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Overview of Latest Trend in Solar Cell Technology, Module, Array and PV Systems

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Abstract

As the world gears towards more sustainable and broadly available energy, solar PV is attaining tremendous gains in the power industry. A solar power plant is reliant on the conversion of energy from the sun into electricity, either directly using photovoltaic (PV), or indirectly using concentrated solar power (CSP).

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Photovoltaics' a simple and unique way of harnessing the sun's energy. PV modules (solar cells) are unique as they directly convert the incident solar radiation into electricity without noise or pollution as obtained in conventional power generating techniques making them robust, reliable and long lasting. This past decade has witnessed various advancement in efficiency of solar cells, which has culminated in increased efficiency, current and reduced overall costs. This article furnishes an in-depth review on PV systems, modules and latest trends in solar cell line technologies like PERC, TOPCon, Heterojunctions cells with efficiencies ranging from 20% - 29%. This paper further examines cell manufacturing processes and PV technology of solar module (monofacial and bifacial) and their performance based characteristics.

Keywords: Silicon; Polycrystalline cell; Monocrystalline cell; Solar PV cell; MPPT; PV modules.

1. Introduction

Semiconductors can be said to be materials intermediary of a conductor (metals) and non-conductor (insulator). Semiconductors are often pure elements like silicon; as well as compounds like gallium arsenide or cadmium selenide. In a bid to modify the conductivity of pure semiconductors, little amounts of impurities are added to them, this phenomenon is doping [1]. Basically, semiconductors are either intrinsic or extrinsic. In an intrinsic semiconductor, impurities are not needed, rather more temperature and pressure are required to excite the electron to a higher level while in an extrinsic semiconductor, bulk of the material is doped with impurities which allows the electrons to excite from valence band to the conduction band [2]. Where impurities are introduced thereby creating more electron holes, it is a P type and when we add n-type, impurities and more electron band are created. A predominantly used PN junction is a diode. [3]

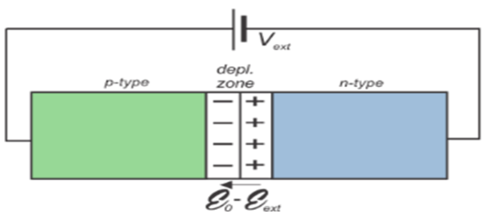


Figure 1: PN junction diode

1.1. Types of Solar PV Technologies

Photovoltaics (PV) are majorly classified into two namely; [4]

1. Crystalline

- Monocrystalline silicon
- Polycrystalline silicon

2. Thin film

- Perovskite
- Organic
- Cadmium Telluride (CdTe)
- CIGS
- Dye Synthesized
- Quantum Dots

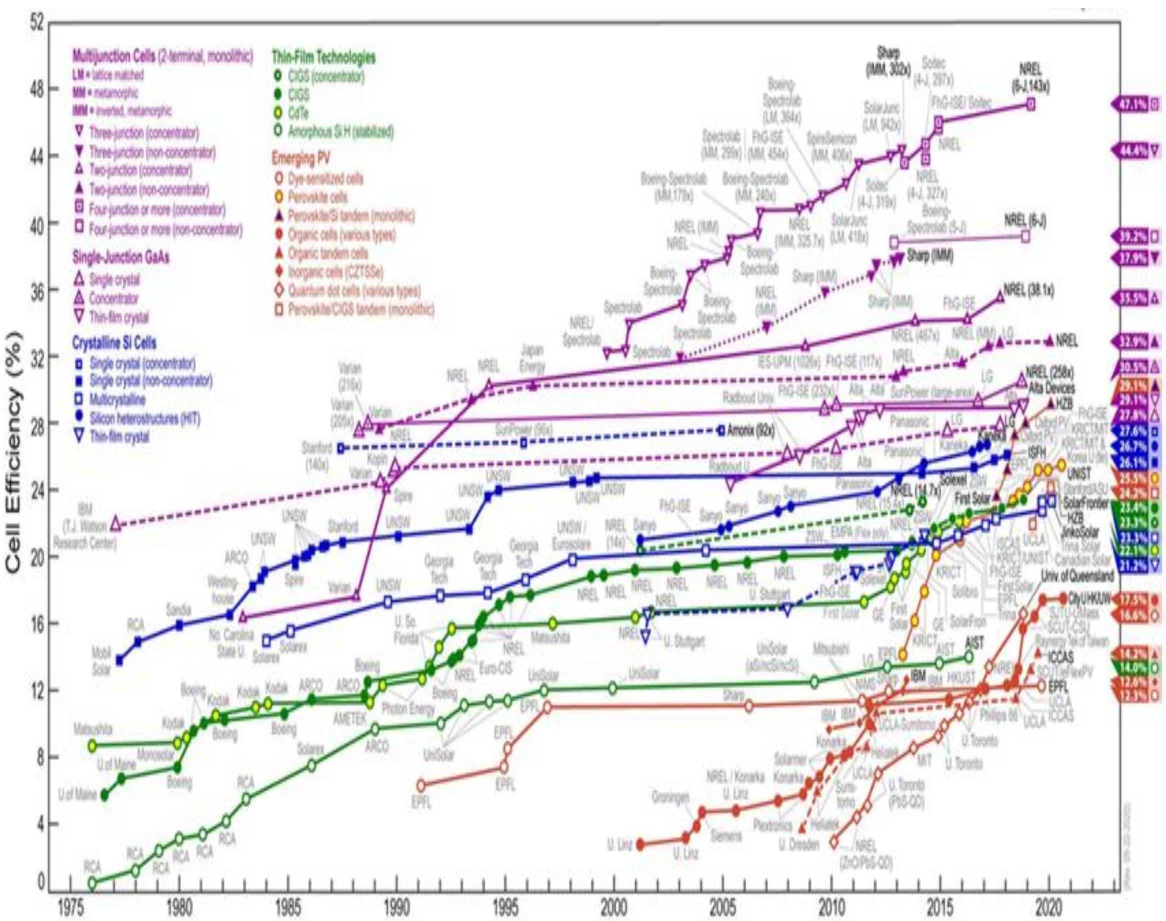


Figure 2: Best cell research efficiency from inception

Earliest solar cells were made from silicon in 1954 with about 6% efficiency. Approximately 85% of photovoltaic panels available today are silicon crystalline solar technology and is majorly restricted into two segments; Monocrystalline silicon and Poly multi crystalline silicon. There is also silicon based thin film technologies, which revolve around amorphous or tandem segments.

2. Cell Manufacturing

Before a cell is manufactured, it goes through two large industry segments namely; polycrystalline industry segment and wavering segment. The polysilicon industry segment is where quartz is used as raw material and the extracted silicon from it is dope.

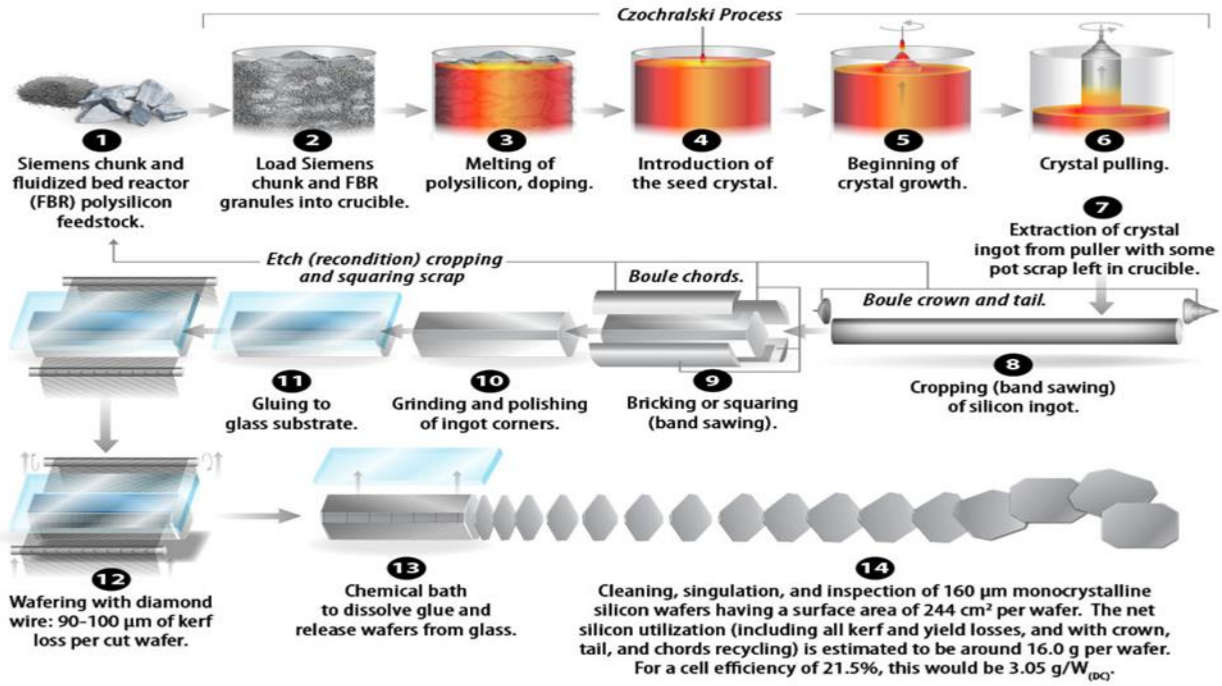


Figure 3: Solar cell manufacturing process

A standard monocrystalline wafer is 158.75mm; however, the industry has currently adopted a 210mm wafer and is projected to further reach 225mm.

Figure 4: Complete PV value chain

As seen in Figure 4 above, the process starts with polysilicon chunks been melted into monocrystalline ingots and further sliced to form wafers. Various methods are then implored to convert these wafers to solar cells, which are in turn connected or merged to form a solar module. There are two types of wafers namely Polycrystalline and monocrystalline wafer

2.1. Standard Poly Cell Line

The moment the wafer comes in, it's tested for sensitivity after which it is sliced causing a lot of surface damage. It is then texturized to form pyramids on the wafer surface. The texturization process is foremost process of the whole cell line. Reflectivity of light is then tested as the more the light the wafer surface absorbs, the more the conversion [3]. The wafer already has boron impurity making it p-type; the top layer is then diffused of silicon with phosphorous. The top layer then becomes n-type. This results to a PN junction.

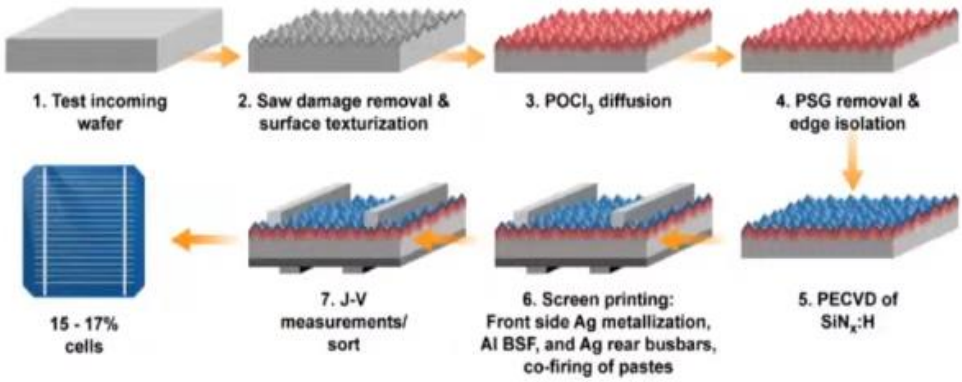


Figure 5: Polycrystalline solar cell process

A silicon nitrate layer is stashed on top using PECVD (Plasma-enhanced chemical vapor deposition). The silicon nitrate essence is to serve as an antireflective covering to capture more light similar to earlier process of texturization [5]. A sequence of printing stages follows where the cell forefront is silver, the rear is aluminum for back surface steel or silver mixed with aluminum as the back conductor. The concluding cell end-product has an efficiency of about 15% - 17%, however its currently at 19.2% - 19.4% for a polycrystalline cell [4].

2.2. Standard Mono Cell

The manufacturing procedure is comparable to polycrystalline cell, however a multi-crystalline uses alkaline texturization whereas a monocrystalline wafer uses acidic texturization after which a boron diffusion is done if the wafer is p-type or a phosphorous diffusion if n-type wafer [5]. The ensuing stages are quite similar except that in a monocrystalline, almost the entirety of the cell is one crystal whereas in a polycrystalline wafer, multiple crystals form one-bulk cell i.e. there exist some boundaries between the crystals respectively [5]. These boundaries take the role of a local shunt, which reduce the current resulting in lower efficiency for a polycrystalline cell and higher efficiency for a monocrystalline cell.

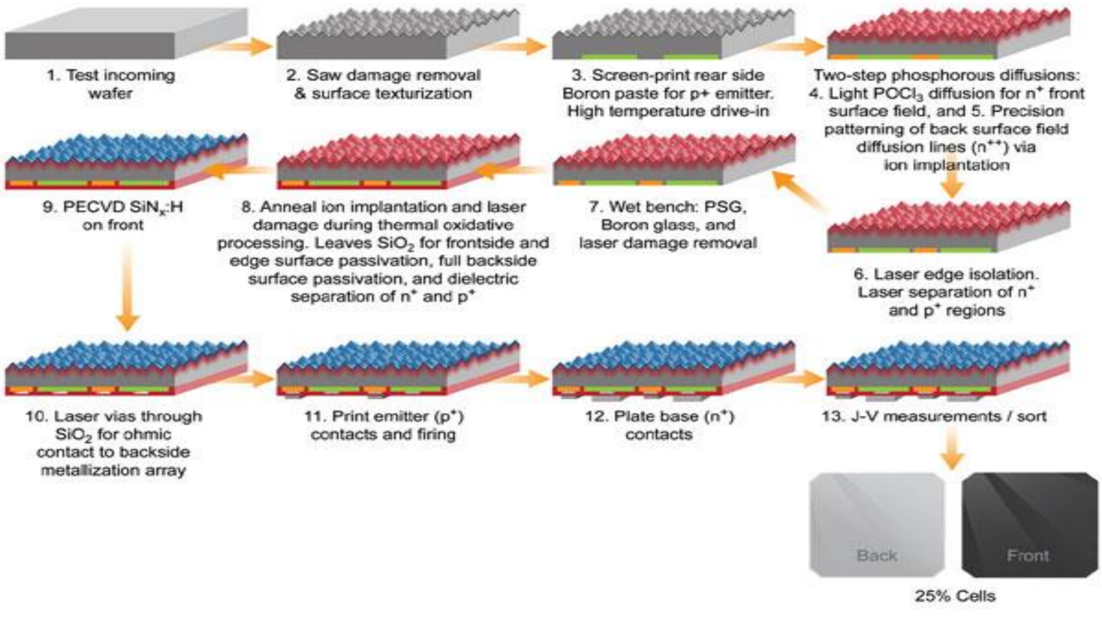


Figure 6: Monocrystalline solar cell process

2.3. Passivated Emitter Rear Cell technology (PERC)

This ranks amongst the latest tools that is been utilized in the race to make more efficient solar panels. It was first developed in 1980's but commercialized in 2016, however, since the technology was revolving around precision and usage of complex deposition techniques then, it took over two decades to be commercially viable [5]. Standard cell process to manufacture a PRC cell includes

- Laser scribing
- Passivation of the rear [5]

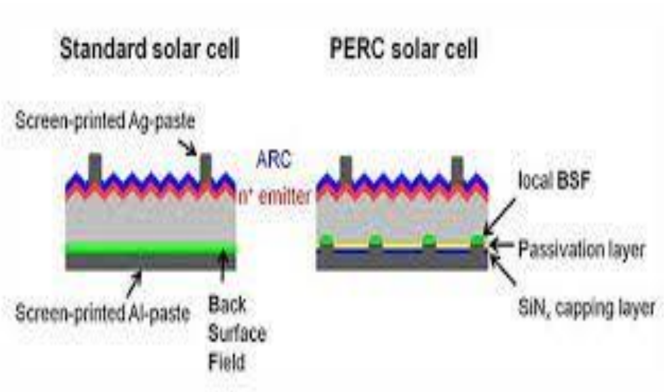


Figure 7: Standard solar cell versus PERC [5]

2.4. TOPCon (Tunnel Oxide Passivated Contact) Technology

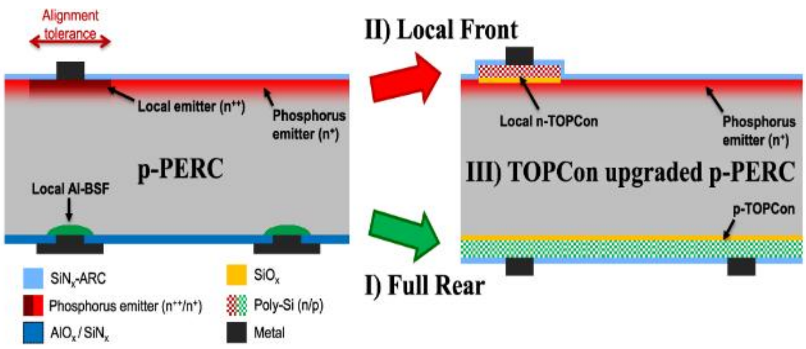


Figure 8: Upgraded TOPCon cell architecture

TOPCon is largely commercialized for n-type wafer, passivating contact are created via a thin interfacial oxide and a highly doped silicon layer to enable absorption of more light. The voltage is a resultant of wafer purity whereas current is an outcome of absorbable light quantity [3]. The back comprises a tunnel layer (Aluminum oxide) that helps passivate all the and a transparent conductive layer right at the top to help absorb as much light as there is. TOPCon fully at the rear and locally aligned at the fingers in front can boost the PERC efficiency by about 1%. The Fraunhofer Institute for Solar Energy Systems (ISE) has achieved an efficiency of 25.1% on both sides-contacted silicon solar cell [5].

2.5. Heterojunction Cells

In amorphous/crystalline silicon heterojunction cells, by replacing the amorphous silicon films by wider bandgap with amorphous silicon oxide layers, optical losses are reduced [6].

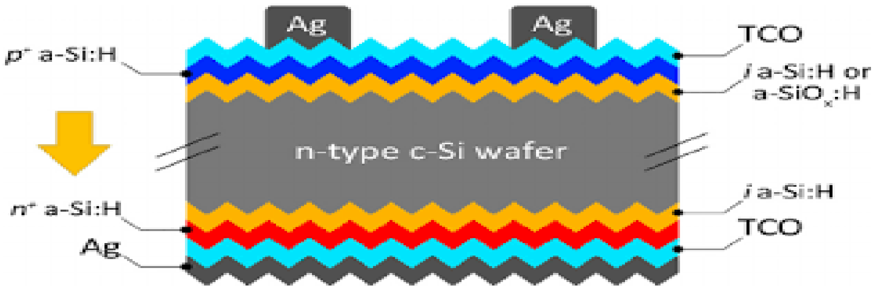


Figure 9: Silicon heterojunction solar cell structure

This technology has gone beyond just amorphous silicon or p-type and n-type above or beneath, as 4 or 5 junctions are now implored by adding microcrystalline silicon on top [6]. The multiple layer's aid in absorbing much wider sunlight wavelength. This technology currently has efficiency of 24.63%. However, it is expected to dominate the market in the nearest future owing to an expected efficiency of 29% from additional layers.

2.6. Evolution of Silicon Solar Cell

The rear of the multi-busbar monofacial cell is completely printed with aluminum, the white portion depicts silver or silver coated aluminum for the rear conductor. The silver metallization of the front cells is known as "busbars" while the fine lines are "fingers". Electrons collection in the cell are done by the fingers, which in turn push them towards the busbar. Multi busbar technology is been adopted in a bid to achieve cost effective cell and conduction of silver (thereby increases the current) as aluminum is quite inexpensive when likened to silver, the metal constituting the cell front which accounts 35% the total budget of solar cell [5].

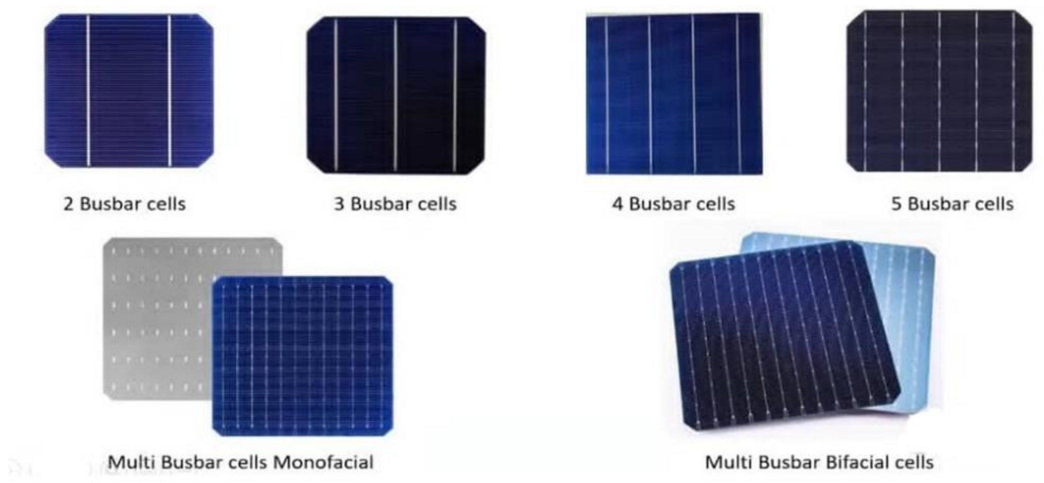


Figure 10: Types of solar cell bus-bars

2.7. Importance of Silicon PV Cell

A significant concept of manufacturing solar cell revolves around;

1. To reduce impurities to largest extent possible to get higher voltages.
2. To absorb as much light as probable [7].

Table 1: Attributes of Silicon PV

Silicon is transparent at wavelengths other than 1.1 microns(1100nm)	23% of sunlight passes right through without effect
Excess photon energy is wasted as heat	near infrared light typically delivers only 51% of its photon energy into electrical current energy. red light (700nm) only delivers 33% blue light (400nm) only delivers 19%
All together the maximum efficiency for silicon PV in sunlight is about 23%	Defeating recombination loss puts the limit in the low 30%

Figure 11 below shows the quantity of light currently been utilized. About 77% of solar spectrum is utilized by silicon of which 30% is used as electrical energy i.e. only 23% of light shown unto the module is converted to power while 54% of light transforms to heat. Nevertheless, there is failure to absorb the lengthier wavelength hence 23% is transparent [5- 8].

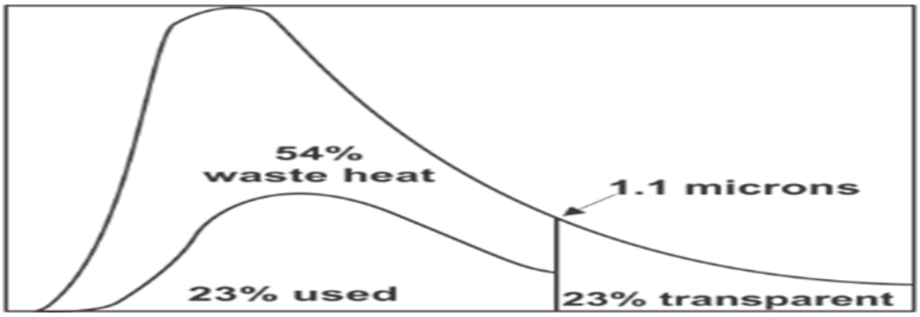


Figure 11: Silicon photovoltaic budget

3. Solar Module

A PV module is an assembly of photovoltaic cells mounted on a structure for installation. However, a bare single cell cannot be used for outdoor energy generation because

- The output of the cell is very minute (0.6V)
- It requires protection against dust, moisture, mechanical shocks and harsh outdoor conditions.

Hence the need to combine many cells to obtain a module. The interconnecting (series & parallel) of appropriate number of cells yields workable voltage and reasonable power. The most obtainable or common modules have series connection of 36 silicon cells to make it capable of charging a 12v storage battery.

Figure 12: Layers composition of a PV module

Modules are either bifacial or monofacial. The latter are currently the standard modules currently used. In a monofacial module, the front is actually the cell, which are positioned on the glass and back usually made of tedlar (polyvinyl fluoride) or kynar (polyvinyldenefluoride) [9]. In a bifacial module, both front and rear side has the same surface i.e. the light passing from the gaps in the middle of the cells and modules adjacent to one another that hit the ground and reflects; hence the rear of the cell also converts the reflected light to power as the module produces current and power not just from the incident sunlight but also from the albedo [9]. Bifacial technology allows a usual energy production between 3% to 10% to the variety of 30%, however this is reliant on on factors like elevated height of the structure, albedo, ground cover ratio (GCR) and also the back i.e. is it grass, sand, glass or white reflective material.

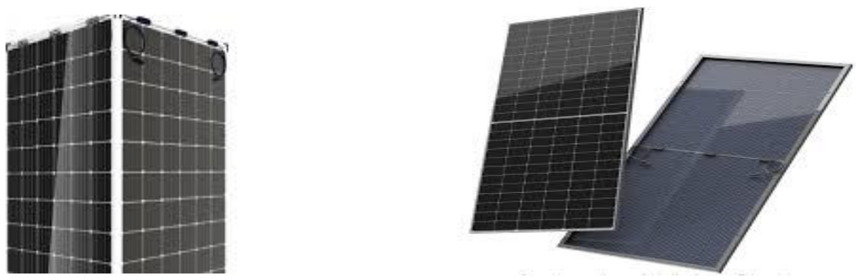
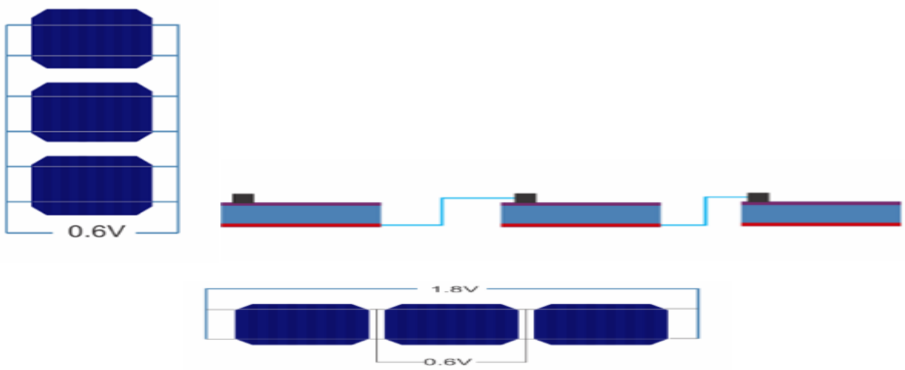


Figure 13: a.) Bifacial module b.) Monofacial module

The production cost between bifacial mono PERC and monofacial mono PERC modules are now approximately $0.50 [9].

3.1. Series & parallel connection in a PV module



(a) Parallel connection (b) Series

Figure 14: Parallel and series connection of PV module and battery

A single cell can provide a voltage of 0.6V and a current intensity

$$I = 200 - 300 A / m^2$$

If the cells are connected in series, I will be fixed but voltage will vary. If we connect cells in parallel, voltage will be constant but current will add up [5].

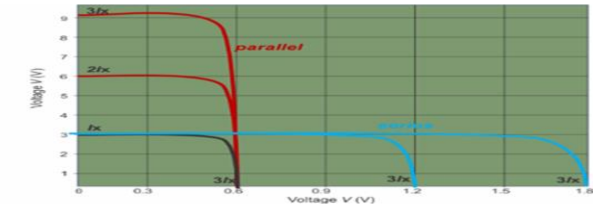


Figure 15: I-V characteristics of series & parallel connection

3.2. Classification of module

Modules are classified based on the material of the back cover used. Primarily, there are two categories;

- If the back cover of the module is made of Opaque Tedlar, it is known as a glass-to-tedlar [polyvinylfluoride-(C2H3 F)n] or opaque PV module.
- If the back cover of the module is made of glass, it is known as a glass-to-glass or semi-transparent PV module.

The amount of light transmitted from a semi-transparent PV module depends on its packing factor.

Table 2: Typical PV module specification

Module size	119.1 cm x 53.3 cm
Module Weight	7.5 kg
Cell size	12.5cm x 12.5 cm
Number of cells	36
Nominal output	80 W
Nominal voltage	12 V
Maximum voltage	17 V
VOC	21.2 V
ISC	4.9 A
Conversion efficiency	12.5 %

3.3. Difficulties associated with PV modules

There are certain setbacks, which are synonymous to PV modules namely; cell mismatch and shadowing effect.

3.3.1. Cell mismatch in a module

For instance, if two or more cells differ in characteristics and are connected in parallel or series, their behavior will be different. Hence, parameters of the cell such as VOC, ISC, Vm, Im must be the identical during cells connection as any form of alteration or mismatch in any of the stated characteristics of these cells results to further mismatched loss. Considering two cells (Cell 1 and Cell 2) connected in series, we can generate a combined IV characteristics and a combine voltage of V1+V2 In an ideal case considering the peak power,

$$\text{Pcombined} = \text{Psum of individual cells (Ideal)} \qquad (1)$$

In actual situation, if these different cells of mismatch characteristics are compared and combined; [5]

$$\text{Pcombined} < \text{Psum of individual cells (Actual)} \qquad (2)$$

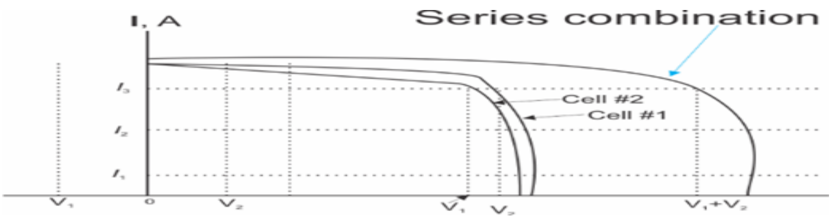


Figure 16: Combined IV characteristics of two cells

Furthermore, in the scenario of connecting two cells in series and applying a load, both cells are certain to carry same current, hence one cell will dissipate power and another will produce power which will result in reduce fill factor of their combined IV [5]. In addition, when two connected cells in parallel having mismatch characteristics, their volt are bound to be equal. Generally, the higher the amount of cells in a module, the more likelihood the prospects of quantum mismatch loss. Some means of minimizing these mismatch losses include; [5]

- Fabricating modules from cells belonging to the same batch.
- Carrying out cell sorting to categorize cells having matching parameters with specified tolerance.

3.3.2. Effects of Shadowing

Partial shading can have significant consequences for the outcome of solar module. In an occasion, where a plant leaf falls on a cell, the current produced by that singular shaded cell is greatly reduced. In the instance of a series connection, the current is limited by the cell that generates current i.e. the sixth cell which is shadowed as shown below will have low current generated. This cell dictates the maximum current flowing through the modules [10].

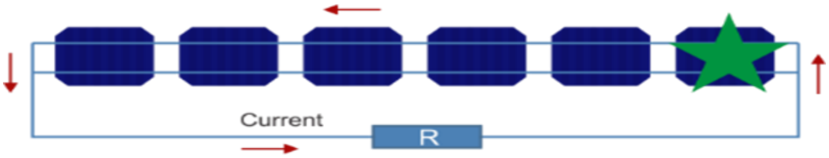


Figure 18: Partial shading in a series cell connection

The shadowed solar cell does not generate energy but starts to dissipate energy and heats up, which culminates in decrease of PV output (encapsulation material cracks/wear out of other material). By installing bypass diodes in the module, these effects from partial shading can be rectified.

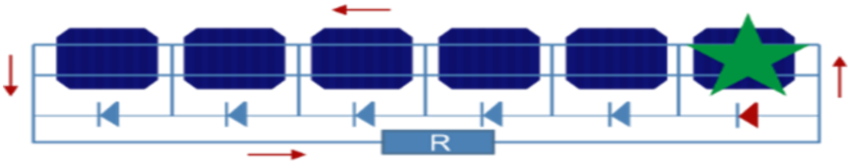


Figure 19: Partial shading with installed bypass diode

However, in the instance of a parallel connection, partial shading is less of a problem because the current generated in other cells need not to travel through the shaded cell. Hence for a module consisting 36 cells in parallel, a very high current (above 100A) combined with a relatively low voltage (0.6V) will be generated which would lead to high resistive losses in cables [5]. Combining the cells via a series connection and using one by-pass diode for every crystalline silicon solar cell provided. Thus, the module having 36 cells would contain two by pass diodes placed inside its terminal box.

3.4.2. Series-parallel connection of modules with blocking and by-pass diode

In parallel connection, blocking diode are connected in series so that is any string fails, the remaining strings output power won't be absorbed by the failed string i.e. bypass diodes are installed across each module and as such, when one module fails, the remaining modules output in the string will bypass the failed module. In advanced module nowadays, such internally embedded bypass diodes can be found [5, 10].

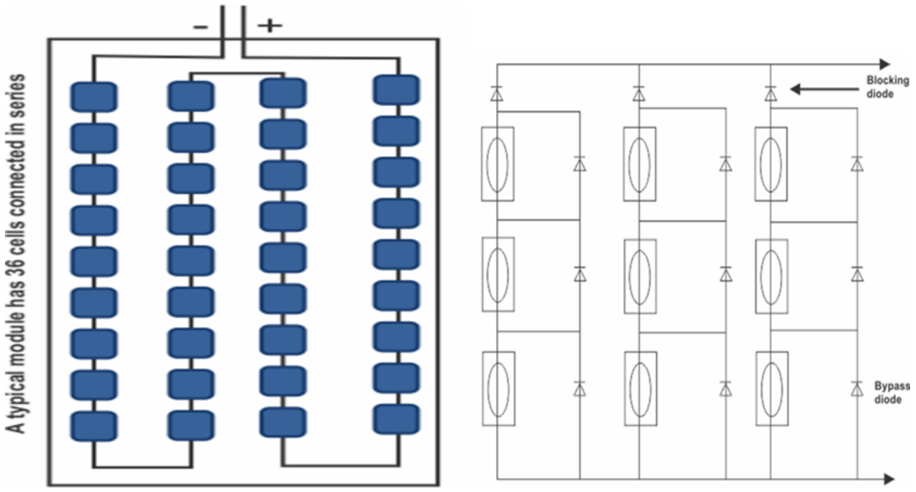


Figure 19: Typical Photovoltaic (PV) module with installed bypass and blocking diode

3.5. Efficiency of PV module and packing factor

This is the total cell area ratio to the total module area ratio, expressed as

$$\beta_c = \frac{area\ of\ \ solar\ cell}{area\ of\ \ \text{PV module}} \tag{3}$$

Clearly, packing factor is below unity (i.e. < 1) (pseudo solar cell), and it has maximum value of 1 when all area is covered by the solar cell.

PV module electrical energy can be expressed as

$$\eta_{em} = \tau_g \text{ x } \beta_c \text{ x } \eta_{ee} \tag{4}$$

For unity power factor i.e. $\beta_c = 1$;

Hence, $\eta_{em} = \tau_g \text{ x } \eta_{ee}$

OR $$\eta_{em} = \tau_g \text{ x} \left[\frac{FF \text{ x} I_{SC} \text{ x} V_{OC}}{A_m \text{ x} I_p} \right] \text{x} 100 \quad (5)$$

Where η_{em} is electrical efficiency of module. β_o is temperature coefficient. η_{ee} is electrical efficiency. T_c is ambient temperature. τ_g is transmissivity of the glass. β_c is packing factor. η_{mo} is PV module efficiency under S.T.C. This shows that the PV module electrical efficiency is less that of the solar cell due to presence of glass over solar cell. The temperature-dependent electrical efficiency of the PV module; [5]

$$\eta_{em} = \eta_{mo} \text{ x} \left[1 - \beta_o (T_C - 298) \right] \quad (6)$$

3.6. Solar PV output maximization

Primarily there are two ways to maximize output;

- Mechanically tracking the sun.
- Electrically tracking (by manipulating the load to ensure maximum power output under changing condition of insolation and temperature). [11]

3.6.1. Load Matching

The intersection of source and load characteristics of an electrical system determines its operating point.

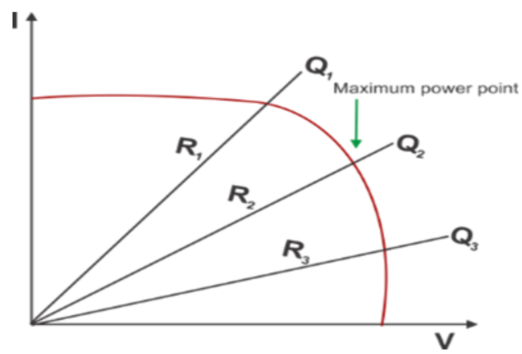


Figure 20: Load matching with reactive load

From Figure 20 above, if R1 is the resistive load for a set of operation and R1 is extended, it intersects the source line at point Q1, i.e. the operation point. If the resistive load is increased to R2, its point of operating becomes Q2 and likewise in the same manner, R3. To achieve system operation at maximum power point, the load R2 is connected at condition Q2, hence the PV system output power can be maximized enabling load matching to be achieved and allowing connection of different loads so as to determine which load gives the best performance.

3.6.2. Maximum Power Point Tracker (MPPT) factor

Its significance is of essence in a bid to electrically control the maximum power. The I-V characteristics continuously variates with respect to insolation and temperature at different times of the day [5].

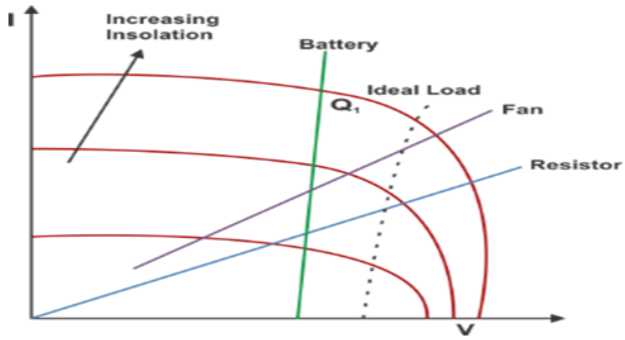


Figure 21: I-V Characteristics of MPPT

The load mandatorily fine-tunes itself to duly track the point of maximum power, hence obtaining it as this is what makes a load an ideal load. At every I-V characteristic, a maximum point exists; therefore, the target is to operate at this maximum point. However, peradventure there is significant deviation of the point of operation from the maximum power point; it is desirable to interpose an electronic MPPT in the middle of the load and PV system. MPPT is more of an adjustment of dc-dc switching voltage regulator. Higher or lower voltages for corresponding lower or higher currents aids the load in coupling for maximum power transfer. Normally, a buck-bust structure is frequently utilised with voltage and current sensors bound into a feedback loop via a controller to fluctuate the switching time.

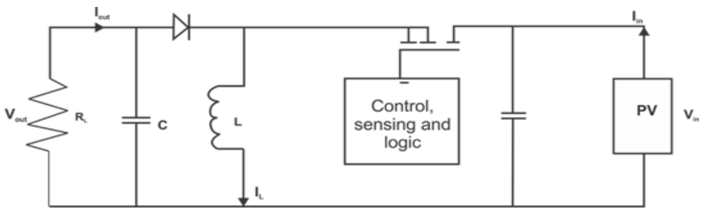


Figure 22: MPPT using buck-boost converter

If we consider the output power of a PV system

$$P + \Delta P = (V + \Delta V) + (I + \Delta I) \tag{7}$$

$$P + \Delta P = V \text{ x } I + V \text{ x } \Delta I + \Delta V \text{ x } I + \Delta V \text{ x } \Delta I \tag{8}$$

Ignoring inconsequential terms simplifies to

$$\Delta P = \Delta V \text{ x } I + V \text{ x } \Delta I \tag{9}$$

ΔP should be zero at peak point, hence

$$\frac{dV}{dI} = -\frac{V}{I} \tag{10}$$

Where $\frac{dV}{dI}$ is dynamic impedance. $-\frac{V}{I}$ is static impedance.

3.6.2.1 Possible strategies for operation of a MPPT

- By monitoring static and dynamic impedances: A minute amount of current is occasionally injected into the array bus with impedances of both dynamic and static bus measured [5, 12]. To attain the state $Z_d = -Z_s$, the voltage of operation is modified accordingly.
- Observation of power output: Voltage is adjusted and power output is sensed. Consequently, so long $\frac{dp}{dV}$ is positive (increased output), the operating voltage is increased and consequently, there is a decrease in operating voltage if $\frac{dp}{dV}$ is sensed negative. Voltage is unchanged at $\frac{dp}{dV}$ near zero.
- By fixing output voltage as a portion of V_{OC} (frictional open circuit voltage method – indirect)

$$Vm = K \text{ x } V_{OC} \tag{10}$$

Where V_{OC} is open circuit voltage. Vm is voltage at maximum power.

For crystalline silicon cell of top quality, K=0.72 [12]. As it is not important to know the open circuit voltage always whilst evaluating maximum voltage, an additional identical unloaded cell is installed on the array to face same environment as the module in use and its open circuit voltage is continuously evaluated [4]. The array operating voltage is then set at K times VOC.

4. PV Array and Systems

A photovoltaic array is a collection of series, parallel or both series and parallel, connected photovoltaic (PV) modules [5, 9]. Primarily, there are two classifications of PV systems namely:

- Central Power Station System: a large power station just like a conventional coal based power generation unit which generates huge amount of power to be
- Distributed System

  - ✓ Standalone System: It is located at the load center and dedicated to meet all the electrical loads of the environs or specific set of loads.
  - ✓ Grid Interactive System: here, connection to the utility grid is via a two-way metering system. It could range from a small roof top system or a relatively bigger system meant for a whole village.
  - ✓ Small system for consumer applications: These systems are meant for low energy consumer devices requiring power to the tune of microwatts to 10W.

Solar PV applications include [3, 6]

- Grid-interactive power generation
- Water pumping
- Lightning
- Medical refrigeration
- Telecommunication and signaling
- Village power
- Space applications

5. Conclusion

In this article, we analyzed trends in solar cell line technology. The technologies studied are dependent on their laboratory research along with their potentiality. Wafer based crystalline silicon technologies is tipped to continue dominating PV power generation over the next decade. Integrating TOPCon on P-PERC is very viable technology hence these trending technologies though still evolving will yield even better efficiencies at inexpensive cost. This paper further discussed classification of PV modules, associated difficulties and maximization of PV modules performance. Without doubt, PV energy is arguably the most essential alternate energy source, however more is to be done with respect to production of better cell efficient modules.

6. Conflict of Interest

The author declares that there is no conflict of interest.

7. Financial Support

No financial support was provided fir this study

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