



# Introduction to Photovoltaic Cell Manufacturing

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## Abstract

Solar photovoltaics are synonyms to renewable energy resources. It is rare to find a poster or a presentation about renewable energy without a photovoltaic panel in the background. This introduction is a concise presentation on the importance of manufacturing technologies on the price, development and prefabrication of the solar panels. It is important to realize how critical the effect of manufacturing technologies is on the performance and cost of panels, which will be gradually introduced throughout this book.

## 1 Introduction to Solar Photovoltaics Manufacturing

Energy conversion is a fascinating concept. It is especially true when it takes place spontaneously, or with minimal external coercion. For example, the massive exothermic energy that results from fossil fuel combustion is initiated by a small amount of energy input (in the form of a spark). This

energy is then converted into pressurized steam, the release of which into turbines converts the thermal energy into kinetic energy and subsequently electric energy. This spontaneity is a strong reason why fossil fuels have dominated as long as they did and are currently the most reliable form of energy.

In a more intuitive manner, energy from the sun can also be converted into thermal energy once a proper receiver is introduced. The interaction of electromagnetic energy from the sun on a human body causes the absorbed fraction of this radiation to be converted into sensible heat. The rest is either reflected or transmitted, depending on the radiation wavelength and receiving surface condition and dimensions. Heat, however, is not a coveted form of energy, and direct electricity from the sun would be a better option.

Since the whole world is electrically plugged, the energy most sought-after is indeed electrical. Giving someone a fistful of thermal or kinetic energy would be a cruel joke when all they require is enough electricity to recharge a dying smart phone. Almost all energy conversion operations will eventually lead to electrical energy as evident from Fig. 1.

Unfortunately, with each energy conversion step there exist losses. Hence, the concept of efficiency was coined to quantify these losses and entice engineers to reduce them. Efficiency is defined as the ratio of input/output, and many energy conversion steps will drop the overall efficiency of a system by quite a lot. Remember that the overall system efficiency is the multiple of the individual efficiencies of each conversion process that occurs in series. Figure 2 shows an example of losses for a wind energy system, from generation to storage. These losses will accumulate and the energy retrieved from the battery would be a small fraction of the energy originally available in the wind.

The above discussion emphasizes the appeal of having a material or a device that is capable of converting solar radiation directly into electricity. Solar photovoltaic (PV) wafers and materials are devices that can do just that.

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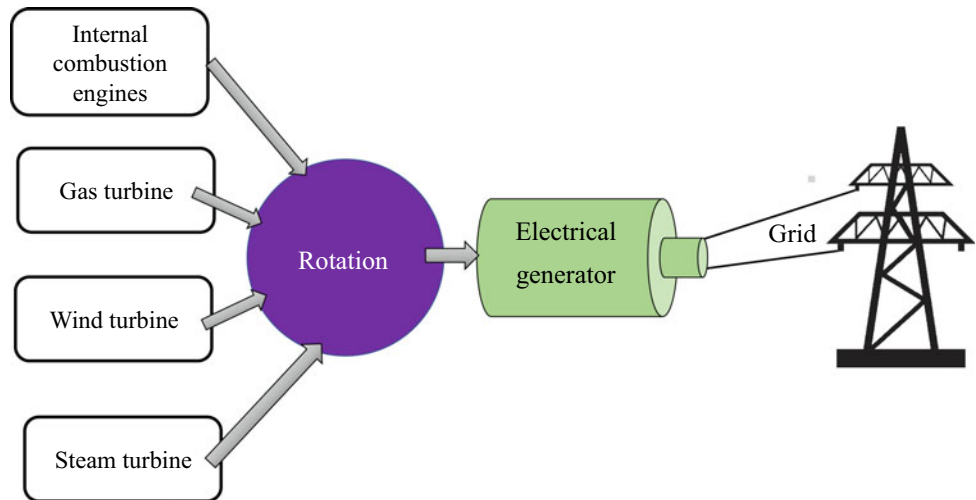
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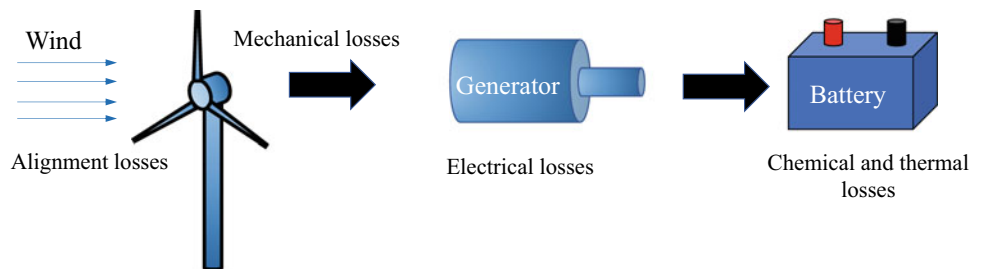
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**Fig. 1** Energy conversion steps to obtain electrical energy (Alami 2020)



**Fig. 2** Various energy conversion losses for a wind energy system (Alami 2020)



The story of PV technology is quite old: Around three hundred years old, ever since A. E. Becquerel published his work on the electrical effect derived from solar radiation in 1839 as will be discussed in subsequent chapters.

The development of solar PV technology can also be chronicled in different ways. One can focus on the leaps made in enhancing their figure of merit (FOM), which is the cost to generate a unit of electrical energy (dollar per kilowatt-hour, or \$/kWh). Figure 3 shows the rapid drop of module prices, which is a direct reflection of the total cost of any installed system (International Renewable Energy Agency 2019) and is a driving force in reducing the \$/kWh in all major PV installations.

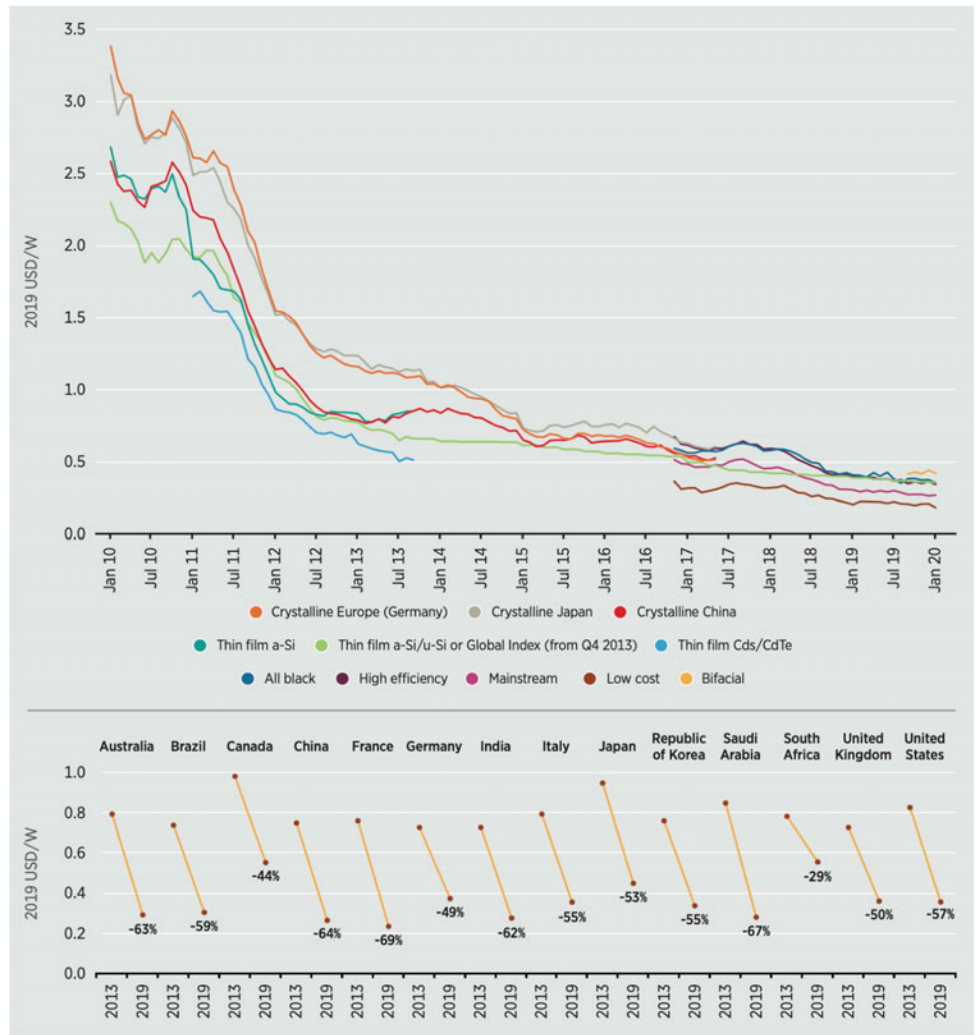
From Fig. 3, China stands out as one of the main players in the PV market, since it has achieved the steepest cost reduction slope. It is very interesting to note that China is a late comer to the PV manufacturing market. Being almost non-existent before 2007, China currently controls more than one-third the world production of PV modules according to Fig. 4. The price of PV panels has fallen by around 80% as China dominated the production of silicon-based PV after 2007 (Fialka 2016). Having the only net-positive economy in a world hit by the 2007/2008 crises, China did not simply purchase mature technology from USA and Europe, but they also carefully examined the pertinent manufacturing processes and proceeded to apply crucial

changes to the utilization and consumption of silicon material and the energy needed to make solar cells. Adapting manufacturing processes that are amenable to mass production of solar wafers with high quality and at a competitive cost is hence the main key to push the PV industry into the future.

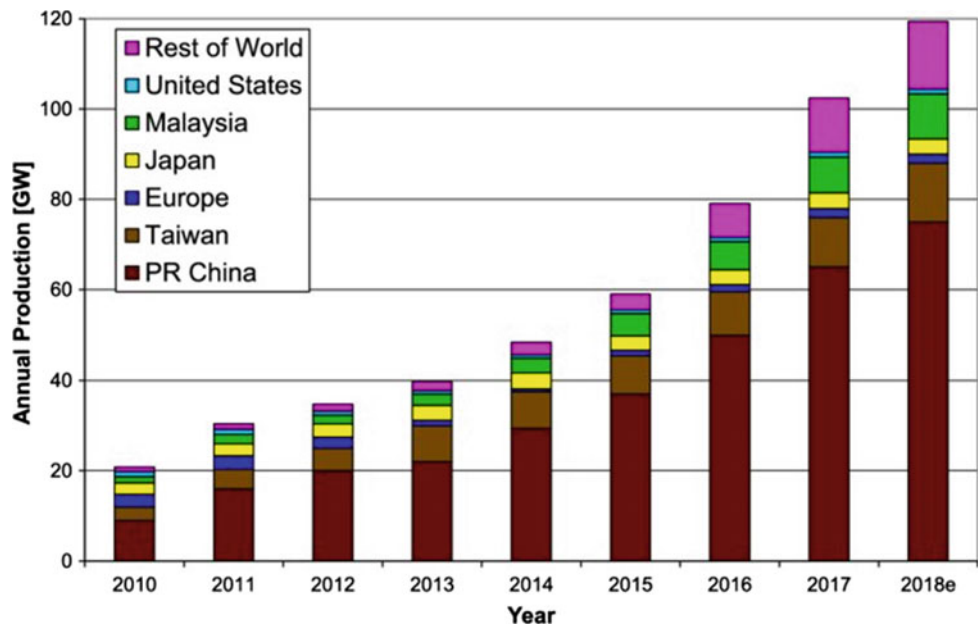
Another interesting and important resource to understand trends in PV manufacturing is the efficiency chart that is kept by the National Renewable Energy Lab (NREL). This chart chronicles the efficiency of solar cells with time. All technologies are represented in this graph, and thus, it provides a roadmap of available technologies from 1976 till present. This chart is found on <https://www.nrel.gov/pv/cell-efficiency.html> and the current iteration of it is shown in Fig. 5.

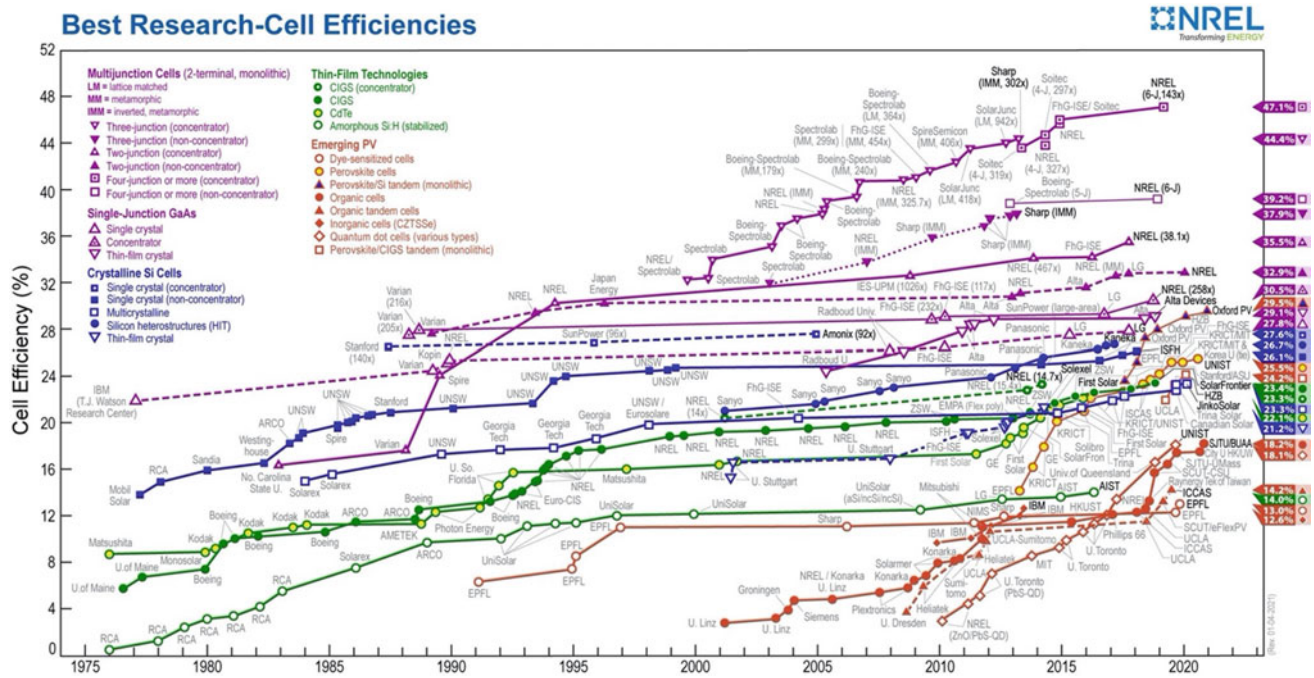
The choice of manufacturing processes for various PV technologies is a key factor for determining the energy payback time (EPBT) of the produced panels. So far, current PV technologies are not net-positive energy devices, meaning that the energy required to produce them, starting from raw materials such as silica, is more than they will produce in their operational lifetime (Dale and Benson 2013). Expanding the installation of PV panels is understandably desirable to conform to governmental mandates of switching to renewable energy sources by a specific timeline. This guarantees that the generated electricity produces no

**Fig. 3** Average monthly solar PV module prices by technology and manufacturing country sold in Europe, 2010 to 2020 (top) and average yearly module prices by market in 2013 and 2019 (bottom) (International Renewable Energy Agency 2019)



**Fig. 4** Annual PV panels production by country (Jäger-Waldau 2018)





**Fig. 5** Best research PV cell efficiency (<https://www.nrel.gov/pv/cell-efficiency.html>)

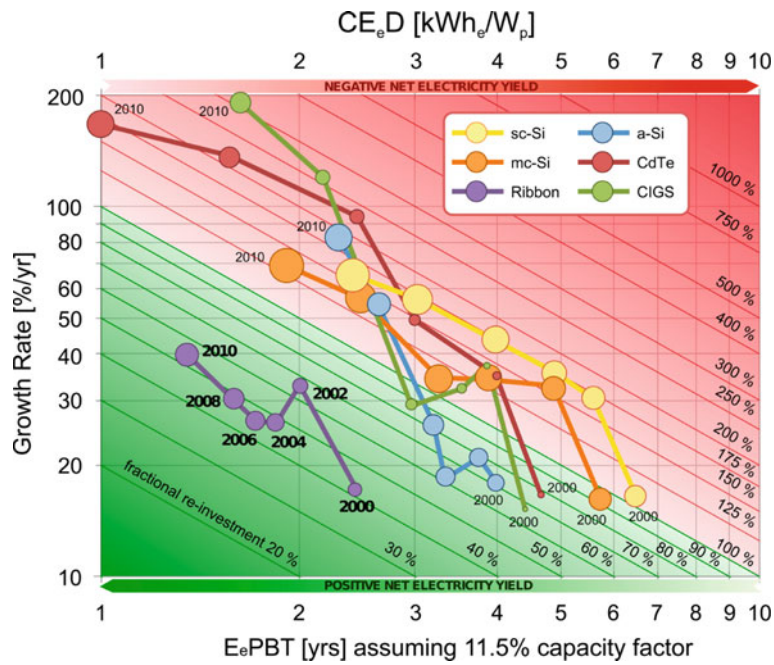
pollutants and allows the diversifying of available energy mix. But unless the EPBT becomes more reasonable by either lowering the cumulative energy demand (CED) or enhancing the capacity factor of available technologies, the probability of having PV technologies as net-positive remains a 50–50 chance. It is interesting to note from Fig. 6 that the only technology that allows a tangible EPBT are ribbon technologies as their production is less energy intensive than other technologies. But by re-examining Fig. 5, the efficiency of such thin-film technologies is still inferior to that of other mature technologies, and the number of required modules to produce a similar level of energy has to indeed be larger. Thus, any contribution in making the PV manufacturing processes more productive at lower prices and lower energy requirements is full of future opportunities for material scientists and engineers.

In this textbook, the manufacturing processes and technologies will be introduced and discussed for the three generations of PV modules. In general, and seen in Fig. 5, the technologies are divided into first, second, and third generations. First generation covers the conventional silicon-based modules that have classically dominated the market since late seventies of the twentieth century. The available silicon purification and processing technologies paved the way for adopting silicon as the material of choice for PV, since it is well-known that PV processing technologies were directly inherited from the silicon-based transistor technologies that produced microprocessors. Historically, monocrystalline silicon solar cells preceded the

cheaper and easier to produce polycrystalline ones, as seen in Fig. 7, only because monocrystalline silicon was used in the microprocessor industry.

Thin-film PV technologies are the second-generation cells made from thin-film materials, to reduce cost and material waste. Thin-film manufacturing processes are independent of the large-scale installations required to produce silicon cost-effectively. Processes such as chemical vapor deposition (CVD), sputtering, thermal evaporation, and others can be housed in a relatively small facility and used to produce high-quality thin films. Cadmium telluride (CdTe) cells and copper–indium–gallium–diselenide cells (CIGS) as well as gallium arsenide (GaAs) solar cells have been the most notable of these thin-film technologies, along with a resurrection of silicon wafers in the form of the large bandgap amorphous silicon films. Those can be used in tandem with their crystalline counterparts or are heat-treated to create crystalline films using manufacturing techniques that will be discussed later in this book.

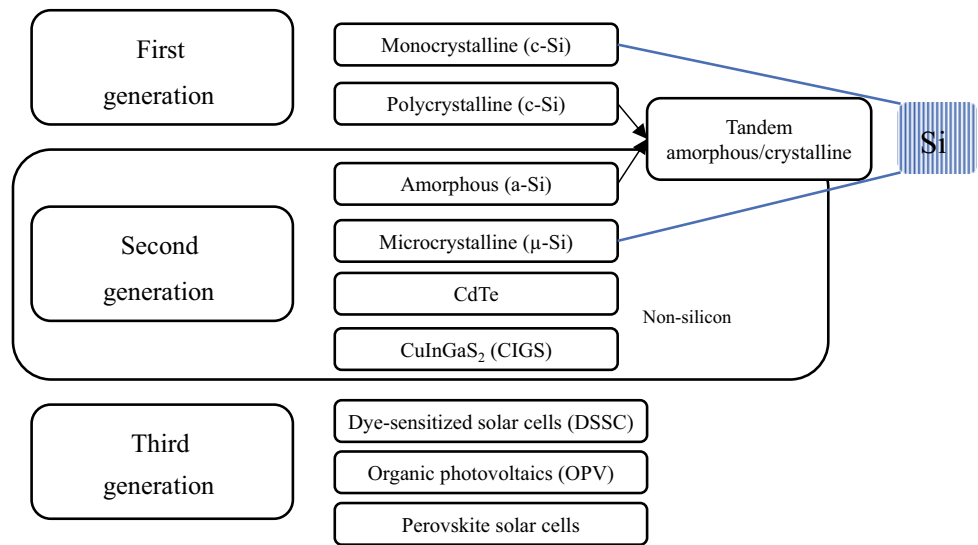
Finally, the third-generation solar cells came as a complete departure from conventional silicon material and processing. They comprise three main technologies that can be manufactured using smaller scale equipment and setups to assemble and produce the cells, compared with the first two generations. The down side is that the produced cells still lack the reliability, stability, and power output of silicon solar cells. This being said, the promise they carry in terms of lower energy demand to produce as well as easier recyclability compared to silicon panels makes them serious



**Fig. 6** Growth rate [%/yr] as a function of CE<sub>e</sub>D [kWh<sub>e</sub>/W<sub>p</sub>] (top axis) and electricity payback time (E<sub>e</sub>PBT) [yrs] assuming an 11.5% capacity factor (bottom axis) for a number of fractional reinvestment rates [%] (diagonal lines). Red lines indicate negative net electricity yield, and green lines indicate positive net electricity yield. The

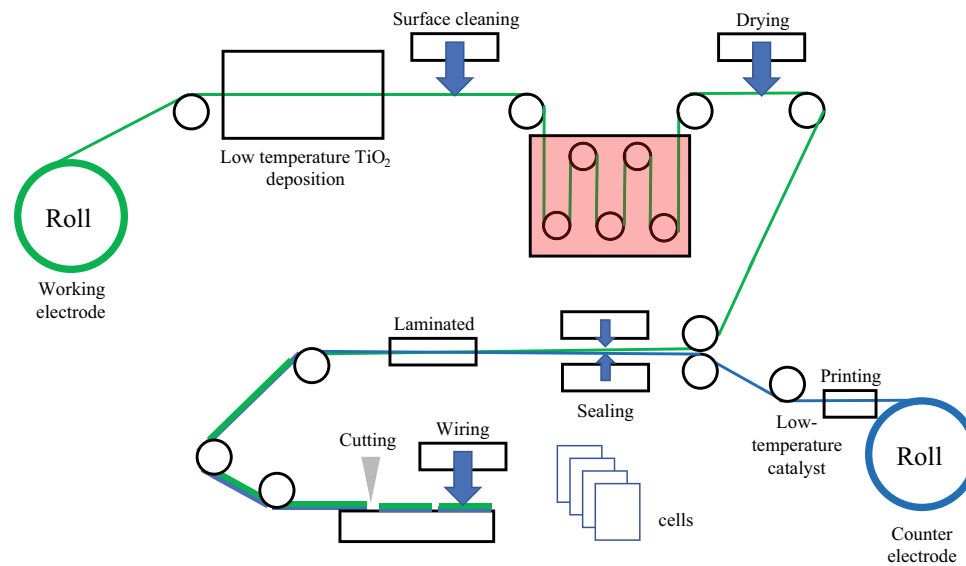
trajectories of CE<sub>e</sub>D (or E<sub>e</sub>PBT) and annual growth rates for PV technologies are depicted on a biannual basis between 2000 and 2010. The size of the circles represents the amount of installed capacity [GW] of each technology on a logarithmic basis (Dale and Benson 2013)

**Fig. 7** A depiction of various photovoltaic technologies (Alami 2020)



future contenders in the PV market. The three technologies are (i) dye-sensitized solar cells, (ii) organic cells, and (iii) perovskite cells; each has a separate chapter devoted to their development and construction. The aim from pursuing such technologies is that one day they can be adapted into roll-to-roll (R2R) technologies, which use solution-processes to deposit and combine precursors and electrodes, respectively, into a single device in a rapid and continuous manner.

The active inks and materials are similar to old printing inks for newspapers in old printing presses, but instead of producing ink-heavy newspapers, thin-film solar cells can be produced as fast (see Fig. 8), which would make up for their lower efficiency and stability issues. This concept is not far from being the norm in PV manufacturing, but there are several obstacles along the way that require creative solutions and combinations of materials and substrates.



**Fig. 8** Roll-to-roll (R2R) production of solar cells using solution-based processing

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