PHOTOVOLTAICS

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Summary

Interest in Photovoltaics is currently soaring as a result of incentive policies in some countries, and with a rapidly expanding manufacturing capacity. Behind this recent boom there is a long scientific history: the physical basis for energy production from sunlight is the photovoltaic effect, which was discovered in the first half of the XIX century. Solar cells are devices designed to make use of sunlight. When integrated into modules they are used to build photovoltaic systems that can be very different in purpose, size and location. Nowadays, however, building-integrated, grid-connected PV is the most important application. The input to these systems is solar radiation, a renewable energy source with special characteristics. A very important one is its huge potential so that photovoltaic technology is destined to become a major source in the

future. But today's technology, based in crystalline silicon, does not seem capable of taking the definitive step towards cheap, mass production. Novel approaches are being sought in several systematic, scientific undertakings that start from the physical fundamentals of Photovoltaics.

1. Introduction

Through the photovoltaic (PV) effect, electrical power can be obtained from sunlight. PV energy is a ubiquitous source both in consumption and production, since electricity can be used for almost any application and sunlight is found everywhere; it is extremely modular, being able to produce watts or megawatts under essentially the same configuration; it is versatile, both a potential world-scale energy source and a suitable solution for numerous small powering problems. It can be integrated in city buildings or in remote dwellings with no access to conventional electricity and is both inexhaustible and clean. On the negative side, the sun's energy has a low density and is intermittent, and PV electricity is, at the moment, expensive.

The basic element of a PV installation is the module that contains a set of electrically interconnected solar cells. When illuminated, each solar cell produces voltage, (typically, about 0.5 V) and current (3 to 5 A under brilliant sunlight, depending on its size). Inside the module, the cells are connected in series or in parallel, so that their voltages or currents total up, respectively.

Photovoltaic installations consist of arrays of modules connected together in series-parallel configurations to achieve the voltage, current and power levels required by the application. In Figure 1 the photovoltaic pergola of the Forum of the Cultures of Barcelona, of some 450 kWp (kilowatts peak, to be defined later), is shown, together with pumping system in Morocco, of around 1 kWp.

Figure 1: The photovoltaic pergola in Barcelona's Forum of the Cultures (left) and the generator for a pumping system in Morocco (right)

PV systems can operate either in DC or in AC, in which case an inverter is needed to convert the DC current provided by the generator into AC. In isolated installations, batteries are connected to the DC circuit to store the energy produced for use during the night and on cloudy days.

This chapter begins by describing the current situation of the photovoltaic industry and surveying the history of the technology. The solar cell is the device designed to exploit the photovoltaic effect and is at the heart of a PV system. Both the effect and the device are explained later. The input power for PV conversion is solar radiation, some of whose main features will be analyzed. The main system configurations and existing module technologies are then presented. The chapter will start by looking at the present and past and will finish with some considerations on the future of PV.

2. What We See Today

As shown in Figure 2, interest in photovoltaics is currently growing very rapidly. It took some 25 years to produce the first Gigawatt peak of solar cells,. It has taken less than three years to build the second and a third one was produced last year. Although the present pace, according to our own prospective studies, will not be maintained beyond this decade, PV is destined to become one of the major suppliers of electricity. It is not only our own opinion. Let us quote Shell International, the big oil company, in a when it says, in a study called *Energy Needs, Choices and Possibilities Scenarios to 2050,* that "Two potentially disruptive energy technologies are solar photovoltaics, which offer abundant direct and widely distributed energy, and hydrogen fuel cells, which offer high performance and clean final energy from a variety of fuels." They then add, describing one of their scenarios for the future: "By 2050 renewables reach a third of world primary energy and are supplying most incremental energy".

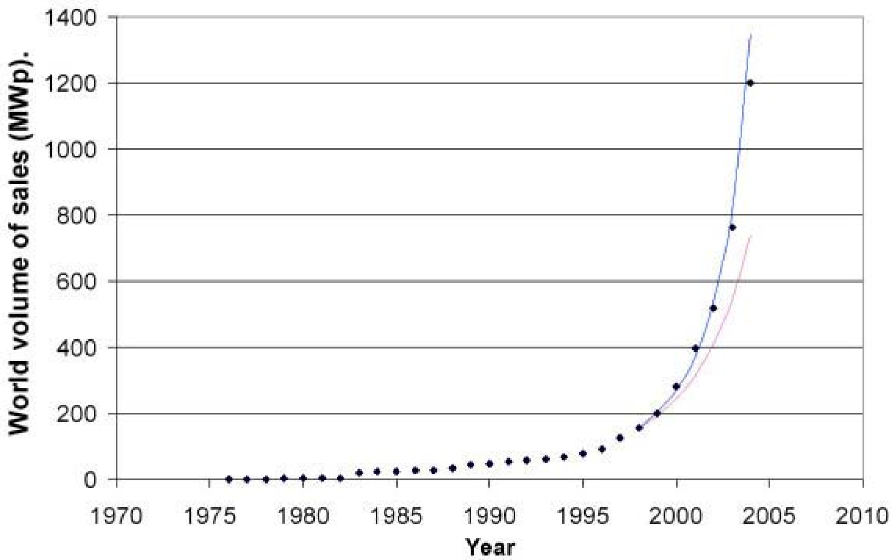

Figure 2: Points: PV cells world market according to P. Maycock, PV News (February issue of the successive years) and Photon International, March 2003. The line: Calculations with the growth model by one of the authors

It is interesting to see which companies are the protagonists in this technological revolution. The top ten in 2003 are represented in Figure 3. Together they make up 77.5% of World production.

We can see the total predominance of the Japanese company Sharp, not only the biggest in the world but also the oldest still operating, as it started selling PV modules in 1963.

It can also be seen that most of the main protagonists are big multinational corporations well situated in the high tech field, in particular in electronics and communications (Sharp, Kyocera, Sanyo, Mitsubishi), or they are divisions of big oil companies (BP Solar, Sharp Solar) or utilities (RWE).

Some German (Q Cells, Deustche Solar) and Spanish (Isofoton) companies are however specialized companies entirely devoted to the PV business. The latter is actually the only University spin-off among the top ten, originated at the Institute of Solar Energy in the Polytechnic University of Madrid.

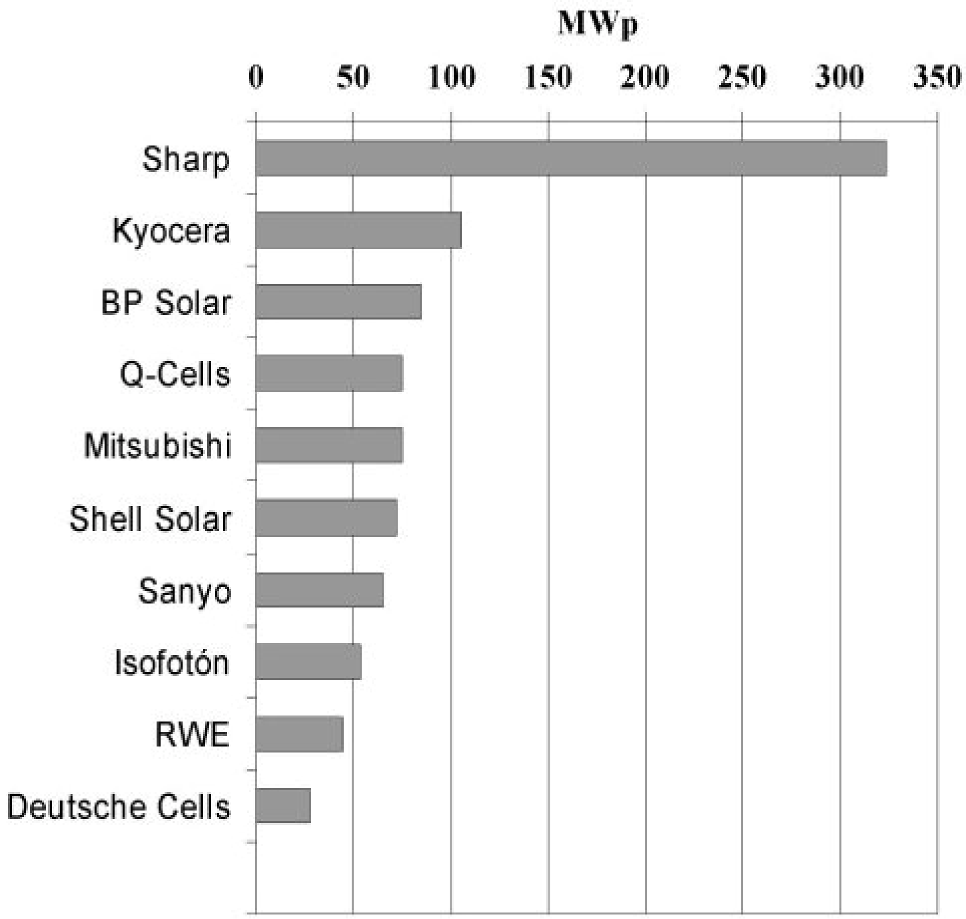

Figure 3: The top ten solar cell world manufacturers in 2004 making up 77.5% of the world market. Drawn up from data in PV News, by P. Maycock.

The involvement of big high tech or energy corporations is proof, we think, of the seriousness of the photovoltaic endeavor and its future.

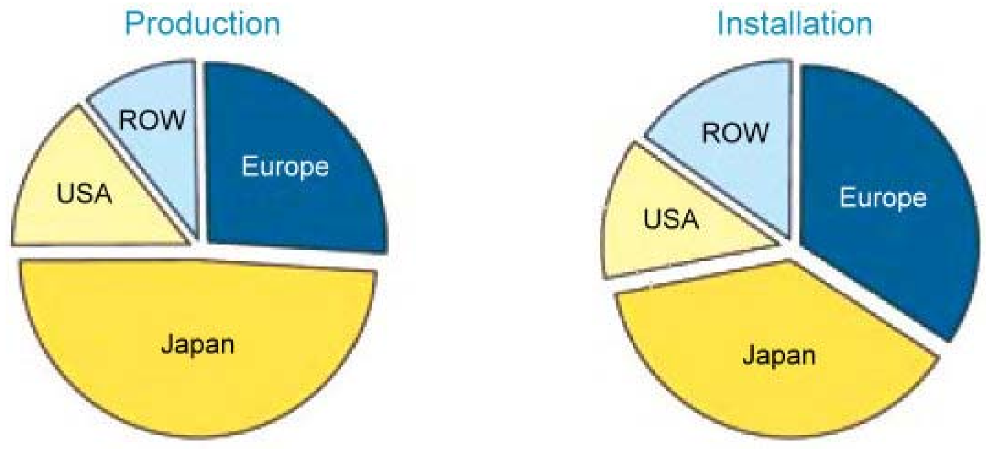

Figure 4: Production and market of PV modules by regions in 2003. PV-TRAC *A vision for photovoltaic technology*, ISBN 92-894-8004-1 - EUR 12242 /EN (2005)

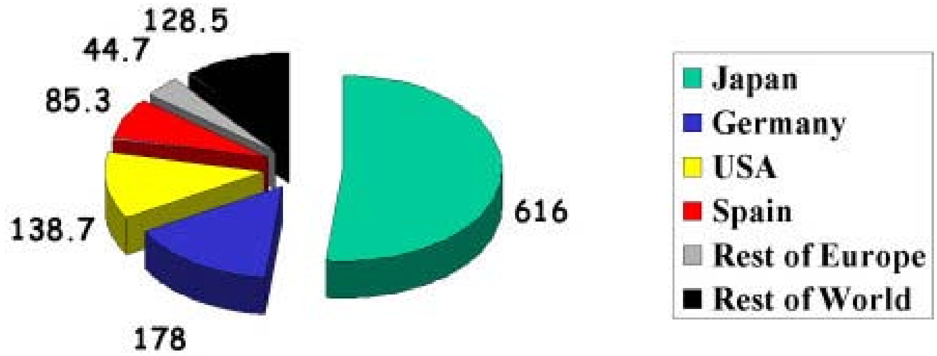

Figure 5: Production of PV modules per countries in 2004. Drawn up from data in PV News, by P. Maycock.

The main cell-user and cell-producer regions or countries are represented in Figure 4. We can see that Europe and Japan are in the first place, at a similar level, but Japan is a net exporter and Europe a net importer. The USA has a more or less balanced position while the rest of the world is an importer.

This picture hides some important characteristics. For instance Germany is by far the biggest PV installer in Europe and mainly responsible for the brilliant European position in this respect, but its capacity of manufacturing, which has grown very much in the recent past, is smaller.

The reverse situation is that of Spain, whose installation records are not as good as its manufacturing capacity, to the point that it is the fourth world producer, far from its competitors, as seen in Figure 5 and Figure 6, and exports about 80% of its production, much of it to Germany but to a larger extent to the rest of the world.

In the rest-of-the-world producers we must count China and India that together with Australia almost complete the list (the rest of Europe is not included in this category).

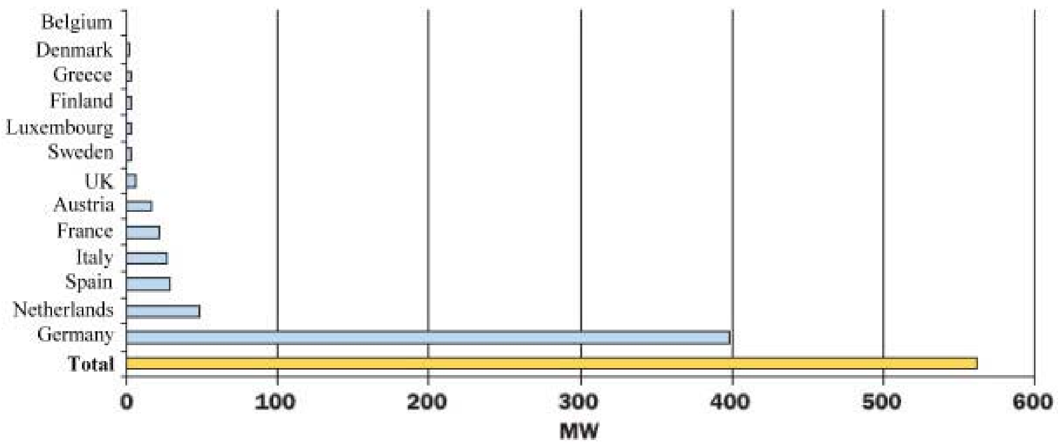

Figure 6: Total PV installed in selected countries by the end of 2003. PV-TRAC *A vision for photovoltaic technology*, ISBN 92-894-8004-1 - EUR 12242 /EN (2005)

In Figure 7 we can see the trends in the PV market per application. Taking into account the logarithmic ordinate, the explosive growth seen today is clearly due to grid connected applications. This contrasts with the general belief that PV is mainly used in isolated remote areas.

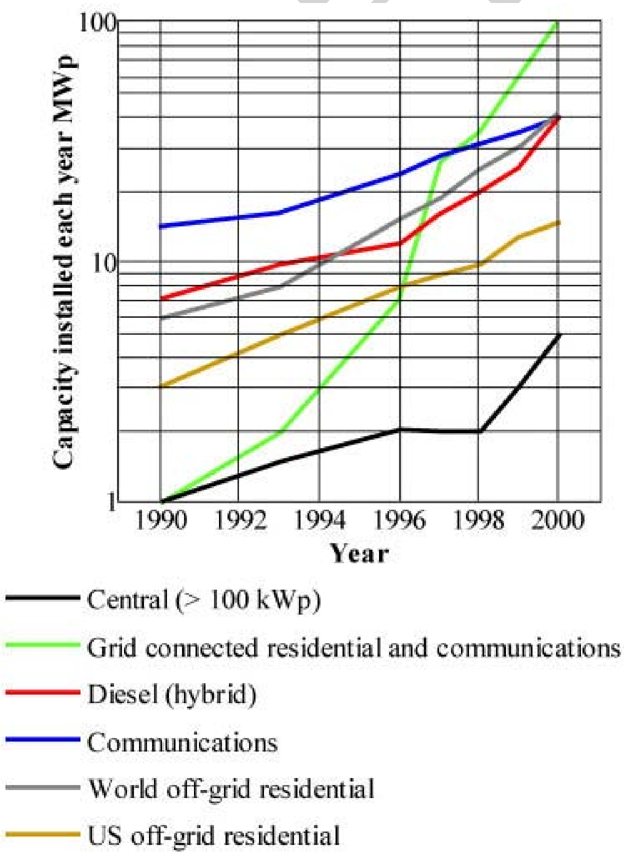

Figure 7: Trend in worldwide energy applications, from P. Maycock, *Renewable Energy World*, 3, 59-74, (2000).

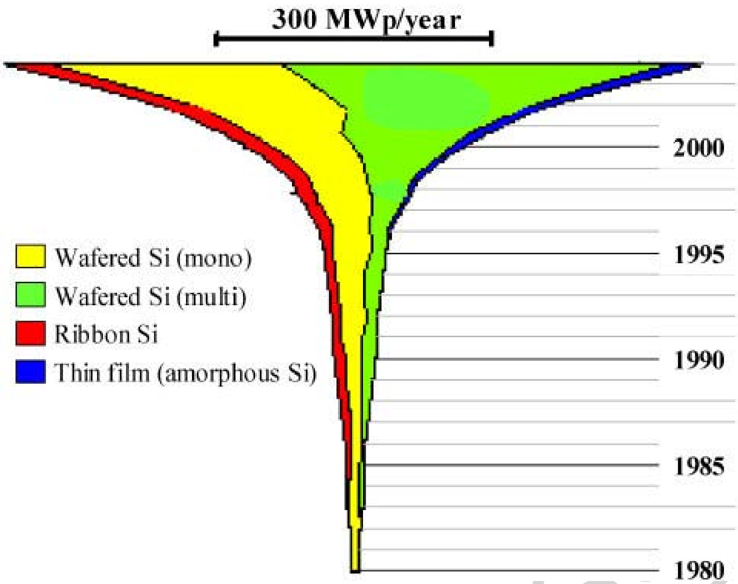

Figure 8: PV production per technologies. EPIA PV Roadmap http://www.epia.org/04events/docs/EPIAroadmap.pdf (June 2004)

In Figure 8 the PV production increase is distributed per technology. Although this will be discussed in more detail later we stress here that bulk silicon technology, in its several varieties, is absolutely dominant in the market. This will justify the greater emphasis it will be given in this work.

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Biographical Sketches

Antonio Luque is Dr. Engineer in Telecommunication. Full Professor of Electronic Technology at the Polytechnic University of Madrid, in which he leads the Institute of Solar Energy, he founded. His research activity is mainly devoted to the photovoltaic conversion of solar energy. He has obtained, among others, the Spanish National Prize for Technology in 1989, granted by the King of Spain every 2 years, the Alexander-Edmond Becquerel Prize in PV research, granted by the EC, in 1992 and the King James I award to environmental research delivered by the Crown Prince in 1999. In 2003 he has received the Juan de la Cierva National Prize for Technology Transfer. He is Doctor Honoris Causa by the University Carlos III (Madrid) and the University of Jaen. He is Honorary Academician of the Russian Academy of Engineering (Foreign Member) and Member of the Bielorusan Academy of Engineering. He invented the bifacial cell in 1976. This cell was fabricated by Isofotón, a company he created in 1982. This company is today one of the largest European solar cells manufacturers. He has published about 200 scientific papers in English language as well as some books. Prof. Luque holds 12 patents.

Ignacio Tobías is Dr. Engineer in Telecommunication and Assistant Professor of Electronic Technology at the Polytechnic University of Madrid. He joined the Institute of Solar Energy in 1986. He has worked in a number of international projects in silicon technology and solar cell modeling.