THE LONG ROAD TO CATCHING THE SUN

HOW CAN WE USE ENERGY FROM SUN PHOTONS DIRECTLY?

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A huge amount of solar energy is intercepted by Earth, and can be converted into thermal, chemical or electrical energy in numerous ways. In this article, we analyse the different solar technologies that exist, their costs and potential, with a view to the possibility of transforming enough energy to achieve a sustainable society.

The fields of health and energy are the two main pillars of research in today's society. The important role of energy is due to our need for an abundant and cheap energy supply, free of geopolitical constraints. Energy is essential for the sustainable development of society and, therefore, crucial to the future, in which we must cater to our needs for water, work, food, shelter, comfort, and so on.

To assess the role of energy, it is important to consider that Spain, on average, needs energy equivalent to about 13.5 litres of petrol per capita daily. Probably this amount is meaningless in itself. But if we accept that everyone has the right to maintain the same standard of living, then generalisation of this demand worldwide would triple current use, especially if we consider the population growth expected in the coming years. Currently, consumption in the United States is equivalent to 37.5 litres of petrol per capita yearly, compared with less than a litre in some African countries.

A great deal has been written about the capacity of real and workable fossil fuel reserves (oil, coal, gas), and whether mankind has already exceeded the so-called peak oil (demand exceeds the extraction and processing capacity). However, this is not the real problem. The foreseeable global energy demand requires almost quadruple the capacity of energy production. That means almost quadruple the existing capacity, exceeding 50 terawatts. Such amounts greatly exceed what energy fossil fuels can possibly provide; not to mention the inherent problems associated with CO_2 or CH_4 emissions to the atmosphere, with the consequent impact on our climate. Putting a 100-megawatt power plant into operation every day for forty years would not bring us any closer to our goal, nor are fossil fuels or nuclear fission sources guaranteed for so many power plants.

«ADVANCES IN NANOSTRUCTURED MATERIALS AND CATALYSIS HAVE ALSO FACILITATED MAJOR RESEARCH INITIATIVES IN THE DIRECT CONVERSION OF SOLAR ENERGY INTO CHEMICAL ENERGY, EITHER HYDROGEN OR METHANE»

SOLAR ENERGY IN FIGURES

Having reached this point, the only guaranteed energy source available is the Sun. The solar energy intercepted by Earth amounts to a total of about 1 kilowatt per square metre –5.4×10^{24} joules (J) or 174×10^{15} watts (W) yearly. This exceeds the current amount humans consume by three orders of magnitude. Given a land area of 500 million km^2, of which 71% is water, and an average energy of around 1,000 W/m^2, it provides a power source that is more than sufficient, as well as being independent, inexhaustible and practicable worldwide.

Seventy percent of the solar energy intercepted by Earth each year, representing 3,850,000 exajoules (EJ) and equivalent to 122 billion kilowatt-hours (kWh), is absorbed by the atmosphere, oceans and continents. This energy arrives in photons of different

On the left, Sebastián Nicolau. *Heaven's Oven*, 2012. Digital intervention of *Workin' 6 (Curved Stairs)*. Aluminium, 35.5 x 73 x 18.5 cm (fragment).

energies, ranging from ultraviolet to infrared. One of these, on being absorbed, produces thermal gradients underlying weather patterns, including wind. Indeed, only 0.07% of the solar energy absorbed by the planet is estimated to end up as potential wind energy usable by humans. Even so, a capture and conversion efficiency rate of just 20% would be more than enough to satisfy global electricity demands.

Another portion of solar energy (approximately 0.1%) is absorbed by photosynthetic processes fixing CO_2 to produce organic matter. Here, it should be said that the photosynthetic conversion efficiencies are very low. For instance, the plant commonly grown for palm oil, whose yield is 4,000 kilos per hectare per annum, has an ECE (Energy Conversion Efficiency) of only 0.18%, while microalgae, yielding 91,000 kilos per hectare per annum, have an ECE of 4.5% (representing 956,000 kWh per hectare per annum). In summary, this falls far short of photovoltaic conversion systems, with an average ECE of 14.5% (silicon cells) and yearly energy production per hectare of 3 million kWh. Such a production capacity means just 450,000 km^2 would suffice to generate all the primary energy used by mankind. This surface area represents only one twentieth of the area covered by the Sahara desert.

Untapped energy is radiated back into space by the atmosphere or the soil, at a rate representing 68% of the energy reaching Earth, in other words about 3.7 million EJ. That represents a great deal –one thousand times– more than today's primary energy requirements, confirming that the energy is there and just needs to be captured and transformed for use in a sustainable way.

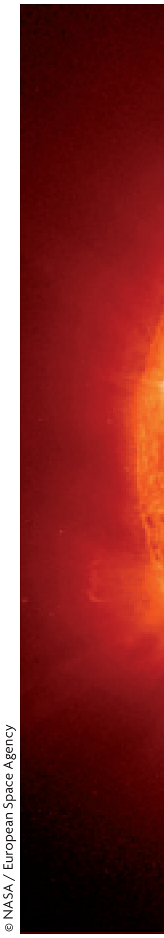
At this point, many questions arise, and here we highlight three that are fundamental to explaining and understanding the status of solar energy, and the long way it still has to go to become a real renewable energy alternative. First, we should address issues relating to solar technologies: how can we directly capture and harness energy from the Sun via its photons? Second, the question of costs: what are the associated costs? What investments are needed? What is the cost of each electric kWh produced? Is it competitive? And the third concerns viability. Are there enough raw materials to manufacture and install all the solar plants needed?

> «ALTHOUGH PHOTOVOLTAIC ENERGY IS NOT A FINANCIALLY VIABLE OPTION AT PRESENT, AND GREATER EFFORT IS REQUIRED TO MAKE SOLAR ENERGY COMPETITIVE, WE ARE PAVING THE WAY AND CAN EXPECT VALUES OF 0.04 EUROS/KWH IN THE SOUTHERN MEDITERRANEAN COUNTRIES BY 2030»

SOLAR TECHNOLOGIES

There are different mechanisms by which solar photons can be absorbed and subsequently converted into energy. Solar energy can be converted into thermal energy (the ECE of solar radiation into electricity[1] of 16%), direct chemical energy[2] (still under development with promising efficiencies for photocatalysis mechanisms) or, the most well known, into electric energy by means of photovoltaics.[3] Although this mechanism was known about previously, it was first used at Bell Labs in 1954, with the development of silicon-based semiconductor technology. Back in 1958, silicon-based photovoltaic solar cells were used on the Vanguard 1 satellite, with an efficiency of around only 6%. Since then, advances made in these fields of research and development have been steady and progressive, with a major turning point in the seventies due to the first fossil fuel crisis; however, commercial implementation is still far from being economically established.

On using one semiconducting material alone, the maximum possible theoretical efficiency is only 31% at cell level, as many photons in the solar spectrum are not useful for producing electricity because they do not adjust to the bandgap of the semiconductor. Thus, multiple semiconductors must be combined in a multi-junction tandem configuration (n = 2, 3, 4...) to increase efficiency up to 42.5% and even reach a maximum of 68%. These efficiencies may be improved by applying high solar concentrations to, respectively, 41% for a single material and reaching a theoretical maximum of 86.8%. Alternatively, there are other mechanisms that seek complementary



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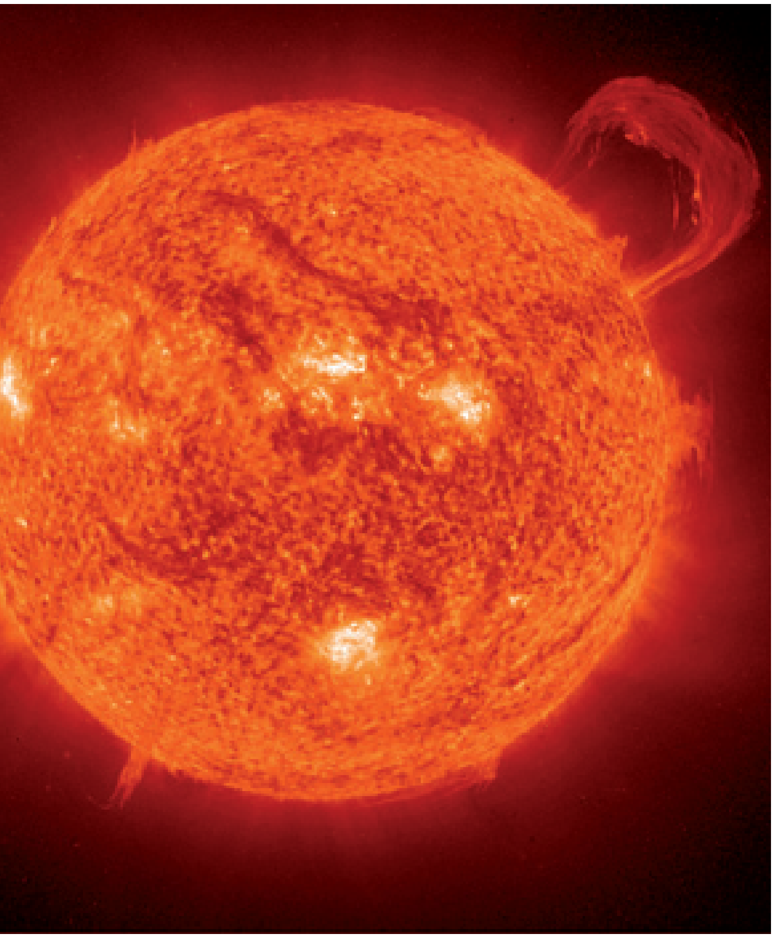
[1] Further information about this technology can be found at the Asociación Española de la Industria Termoeléctrica. Available at: <http://www.protermosolar.com>.

[2] Joint Center for Artificial Photosynthesis <http://solarfuelshub.org>, US Department of Energy, aiming to be a leader in research on solar energy fuel development

[3] Further information on PV energy can be found on the web of the European Photovoltaic Technology Platform: <http://www.eupvplatform.org>.



The Sun is a huge nuclear fusion reactor sending energy out into space, like any other star. The terrestrial biosphere functions with just a fraction of this energy our planet intersects. Humans recover part of this energy via plants and food chains and expressly fossil fuels, where it is saved in organic matter of bygone geological epochs. In recent times we have learned to capture energy directly with photovoltaic and wind collectors, etc. We have also learned to obtain energy through radioactive processes. A complex tricky history fraught with contrasts.

effects such as up conversion, impurity bands or novel mechanisms like thermionic effects, which also have a high direct conversion efficiency of 54%.[4]

To date, the so-called first generation solar module has an efficiency of over 20%, while the so-called second generation, which basically incorporates thin-film technology based on amorphous silicon, cadmium telluride (CdTe) and CIS (copper-indium-selenium), holds the record for efficiency in modules at around 15%, although the record for CIS cells is slightly below 20%. These values are both interesting and competitive with other technologies, making it possible to produce lightweight thin-layer modules, weighing less than 4 kg/m^2, facilitating their integration into buildings.

Meanwhile, the efficiency outlook for concentrated solar power systems is a promising 30%; furthermore, the average service life is guaranteed at over twenty years, with an aim to lengthen it to over thirty-five. However, despite this excellent performance, these values are still unable to meet all our energy demands, even though they do meet the electric energy requirements of a three-person household. These are estimated at an average of about 10 kWh per day, implying a consumption of about 3,600 kWh annually, which could be met by an installation measuring some 15 m^2 with 12-15% efficiencies, but at a high cost.

To overcome this difficulty great efforts are underway, on the one hand to develop very low-cost alternative technologies, such as organic solar cells or Graetzel[5] cells, although these have low efficiencies in intensive applications (<10%) and, on the other hand, to seek high-efficiency systems as a cost-cutting strategy.

[4] More about this point can be found in the article published in *Laser Focus World*, June 16, 2010: «Could Solar Cells Reach 65% Efficiency with Nanowires?». Available at: <http://www.laserfocusworld.com/articles/2010/06/could-solar-cells.html>.

[5] For further information see <http://isic.epfl.ch/>.

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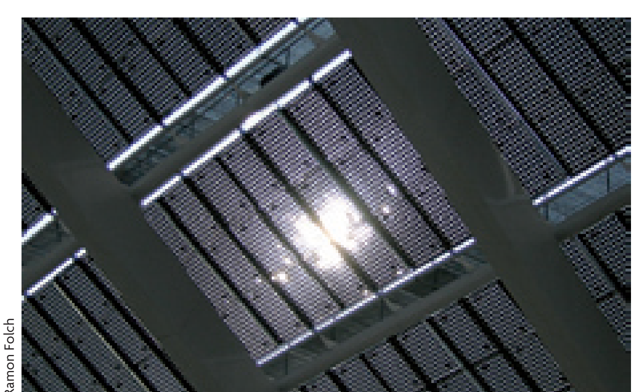

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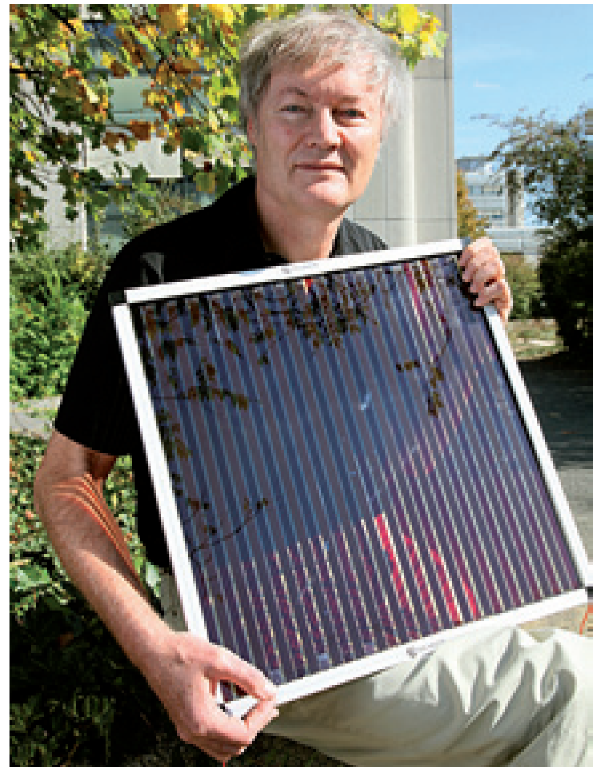
Photosynthesis is solar energy's way into the biospheric system, though its yield is modest. Photovoltaic energy production is the direct technological replica of energy from sunlight.

In this ambit, promising records have been set by combining multi-junction configuration with concentrated systems, exceeding 40% in cells, and nanostructured materials (nanowires, quantum wells…) have been incorporated, with highly promising characteristics. In recent years, advances in these materials and in catalysis have also facilitated major research initiatives in the direct conversion of solar energy into chemical energy, either via hydrogen production (with efficiencies below the 10% range) or in methane production from sunlight, water and CO_2 in artificial photosynthesis.

COSTS AND EXPECTATIONS

Despite the obvious solutions and scientific and technological advantages provided by solar energy systems, generally speaking, our society and the economic structure of this sector –led by the major energy industries worldwide– is based on a free-market system where energy price is fundamental to its implementation. Large investments in new prospection for additional fuel sources must cover their transportation (oil or gas pipelines), processing (refineries) and distribution, or the construction of new electricity production plants (thermal, cogeneration, nuclear...). This calls for huge capital and captive investment, requiring adequate payback. Therefore, a cornerstone of this free market is what is internationally known as LCOE (Levelised Cost of Energy), or the cost of putting power on the grid, independent of the energy source. Clearly, we are talking of hard financial costs rather than intangible values, like those relating to the fact it may be an environmentally-friendly renewable energy source, with social or added value, like lower impact on CO_2 emissions, or issues related to the treatment of radioactive waste.

A detailed study of kWh costs (EPIA, 2011) shows us there are currently significant differences: 0.04 € / kWh for cogeneration systems, 0.074 € / kWh for wind and 0.19 € / kWh for large PV solar plants. These data explain, to some extent, why photovoltaic energy is not a financially viable option at present, and why an even greater effort is required to make solar energy competitive. Notwithstanding, we are paving the way and, according to the European Photovoltaic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The latest photovoltaic technologies, which are cheaper than conventional silicon, could represent a turning point for this sector, as for instance the solar cells developed by physicist Michael Graetzel (pictured), known as Graetzel cells.

Industry Association (EPIA), values of 0.04 € / kWh are forecast for sunbelt countries (southern Mediterranean) by 2030.

Another way of assessing cost is by considering the investments necessary to build a solar plant. In 2010, the investment per kW of installed capacity was estimated to be around 2,800 euros. Financial studies made in Europe and in the United States forecast installation costs to gradually drop to below 1,000 euros by 2030, including costs of the module, BOS (body of system) components and investment; furthermore, service life of the module should also be lengthened to beyond 25 years, rather than the current 15-year lifespan. This would ensure kWh costs below 10 cents, with significant advances in research that could increase efficiencies to maintain acceptable LCOE pricing ranges.

> «DESPITE THESE LIMITATIONS, AND TAKING INTO ACCOUNT BOTH RECYCLING AND CUMULATIVE GLOBAL PRODUCTION CAPACITY, IT WOULD BE FEASIBLE TO BUILD FACILITIES CAPABLE OF PRODUCING SOLAR ENERGY EXCEEDING SEVEN TERAWATTS»

One often wonders which one of the existing technologies


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has the brightest future, and –if necessary– back one of them at the expense of others. Obviously, not all of them have good prospects in terms of achieving the required cost reduction. For example, today's thin-film technologies (CdTe, CIS...) are currently better positioned near the cost threshold. However, there are other assessment criteria concerning the availability of thin-layer materials. For instance, to install a one-gigawatt solar field with CdTe would require approximately 100 km^2 and bearing in mind that every m^2 of thin-layer material (2 mm thick) takes 6.3 g of tellurium, this would need 630 tons of this element. However, according to figures from 2002, tellurium production was only 1,300 tons, and this fact would restrict production to below two gigawatts and even if greater production efforts are made, there are physical and economic limits that make it unlikely to exceed 5,000 tons. The same is true for other elements typically used in the photovoltaic industry: germanium (photovoltaic concentrators, silicon and germanium alloys, aSi:mSi amorphous and multicrystalline silicon cells), gallium and selenium (CIGS –copper, indium, gallium and selenium– semiconductor material), ruthenium (integrating dye-sensitised solar cells or low-cost solar cells) or silver. The use of such material limits production capacity, requiring the global use of all sources[6] year by year, in order to reach the installation capacity required. Despite these limitations, and taking into account both recycling and cumulative global production capacity, it would be feasible to build facilities capable of producing solar energy exceeding seven terawatts.

> «AN AREA OF PHOTOVOLTAIC RECEPTORS COVERING THE EQUIVALENT OF JUST ONE TWENTIETH OF THE AREA COVERED BY THE SAHARA DESERT WOULD SUFFICE TO GENERATE ALL THE PRIMARY ENERGY CURRENTLY USED BY MANKIND»

In summary, a vast amount of solar energy is intercepted by Earth and we can transform it into thermal, chemical or electrical power. Although there are several mechanisms, the most advanced is based on photovoltaics. The last fifty years have witnessed the development of several generations of PV cells and modules with a range of efficiency rates and costs. The first generation is based on mono-and polycrystalline semiconductors, the second is linked to developments in thin film while the latest generations have incorporated new strategies[7] to obtain high efficiency or low cost.

All said, solar energy must overcome the challenge of reducing costs to below 1€ /picowatt or to a few cents (<4) per kWh if it is to be LCOE competitive. Finally, it should be mentioned that the abundance and availability of some key elements are critical, which means several technologies must exist side by side to achieve sufficient energy conversion rates for a sustainable society.

Solar thermal power stations capture heat, not light, using parabolic mirrors to heat a fluid in a tube or by flat mirrors that heat a single central element located in a tower. This hot fluid moves a turbine and generates electricity. Lately, these concentration solar thermal power stations have incorporated a system that can melt salt (500°C or above) able to release the heat outside sunlight hours, in other words they can generate electricity day and night. The picture shows PS10 solar power plant in Sanlúcar la Mayor (Seville).

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6 In this respect, the IREC carried out the KEST-PV project to develop efficient kesterite solar cells for low-cost sustainable PV technologies. Further information can be found at: <http://www.irec.cat>.

7 An example is the SCALENANO project, in which the IREC is developing nanostructured materials and processes for photovoltaic systems based on high-efficiency low-cost chalcogenides. For further information visit: <http://www.irec.cat>.