of productive power plants can begin.
- Space solar power systems appear to possess many significant environmental advantages when compared to alternative approaches.
- The economic viability of space solar power systems depends on many factors and the successful development of various new technologies (not least of which is the availability of exceptionally low cost access to space) however, the same can be said of many other advanced power technologies options.
- Space solar power may well emerge as a serious candidate among the options for meeting the energy demands of the 21st century.

12.2.3 *Wireless power transmission from space to Earth*⁶³

The SBSP concept has several major advantages over terrestrial solar power generation. There is no air in space, so the collecting surfaces would receive much more intense sunlight (by 43%), and also be unaffected by weather, *e.g.* cloudy days. In a geostationary orbit, an SBPS would be illuminated close to 100% of the time; only being in the shadow of the Earth for a few days during the spring and autumnal equinoxes; and even then for a maximum of 75 minutes late at night when power demands are at their lowest⁶⁵. This avoids the expense of storage facilities necessary in many Earth-based power generation systems, especially renewables such as (terrestrial) solar, wind, wave, *etc.* SBSP could also be applied on a global scale. In comparison with nuclear power which is a technology that many governments are reluctant to sell to developing nations, where political pressures might lead to the development of nuclear weapons, SBSP appears completely safe. In the 1980s, NASA investigated the potential use of lasers for space-to-space power beaming, focussing primarily on the development of a solar-powered laser. It was proposed in 1989 that power could also be usefully beamed by laser from Earth to space. 1991 saw the inauguration of the SELENE⁶⁶ project (Space Laser ENergy)

which included a study of laser power beaming for supplying power to a lunar base.

In 1988, Grant Logan suggested that an Earth-based laser could be used to power an electric thruster to enable space propulsion, along with more detailed technical specifications in 1989. Logan's proposal was ambitious, since it required diamond solar cells working at 600°C in order to convert ultraviolet laser light, a technology that has yet to be demonstrated even in the laboratory, to a wavelength that is not easily transmitted through the Earth's atmosphere. SELENE program was closed after two years on grounds of the cost of taking its findings into practical operation⁶⁶.

An obvious question is that of how large the SBSP should be, and there are two factors to be considered: firstly the size of the collecting apparatus (*e.g.*, panels, mirrors, *etc.*) and secondly the size of the transmitting antenna (which in part depends on the distance between the two). It has been suggested that the satellite antenna should be circular and about 1 kilometre in diameter or larger, while the ground antenna (rectenna) should be elliptical, 10-km wide, and a length that makes the rectenna appear circular in respect to the GEO (geostationary orbit). This would correspond to typically, 14 km at some North American latitudes. Smaller antennas would result in increased energy losses. For the desired (23 mW/cm²) microwave intensity such antennas could transfer between 5 and 10 GW (5,000–10,000 MW) of power⁶⁷. It is reckoned that if 14% silicon solar cells were used, the satellite collector area would be between 50 and 100 km². In principle, this area might be reduced if more efficient solar cells were used, but there is no avoiding the fact that the collector would be of kilometre dimensions, and larger than all human created structures here on Earth. While it cannot be ruled out entirely, the scale of engineering, and done in space at that, is uncharted territory (Figure 22).

12.2.4 Environmental impacts

A critical part of the SBSP concept is the Earth-based antenna (rectenna) receiver system, which would in all likelihood consist of many short dipole antennas, connected via diodes. It is thought that microwaves broadcast from the SPS will be received in the dipoles with about 85% efficiency which is less than that expected for conventional microwave antenna, but the latter are more complex and more expensive⁶⁸. The rectennas would be many kilometres across, but crops and animals may be farmed underneath one, as only thin wires will be used to support the structure and to make the

Robotic Assembly, Maintenance, Repair and Servicing for Large Flexible Space Structures

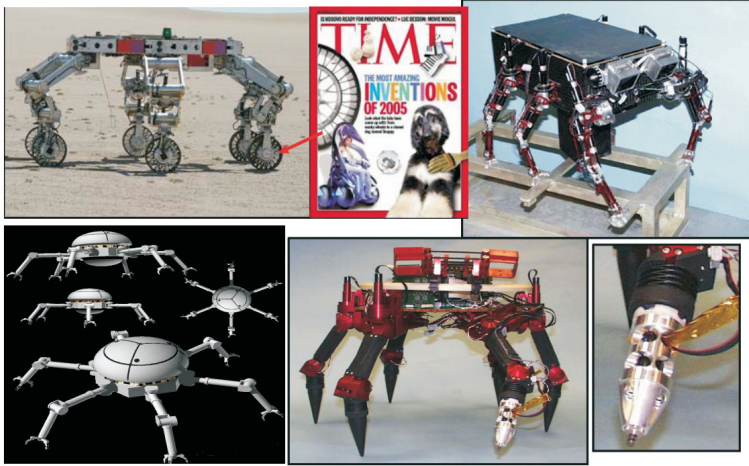


Fig. 22. Hypothetical robotic assembly and maintenance for large future space structures. With permission from Dr Neville Marzwell.
<http://spaceinvestmentsummit.com/sis3/2A-Marzwell.pdf> Page 19.

dipoles, which will marginally reduce sunlight. Otherwise non-arable land can be used. Thus the technology is less demanding in terms of its land requirement than is often claimed. Other concerns concern the effect on the atmosphere. When rockets launch through the atmosphere, the hot rocket exhaust reacts with the atmospheric nitrogen and can form NO_x which can destroy the ozone layer. This is, indeed, a criticism that can be levelled at all kinds of high-altitude aircraft.

Since the whole reason for placing a solar power satellite is to increase the amount of solar energy reaching Earth, the additional energy will be terrestrially dispersed as heat, and this may be significant if the scale of operations is large enough. Rather the prevailing view seems to be that increasing concentrations of greenhouse gases, principally carbon dioxide and methane, are causing the Sun's energy to be trapped rather than being radiated into space, which hence is causing the Earth to warm-up^{4,5}. As an alternative to fossil fuels as a source of energy, SBSP would contribute greatly to a reduction in greenhouse gas emissions.

12.2.5 Safety

At first glance, the idea of sending a beam of microwaves from space to Earth is alarming to say the least. The term “death ray”

comes to mind, and one wonders what would happen if the beam accidentally drifted off-course and hit some unsuspecting bystander, incinerating them to dust! In reality, microwave relay beams have been used without incident for many years for telecommunications purposes.

The following sums are illustrative in putting one's mind at rest. A proposed microwave beam would have a maximum intensity at its centre, amounting to 23 mW/cm^2 (which is less than a quarter of the solar irradiation constant), and an intensity of less than 1 mW/cm^2 outside of the rectenna fence⁶⁷. Even within its most intense region the beam energy is far below what is regarded as dangerous even for an indefinitely prolonged exposure⁶⁹. Exposure to the centre of the beam can in any case be avoided at ground level (*e.g.*, via fencing), and most aircraft are fitted with a protective metal shell (*i.e.*, a Faraday Cage), which will intercept the microwaves, should they fly into the beam-path. >95% of the beam energy will fall on the rectenna while any remaining microwave energy will be absorbed and dispersed well within standards currently imposed upon microwave emissions around the world⁷⁰.

The microwave beam intensity at ground level in the centre of the beam would be a built-in feature the system for the simple reason that transmitter (in space) would be too far away and too small to be able to increase the intensity to unsafe death ray levels, even theoretically. An important design constraint is to ensure that the beam is of sufficiently low power that wildlife, mainly birds, will not be injured by it. It is interesting that wind-turbines are thought to be much more dangerous to birds who inadvertently fly into their sweep. It has been proposed that the rectennas should be placed offshore^{71,72}, but this would cause problems, of corrosion, mechanical stresses, and biological contamination. One well established means by which to ensure fail-safe beam targeting is to use what are called retrodirective phased array antenna/rectenna. Here the principle is that a "pilot" microwave beam emitted from the centre of the rectenna on the ground establishes a phase front at the transmitting antenna. Circuits in each of the antenna's subarrays measure the pilot beam's phase front against an internal clock phase. Thereby, the transmitted beam is centred precisely on the rectenna and has a high degree of phase uniformity. If the transmitting antenna is turned away from the rectenna, for example and the pilot beam is lost, the phase control fails and the microwave power beam is automatically defocused⁷³. Simply put, a system of this kind is a fail-safe and incapable of focusing its power beam anywhere that did not have a pilot beam transmitter.

12.2.6 Launch costs

One problem facing the SBPS programme is that space launches are very expensive especially at GEO altitude. Current rates on the Space Shuttle run between \$6,600/kg and \$11,000/kg to low Earth orbit, depending on whose numbers are used. Alternative vehicles, such as the Falcon 9 Heavy, are predicted to launch to LEO for approximately \$2,900/kg. However, it is not necessary to put all of the satellite material directly into the GEO, and so it may prove possible to employ high efficiency (but slower) engines to move SBPS material from a LEO to GEO much more cheaply, *e.g.* using ion thrusters or nuclear propulsion engines. The scale of the problem may be indicated by assuming an arbitrary solar panel mass of 20 kg per kilowatt (without considering the mass of the supporting structure, antenna, or any significant mass reduction of any focusing mirrors), on the basis of which a 4 GW power station would weigh about 80,000 tonnes, which would have to be launched from the Earth in its entirety, given current technology. It is possible that very lightweight designs could achieve 1 kg/kW⁶⁴, meaning that the solar panels for the same 4 GW capacity station would be reduced in mass to a “mere” 4,000 tonnes, or the equivalent of between 40 and 80 heavy-lift launch vehicle (HLLV) launches to send the material to LEO, where it would likely be converted into subassembly solar arrays, which could be carried on high-efficiency ion-engine style rockets to (slowly) reach GEO.

A consideration of costs has been made⁶³: “With an estimated serial launch cost for shuttle-based HLLVs of \$500 million to \$800 million, and total launch costs for alternative HLLVs at \$78 million, total launch costs would range between \$11.3 billion (low cost HLLV, low weight panels) and \$320 billion (‘expensive’ HLLV, heavier panels). Economies of scale on such a large launch program could be as high as 90% (if a learning factor of 30% could be achieved for each doubling of production) over the cost of a single launch today. In addition, there would be the cost of an assembly area in LEO (which could be spread over several power satellites), and probably one or more smaller one(s) in GEO. The costs of these supporting efforts would also contribute to total costs. So how much money could an SPS be expected to make? For every one gigawatt rating, current SPS designs will generate 8.75 terawatt-hours of electricity per year, or 175 TWh over a 20-year lifetime. With current market prices of \$0.22 per kWh (UK, January 2006) and an SPS’s ability to send its energy to places of greatest demand

(depending on rectenna siting issues), this would equate to \$1.93 billion per year or \$38.6 billion over its lifetime. The example 4 GW ‘economy’ SBPS above could therefore generate in excess of \$154 billion over its lifetime. Assuming facilities are available, it may turn out to be substantially cheaper to recast on-site steel in GEO, than to launch it from Earth. If true, then the initial launch cost could be spread over multiple SPS lifespans.”

12.2.7 Building from space

This final section is the most speculative and at the present time much of it does sound like science fiction. Noting the problem of high launch costs in the early 1970s, Gerard O’Neill proposed building the SPS’s in orbit with materials from the Moon⁷⁴ on the grounds that launch costs from the Moon are about 100 times lower than from Earth because the Moon’s gravity is accordingly less. This 1970s proposal was based on the contemporary future launch costing of NASA’s space shuttle. By 1980 it was clear that NASA’s estimates of launch costs for the space shuttle were grossly optimistic, and O’Neill *et al.* published another manufacturing strategy which employed lunar materials. The start-up costs were far lower⁷⁵ since the concept relied more on partially self-replicating systems on the lunar surface under the robotic control of workers stationed on Earth. Since automated systems of this kind do not as yet exist on Earth, it is some way before they could be developed for Lunar use.

As we begin to run short of various materials including metals (Section 6) on Earth, the prospect of asteroid mining is increasingly being considered seriously. One NASA study⁷⁶ has analysed the prospects of a 10,000 ton mining vehicle, which would need to be assembled in orbit, and would bring a 500,000 ton asteroid ‘fragment’ to GEO. 7,000 tons of the vehicle would consist of reaction mass for the mass-driver engine and the spent rocket stages used to launch the payload could provide this. Accepting that it is probably not realistic, it has been concluded that if 100% of the returned asteroid was useful, and that the asteroid miner itself could not be reused, a nearly a 95% reduction in launch costs could be achieved. In reality however, to evaluate the probable success of the method requires an accurate and detailed mineral survey of the candidate asteroids, rather than the estimates of their composition that are available currently.

13. Conclusions

Solar energy is a complex and multifarious topic and one that is of pressing attention as the problems of providing energy for the world become more acute. There are some very extravagant schemes proposed, for example Desertec, which require the scale-up of tested technology, and others like space-based solar power production (SBSP) which are entirely untested in all respects. At a more prosaic level, solar energy is likely to become very useful in providing for more localised communities, as civilization will devolve to being as fossil fuels, most notably crude oil become more expensive and *per se* more scarce. It is debatable just how much time we have left in the free bestowal of fossil energy, oil, gas and coal, and indeed uranium for nuclear power, in order to supplant them by new and alternative technologies, including solar energy. Whatever time there is remaining must be judged against the likely scale of resources, of metals and energy and time that will prove necessary to bring in this brave new world. Even if solar can provide all the world's electricity demand, only 20% of our total energy requirement is met; the remaining 80% is used as thermal energy, and 40% of the grand energy total comes in the form of oil, used mainly to run our globalised world and its transport. Without a wholesale establishment of transportation via an electrified system, rather than the present one one which is underpinned almost exclusively by oil, it is the arrival of peak oil³ and the loss of cheap and freely available liquid fuels on the world markets that will change the face of the world, from the global to the local, and all that will entail. Surveying future energy prospects, in a way, the production of electricity is the least of our troubles.

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