

16. Advances in photovoltaics and specialised topics

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Learning outcomes

After completing this chapter, the student should be able to understand the:

1. Advancement of materials in photovoltaic systems and alternate PV technologies
2. Large PV systems and to examine the technical characteristics
3. Advances in the inverter technology

Advances in materials of PV systems

The global total annual consumption of all forms of energy increased more than tenfold during the twentieth century, and in the year 2011, the energy production and consumption were close to 518.546 and 520.272 Quadrillion Btu, respectively. This increased to 537.266 and 524.076 Quadrillion Btu respectively, in 2012, as estimated by the International Energy Agency (IEA) [1]. The non-renewable energy resources such as coal, oil and gas have several significant and harmful impacts on the environment that contribute to climate change, hence, there is an urgent need for transition to clean and renewable energy sources such as solar power, wind, water, tidal and geothermal energies. Renewable energy technology, in particular solar photovoltaics, has been viewed as an alternative technology for the past couple of decades. The ever-increasing demand for energy and predicted exhaustion of the non-renewable sources, like fossil fuels, by the end of the century has urged researchers to develop solar power as a clean and abundant form of energy. The total global energy contribution from photovoltaics was <1% in 2013 and it is forecast to increase to ~16% by 2050 [2]. However, the widely accepted silicon technology has inherent unsolved challenges that are restricted by material properties, with the predicted theoretical efficiency of 33% and, as a result, the efficiency of these systems are limited by the source material. Although, there has been considerable research and development in the silicon solar cells over the past decades, the efficiency is barely increasing. In order to meet the world energy demands rising up to 2020 and beyond, researchers are looking for disruptive alternative technology to the conventional silicon photovoltaics.

Solar cells are generally categorised into different generations based on the materials required for their synthesis, applications, and commercial perspective. First generation silicon technology currently dominates the world photovoltaic market, being used by ~90% of the installations. The best laboratory record power

conversion efficiency for silicon solar cells is ~25% for single solar cells and ~22% for modules, with the performance being largely dependent on the quality of silicon used. These devices are reliable as well as robust in nature, but they suffer from the drawbacks of high production cost, as well as implementation into solar modules & the theoretical Shockley Queisser limit of efficiency.

Second generation solar cells involve primarily amorphous and thin-film technology such as amorphous silicon, gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium (di) selenide (CIGS) with an efficiency of ~21% [1] and lower production costs. The vacuum-based complex processes for materials processing and high temperature treatments for the fabrication of 2nd generation solar cells, as well as (and more importantly) the availability of materials and hence the cost, make them less attractive for large-scale production purposes. However, 2nd generation thin-film solar cells have a niche market in certain industries, such as flexible electronics applications.

From the 1st to the 2nd generation solar cells, the cost reduction is a step towards the right direction, but the costs are not yet low enough for substantial commercial uptake by consumers as a result of the inherent issues with those devices.

Third generation solar cells that are based on nanostructured materials from low-cost manufacturing techniques have attracted more attention due to simplified fabrication process, availability of materials and cost competitiveness. These motivated various research communities to develop solutions that, ultimately, will address not only the key challenges on materials availability but also the inexpensive production and high efficiency. Third generation solar cells consist of different types of devices, such as dye-sensitized solar cells (DSSCs), organic solar cells including polymer devices, quantum dot-sensitized solar cells (QDSSCs), perovskites and multi-layer tandem devices with amorphous silicon or GaAs. One of the prime candidates with a vertical increase in the efficiency is the recently explored perovskite materials that have emerged as a promising alternative due to their cost effectiveness and high efficiency.

Photovoltaic Materials

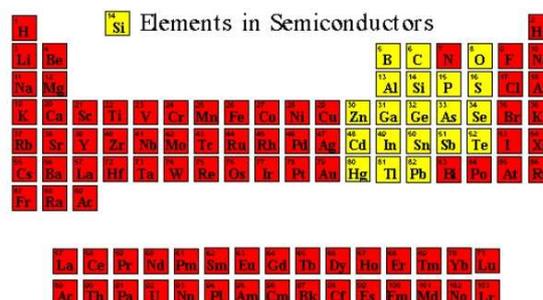


Figure 1. The elements in semiconductor that can be used as PV materials

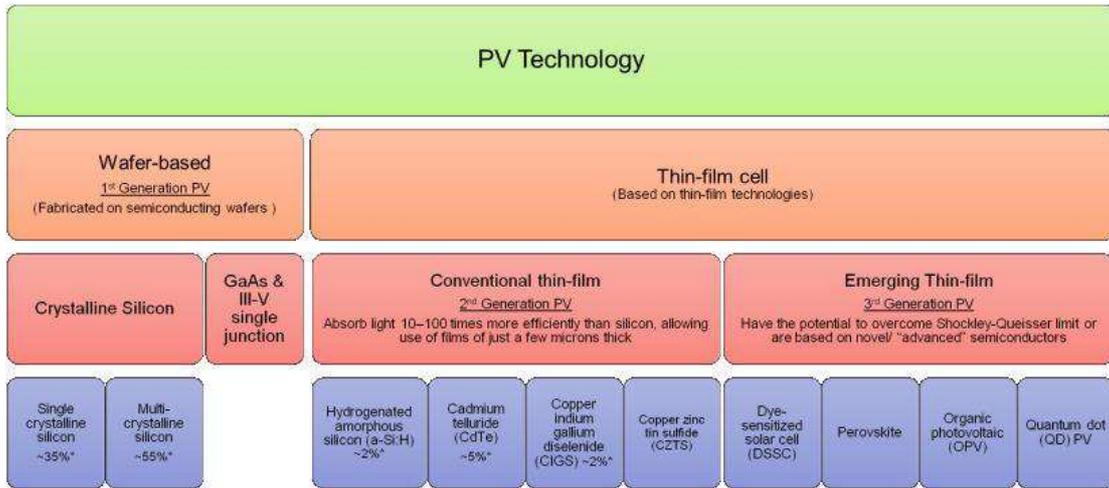


Figure 2. Different generation solar cells are shown as discussed in the section.

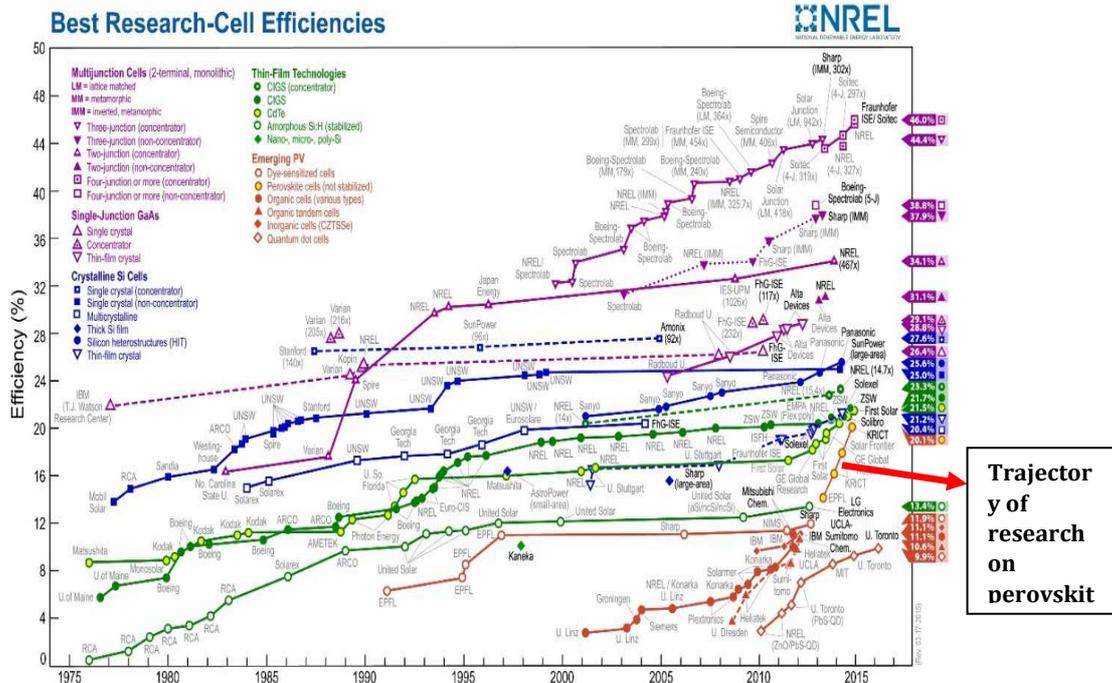


Figure 3. Best Research-Cell Efficiencies chart [1].

Figure 3 shows the best energy efficiency of different solar cells materials. It can be noticed that the recent growth in perovskite solar cell materials is particularly interesting and rapidly growing, as many investments are currently being made in this technology.

Perovskite solar cells (PSCs) are relatively a new technology, which has currently generated enormous interest owing to their multitude of fascinating properties and the prospect of a low-cost viable alternative to silicon. Inorganic-organic hybrid PSCs along with 2-dimensional (2D) nanostructures push the science and technology beyond the era of silicon, bringing these materials and their challenges from academy to industry and, ultimately, society. Only recently, intense research in this field has enabled the efficiency of these devices to improve beyond

20% within a span of few years as shown in figure 3. Unfortunately, the commercialization of these systems is still some way off because of the inherent challenges associated with the organic molecules in these hybrid perovskite devices.

The development of perovskite solar cells is gaining ground along with the conventional solar cell technologies of crystalline and amorphous silicon, as well as the emerging organic photovoltaic systems. This is largely due to their unique properties, low-cost processes of fabrication and the ease of availability of organic-inorganic hybrid materials necessary for their synthesis. The concept of incorporation of perovskites as a sensitizer has emerged from the field of DSSCs, where a light-absorbing dye adsorbed on the surface of a mesoporous n-type conductor and filled-up with a redox electrolyte, functions efficiently as a solar cell.

Concentrating PV systems

Apart from flat panel or flexible thin films, another way to get energy from sunlight is from mirrors or Fresnel lenses to concentrate the incoming solar radiation onto the cells. This form has a unique advantage; depending on the concentration ratio, effectively only a very small area is required (variation between two to several hundred or even thousand times). The concentrating system must have an aperture equal to that of an equivalent flat plate array to collect the same amount of incoming energy.

Systems with the highest concentration ratios use sensors, motors and controls to allow them to track the Sun in two axes (azimuth and elevation), ensuring that the cells always receive the maximum amount of solar radiation. It is important to note that the cells are exposed to much higher temperatures than in a flat plate array, which is one reason why multi-junction III–V cells are used. Systems with lower concentration ratios often track the Sun only on one axis and can have simpler tracking mechanisms.

Most concentrators can only utilize direct solar radiation. This has an adverse effect in most of the European countries where nearly half the solar radiation is diffuse, but in climates with higher proportions of direct solar radiation they can be very effective.

Silicon spheres

In the 1970s, the US firm Texas Instruments (TI) developed an ingenious way of making PV cells using tiny, millimetre-sized, spheres of doped silicon embedded at regular intervals between thin sheets of aluminium foil. This approach has recently been further developed by the Japanese Firm Clean Venture 21 (CV21) by enclosing each tiny silicon sphere in its own hexagonal aluminium micro-reflector cup, which concentrates light on the sphere and reduces the total amount of silicon required, in comparison with conventional crystalline silicon cells, Figure 4 [3]. This technology is currently at a very early stage of commercialization.

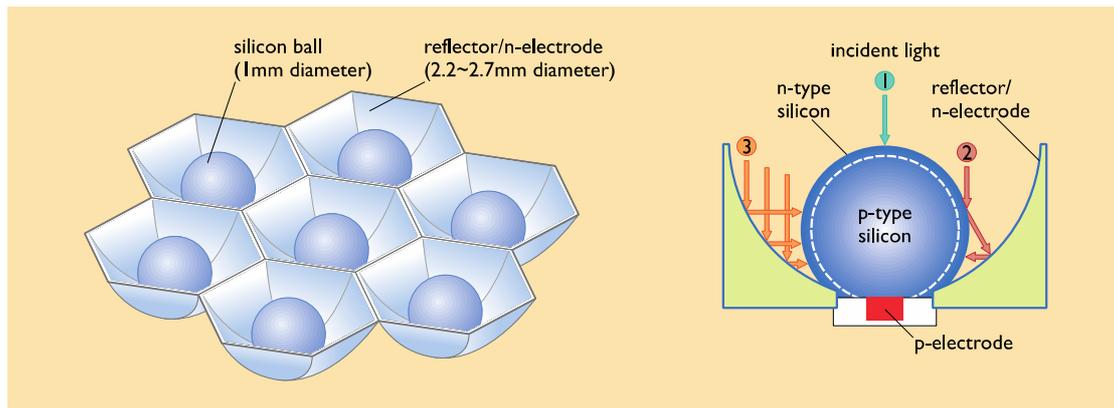


Figure 4. The principle operation of spherical PV technology developed by CV2. Tiny spheres of doped crystalline silicon are embedded in hexagonal micro-reflectors

Impact of advancing PV Technology

Advancing PV technology will provide more opportunities for integrating PV into residential and commercial buildings, as well as into transportation applications. The entire building exterior has the potential to become a power generator.

Thin-film PV is being integrated into visible glass that includes building windows, skylights, facades and atria. The transmittance of glass incorporating thin-film PV can be varied to reduce incoming sunlight and glare just like traditional window tinting.

Opaque PV glass can also be produced for use as spandrel glass that, when coupled with PV glass, effectively turns the entire building envelope into an electric power generator. The building roof has been the traditional place for installing PV.

For flat roofs on commercial buildings, manufacturers are experimenting with integrating PV into traditional roofing materials that can be installed directly by a roofing contractor in exactly the way that traditional single- and multiple-ply roofing materials are currently being installed. For sloped roofs, PV shingles are being produced using either crystalline silicon or thin-film PV technology. These PV shingles are made to look like either asphalt or wood shingles. Thin-film PV panels and overlays are being produced for standing-seam metal roofing that can be supplied in a variety of colours to provide an aesthetically pleasing installation.

Advances in large-scale PV projects

Although PV projects are increasing rapidly, they are not comparable to conventional power technologies. PV has very few large-scale applications. However, the advancement in PV power plant technologies is growing rapidly and different countries started installing large-scale power plants.

The world's largest PV plant constructed so far is the Gujarat Solar Park in Gujarat, India, with a capacity of 600 MW power. The largest plant in the USA is Solar Star with 579 MW. The largest PV plant in Europe, the Cestas Solar Farm in France has a capacity of 300 MW.

Moroccan city of Ouarzazate at the edge of the Sahara Desert has planned for four linked solar mega-plants that, alongside hydro and wind, will help provide nearly half of Morocco's electricity from renewables by 2020. The project is key in Morocco's ambitions to use its untapped deserts and become a global solar superpower with a capacity of 580 MW.



Figure 5. Solar farm in Gujarat, India.

Applications of large-scale PV projects:

Large scale PV projects has evolved due to the need to produce alternate energy generation for many different applications, such as:

- Grid connected power system
- Stand-alone electrification for villages or communities
- Backup power systems for telecommunications
- Water desalination and pumping
- Cold storage for food preservation

It is important to note that many of these applications are applicable locally only, as the storage system has inherent challenges. It is also important to note that large PV projects are less cost effective than standalone in grid connected operation. This is due to grid connected configuration can utilise all the all the produced PV energy, thus reducing the cost of the electricity. Stand-alone applications are heavily

dependent by the power demand of the isolated, hence excess power cannot be utilised.

Advances in Inverter technology of photovoltaic generation in distribution systems

Globally, scientists and technologists are trying to determine how to best accommodate the increasing percentage of solar photovoltaic (PV) power generation on to their electric grids. Utilities are uncertain about the effects of high levels of variable renewable power generation on system reliability, power quality, and the safety of workers and equipment, but recent advances in inverter technology have made them valuable tools for managing these aspects of grid operation. Ideally, all renewable energy sources, and every form of energy storage, produce either direct current (DC) or variable-frequency output power. All power from these sources must pass through a frequency converter (DC to AC or AC to AC) in order to feed the constant-frequency alternating current (AC) power grid. This extra stage of power conversion introduces additional equipment, cost and power losses. On the positive side, the need for frequency conversion has resulted in a rapidly growing class of electronically coupled generators (ECGs) connected to the grid, with control capabilities that are more flexible compared to those of conventional rotating synchronous machine generators. Understandably, electric utilities have viewed the advent of these ECGs with a certain amount of reluctance, both because of their unfamiliar operating characteristics and because of their location in distribution systems where traditionally there has been minimal power generation. The level of concern has increased with the rapidly increasing size of proposed projects relative to the feeder rating and/or the minimum load levels. It is of course perfectly feasible to generate power in new or existing distribution circuits, and even to export power back into the transmission system, but in doing so we challenge some of the traditional assumptions that have been made in the design of protection and voltage regulation schemes for these distribution circuits. This is especially true in the case of higher penetration levels for PV power generation.

Main Issues Delaying or Blocking the Connection of Large PV Projects

With the introduction of favourable feed-in tariff (FIT) rates and tax credits for renewable power, alongside with the rapid decline in the cost of PV modules, there has been an unprecedented rush to install large PV projects in many parts of the world. Consequently, utilities have been inundated with requests for interconnection to the grid. In many cases the distribution grid has been unprepared to deal with this, especially in the case of large-scale projects (5 MW to >10 MW) requesting interconnection at distribution-system voltage levels. Globally, the prevailing IEEE 1547 standard does not provide the answers needed to reassure utilities, because these high-penetration scenarios were simply not anticipated when the standard was drawn up.

The main issues and requirements currently affecting the interconnection of PV systems include:

- Short-circuit capacity
- Power-distance limitation
- Transfer trip for PV system
- Special custom requirements for reactive power deployment
- Customised ride through requirements
- Voltage quality requirements
- PV system grounding method

A detailed description on all of the above is beyond the scope of this chapter.

In summary, the advanced inverter capability could facilitate high penetration levels of PV generation and may also lead to potential savings for utilities by reducing line losses. Advanced inverters can drastically reduce regulator switching operations, thereby extend the life of equipment, reduce maintenance cost, defer the cost of new capacitor banks, etc.

Bibliography

[1] International Energy Agency (IEA) report

[2] International Energy Agency (IEA) report: Technology Roadmap Solar Photovoltaic Energy, 2014 edition (International Energy Agency report 2014)

[3] Graham-Rowe, Duncan. "Solar cells get flexible." *Nature Photonics* 1.8 (2007): 433-435.