200 years of solar electricity

Daniel Suchet (daniel.suchet@polytechnique.org) and **Jean-François Guillemoles** (jfguillemoles@cnrs.fr)
Institut Photovoltaïque d'Ile de France (IPVF) (UMR 9006 CNRS and École Polytechnique)
18 Boulevard Thomas Gobert, 91120 Palaiseau Interdisciplinary Centre Energy for Climate (E4C),
Institut Polytechnique de Paris

Two hundred years after Edmond Becquerel discovered the photovoltaic effect, solar panels have become an everyday technology, to be found on the roofs of houses or alongside railway lines. However, this apparent familiarity conceals the rapid and on going development of the industry: the panels installed today are very different from those installed just a few years ago, in terms of design, cost and the challenges to be met. Photovoltaics has now established itself as a key player in the global energy landscape, and its dynamism means that we need to keep a close eye on developments.

The purpose of this article is to take stock of the current state of the industry, presenting typical orders of magnitude, the dynamics of the sector and future prospects. It can be supplemented by questions and answers prepared by researchers in the field and available at https://solairepv.fr/ .

Solar resources

The Sun is the source of almost all the planet's energy resources (excluding nuclear fission and fusion, and tidal energy). Before entering the atmosphere, solar radiation represents 1300 W/m². A fraction of this power is absorbed as it passes through the atmosphere, and around 1000 W/m² can reach the ground at our latitudes - this is the standard illumination under which the nominal output of devices is evaluated. Taking into account day/night alternation and weather conditions, we have an average of around 150 W/m² available to us over the year in France (fig. 1). On a national scale, solar power represents almost three hundred times the country's primary energy supply. The usable surface area of rooftops, brownfield sites and car park shaded areas alone provides a potential of around 200 TWh of electricity per year, without any further land artificialisation. By way of comparison, the "Energy Futures 2050" report from the French electricity transmission network RTE envisages solar production of between 100 and 250 TWh per year as part of an entirely carbon-free energy mix. It's a real energy windfall that's literally falling from the sky, albeit diffuse and intermittent, but one that we need to make the most of.

There are several possible conversion strategies. Photosynthesis converts solar energy into chemical energy, with a typical yield of less than 1%. Solar thermal energy uses the Sun to heat water, producing low-grade heat (< 100°C) suitable for domestic use. By concentrating sunlight using converging mirrors or lenses, thermodynamic (or concentrated thermal) solar energy achieves much higher temperatures, sufficient to power a turbine and transform the heat collected into electrical

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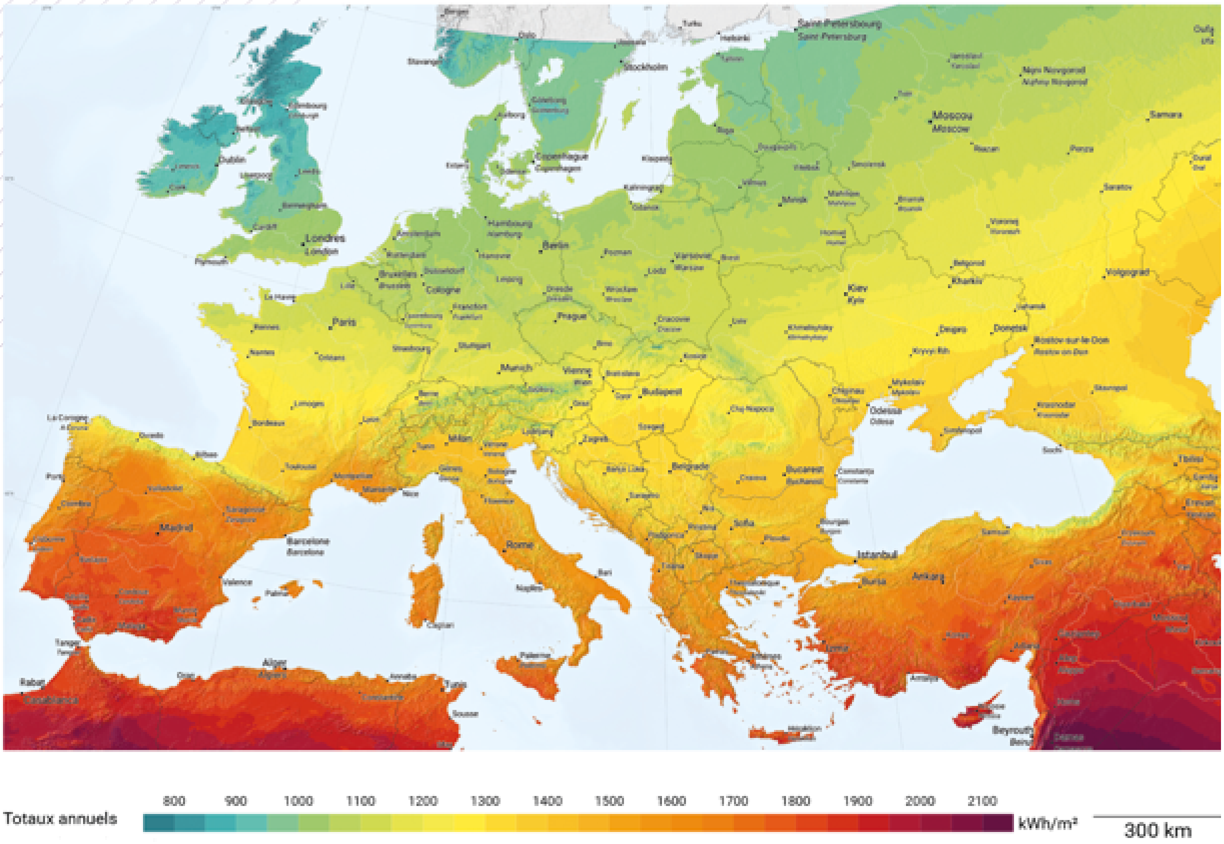

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1. Long-term annual average of solar irradiation received by a horizontal surface in Europe (in kWh/m²), calculated over the period 1994-2018.

work (see the article by G. Flamant, p. 63). Finally, photovoltaic solar energy can also produce electricity, but works by direct conversion and does not require concentration. This is the fastest-growing solar technology, and the rest of this article is devoted to it.

Generating electrical power requires a photovoltaic device to have four fundamental properties. Firstly, sunlight must be absorbed efficiently, which means that the materials used must not have too large a *band gap*. Secondly, the photogenerated electrons must remain excited long enough to be collected: the materials must therefore be sufficiently free of defects to limit non-radiative recombination.Thirdly, the charge carriers must be able to move from the centre of the absorber, where they were generated, to the terminals of the device, requiring good transport properties. Finally, carrier extraction must be selective: electrons are extracted by one contact and injected by the other. The architecture of the device must therefore have a degree of asymmetry to allow the direction of the current to be imposed - this is typically achieved by means of a junction between two materials of different doping (homojunction) or nature (heterojunction), and a *design for* the electrical contacts of each polarity.

There is a wide range of technologies available to achieve these properties in a variety of materials. However, all single-junction technologies are limited in their conversion efficiency by the same compromise between two contradictory requirements. On the one hand, the photogenerated current increases with the number of photons absorbed, which encourages the use of materials with a low bandgap. On the other hand, the greater the band gap, the greater the voltage at the terminals of the device. Electrical power, the product of current and voltage, will therefore be low if the material has a band gap that is too small (limited by the voltage) or too large (limited by the current). There is therefore an optimum band gap, of the order of 1.1 eV for the solar spectrum, which allows a maximum efficiency of around 30% (Shockley-Queisser model) [1].

It is around this optimum band gap that all solar technologies are situated (fig. 2), and they are already approaching this fateful limit. The silicon industry, which accounts for 97% of the market, has succeeded in achieving laboratory efficiency of 27%, and commercial systems available to the general public can achieve 22%. This performance has enabled photovoltaics to produce a total of more than 1,000 TWh by 2020, or 3% of the world's electricity.

The environmental cost of photovoltaics is an important issue. In a market 97% dominated by silicon-based technology, the issue of

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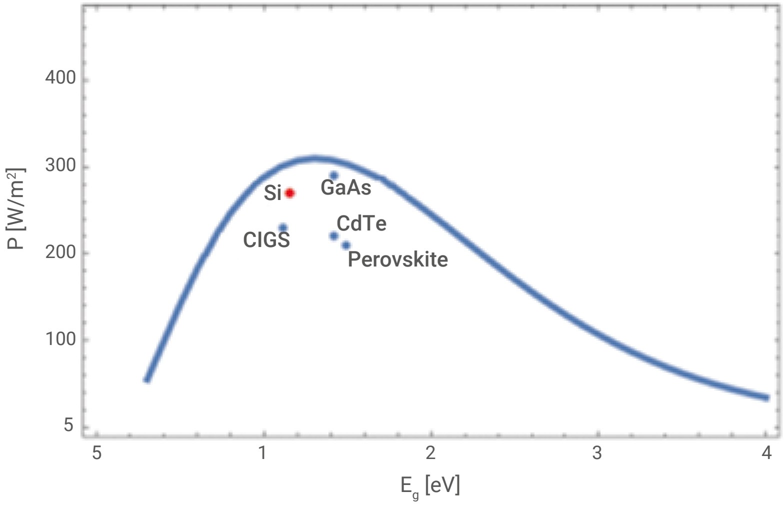

2. Power flux density P under the standard solar spectrum (1000 W/m²) as a function of the bandgap E_g of the material. The solid line gives the theoretical limit for a single-junction device, while the dots indicate the records obtained in the laboratory for different materials: silicon, gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and perovskite structure materials such as $(CH_3NH_3)PbI_3$ [1] .

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materials is not critical. Producing a solar cell essentially requires silicon from quartzite, doped with minute quantities of phosphorus and boron. Assembling the cells into a solar panel requires glass for the encapsulation and aluminium for the frame. The element under most strain is undoubtedly the silver used for the contact on the front of the cells - but processes are becoming increasingly economical with this expensive metal (reduction by a factor of 6 in twenty years [2]) and yields in excess of 25% have already been achieved with copper contacts. Although producing asolar cell requires energy, in particular to purify the silicon, the energy payback time for a panel installed at our latitudes is estimated at less than a year. By comparison, with a typical degradation rate of 0.5% per year, the yield of a silicon panel falls from 20% to 16% in around twenty-five years, and the device remains operational for much longer [3, 4].

While these values relating to panel production are fairly well established, the transition to the concept of EROI *(energy Return On (energy) Invested,* see the article by G. Bonhomme and J. Treiner, p. 24, and [8]) is much more difficult and has given rise to considerable controversy. In particular, there is no consensus on the relevant perimeter for calculating the EROI. For example, in addition to the panel, its fastening system and the electronics needed to connect it, should we include the full cost of adapting the electricity grid, even if this is not yet necessary at current penetration rates? In addition, the estimates of the energy costs of the various ingredients of the calculation are also marred by significant error bars, and vary significantly from one study to another. Taken together, these discrepancies spread the EROI values reported in the literature over almost two orders of magnitude (from 0.6 to 60 depending on the source [5, 6]). In addition, the rapid pace of change in the field (see below) raises questions about the relevance of values calculated on the basis of information that is sometimes several years old.

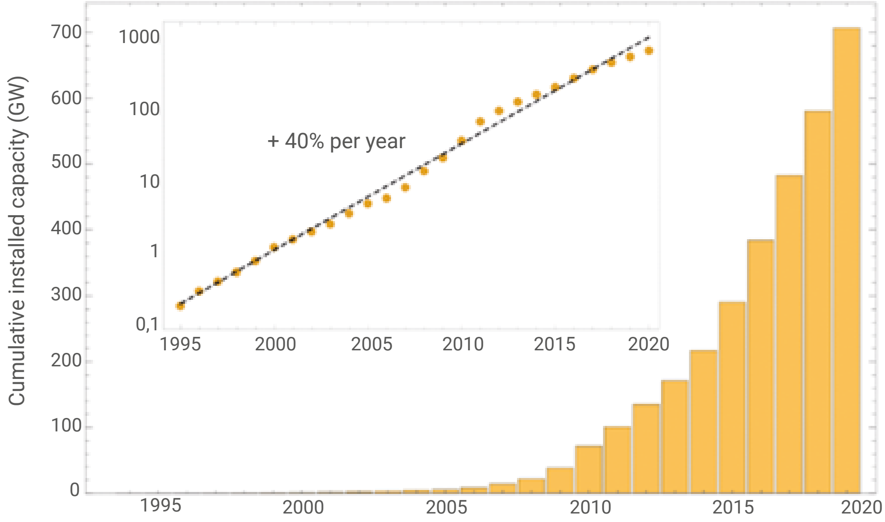
A dynamic industry

In addition to the industry's current performance, it is instructive to look at its development over time. The rapid improvement and spread of solar technologies underlines the need to keep a close eye on developments, or risk relying on obsolete data.

The main driving force behind the industry is undoubtedly the steady increase in the number of installations, which is driving forward the industrial players and fuelling fundamental research. For more than twenty years, "installed" capacity worldwide *(i.*e. the sum of the maximum power achievable by each plant) has been increasing by almost 40% a year (fig. 3). For the time being, this dynamic is ensuring rapid deployment of new technologies, and fuelling a learning curve reminiscent of Moore's Law for transistors: the production price of a module has gone from \$100 per peak watt in 1975 to \$0.21 in 2021 (fig. 4) [2].

The cost of the panel itself is certainly only a fraction of the cost of an installation, which also includes infrastructure, the inverter[a] for connection, land, labour and taxes. For the sake of completeness, we should also add operating and maintenance costs, the effects of panel degradation, the cost of capital, etc. It should be noted that the calculation of the marginal cost of photovoltaic electricity, as presented here, only makes sense as long as the volumes of energy produced do not lead to a significant change in the overall electricity system. Nevertheless, the spectacular reduction in production costs is an effective indicator of the maturity of the technology. First and foremost, it reflects an increase in yields, but also an improvement in manufacturing processes (increasingly thin *wafers*, reduced material requirements for contacts, etc.), which in turn reduces the energy footprint of the panels .

In the field of photovoltaics, understanding in order to do and understanding in order to understand are intimately linked. We are seeing the development in industry of techniques inspired by fundamental approaches introduced shortly before in the scientific literature. For example, the analysis of photoluminescence (generalised Planck's law), which makes it possible to estimate the value of photovoltage without the



3. Photovoltaic power installed over time from 1996 to 2020 (source: BP Statistical Review); insert: same data in logarithmic scale **.**

need for electrical contact, is being used as an example of a new approach. electrical contact, is used to check the quality of silicon *wafers* on production lines on the fly. Nanophotonics is essential for reducing the thickness of cells without damaging their optical properties. Various strategies can be envisaged to further increase conversion efficiency and exceed the limit given by the Shockley-Queisser model (see above). The most widespread approach consists of superposing two (or more) junctions to convert high and low energy photons separately [7]. In the laboratory, these multi-junctions have a record conversion rate of 47% (six superimposed junctions, under concentrated solar flux), and an intense effort is being made to produce tandem devices (two junctions) on a large scale and at low cost. Several pairs of materials can be considered, and particular attention is being paid to combining silicon with a halogenated perovskite - a crystalline structure that characterises a family of materials with excellent properties. Remarkable opto-electronic properties, but which we do not yet know how to protect from environmental damage. One of the key points to emerge from the scientific and technological advances of recent decades is the significant scope for progress in photovoltaic technologies, both in terms of conversion performance and in terms of their critical materials-intensive nature .

The terawatt challenge

With more than one TW installed worldwide, photovoltaic R&D is now attempting to meet the challenges of making a major contribution to the terawatt energy mix. To achieve this global objective, a host of scientific and technological challenges will have to be met throughout the life of solar panels.

Upstream of production, as discussed above, it is particularly important to continue to improve efficiency in order to reduce the price of energy.

Downstream of their use, the massive deployment of photovoltaic panels requires the development of recycling and waste management channels. As historical installations reach the end of their life, the first plant dedicated to recycling solar panels opened in France in 2018[b]. Recycling techniques currently make it possible to recover almost 90% of the panel mass (aluminium frame, glass encapsulation, etc.), but the silicon in the cells is more often than not destine for low-quality reuse. However, it is worth noting the recent development of a solar cell with 20% efficiency produced exclusively from recycled silicon.

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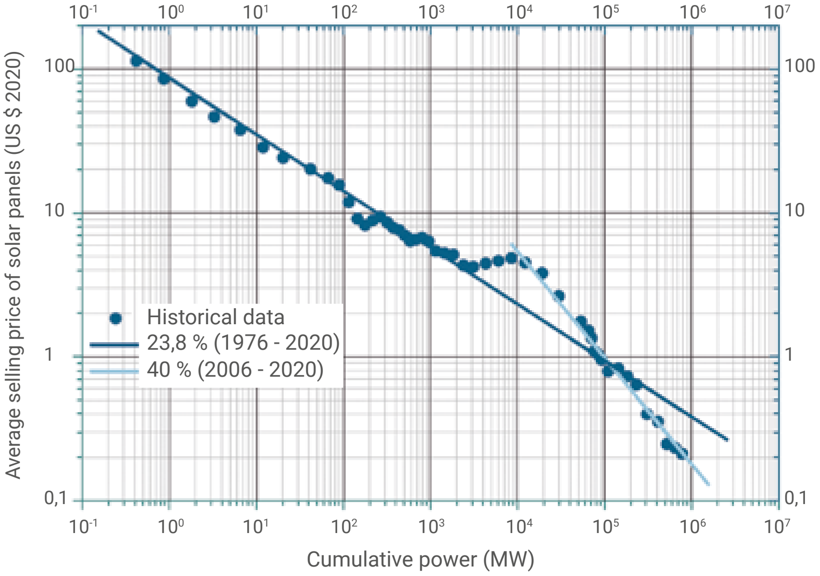

4. Learning curve for the silicon industry: change in the selling price of solar panels, normalised by the nominal power of the device, as a function of cumulative production (source : ITRPV 2021).

> “… the intermittency and lack of inertia of production appear to be major difficulties for the integration of photovoltaics into the grid.”

Finally, as far as operation is concerned, the intermittency and lack of inertia of production appear to be major difficulties for the integration of photovoltaics into the grid (see the article by G. Sapy, p. 135). Although current penetration rates are low enough for electricity grids to be able to handle solar production without difficulty, the International Energy Agency (IEA) and RTE believe that specific developments will be needed in the future. Recent European projects led by transmission system operators have demonstrated the principle of the stability of a grid based on inverters rather than rotating machines, using existing technologies.

When it comes to balancing the grid, the difficulty lies in maintaining the balance between variable consumption and production that is both variable and intermittent. The aggregation of sources spread over a vast territory may significantly reduce intermittency, and the complementarity between wind and solar resources smoothes out seasonal variations; but these techniques do not make the problem disappear. Storage, intelligent management of energy networks and demand management are undoubtedly the essential ingredients of the solutions to be implemented. First of all, particular attention needs to be paid to different technologies depending on the duration (hourly, daily, seasonal) and volume of storage considered. With this in mind, and with a view to decarbonising more uses, one direction of research is to develop multi-sector energy solutions such as solar fuels: this involves either using photovoltaic electricity to power an electrolyser and generate hydrogen, which can then be used as a basis for the production of electricity. This can be done either by using photovoltaic electricity to power an electrolyser and generate hydrogen, which can then be used to produce more complex molecules, or by directly reducing hydrogen using photo-electrochemistry. However, solutions based exclusively on storage risk being insufficient.

In addition to these technical solutions, we probably need to look at the possibility of adapting certain uses to the intermittent nature of production, rather than trying to make intermittence disappear in order to adapt production to all our uses. Solutions of this kind have already been implemented, but in the other direction, to shift consumption from day to night: consider, for example, the activation of hot water tanks.

Particular attention should be paid to air conditioning, which is set to account for a significant proportion of total electricity consumption (estimated at 6,200 TWh in 2050, or around 30% of the building sector, mainly in Asia). Demand for air conditioning is generally correlated with the presence of the sun, and does not require a perfectly controllable supply: the need is not so much to be able to turn on the air conditioner when you want as to ensure a comfortable temperature in the home. Provided that air-conditioned buildings are properly insulated, it is therefore conceivable to cool them only as long as the sun shines. This may not be as comfortable as the current perfectly controlled system, but it will save the grid both the cost of supplying the air conditioner and the cost of evacuating surplus production .

This simple example highlights the systemic dimension of energy issues and the crucial impact of energy efficiency and behaviour on optimising the energy mix. Although the temptation to do so is great, given the abundance of energy sources, it is in fact essential not to be satisfied with surplus production in order to resolve the challenges of the energy transition, but to take the problem as a whole. ▮

(a) Inverter: power electronics device used to generate alternating voltages and currents from a source of direct electrical energy.

(b) In France, the government-approved eco-organisation SOREN is responsible for collecting and recycling end-of-life solar panels.

1• J.F. Guillemoles *et al.*, "Guide for the perplexed to the Shockley–Queisser model for solar cells", *Nat. Photonics*, **13** (2019) 501-505. doi: 10.1038/s41566-019-0479-2.

2• "International Technology Roadmap for Photovoltaic 2023 results", 10^{e} édition (2023), ITRPV et l'association VDMA (Francfort, Allemagne).

3• D.C. Jordan *et al.*, "Compendium of photovoltaic degradation rates", *Progress in Photovoltaics* **24** (2016) 978-989. doi: 10.1002/pip.2744.

4• A. Louwen *et al.*, "Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development", *Nature Communications* **7** (2016) 13728. doi: 10.1038/ncomms13728.

5• F. Ferroni et R.J. Hopkirk, "Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation", *Energy Policy*, **94** (2016) 336-344. doi: 10.1016/j.enpol.2016.03.034.

6• W. Chen *et al.*, "Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China", *Journal of Cleaner Production*, **112** (2016) 1025-1032. doi: 10.1016/j.jclepro.2015.08.024.

7• Entretien de Daniel Lincot avec Michèle Leduc, "Cette énergie pratiquement illimitée qui nous vient du Soleil", *Reflets de la physique* **75** (2023) 32-37.

8• *Annales des Mines - Responsabilité et Environnement*, **111** (juillet 2023).