Tampere University

Shriya Mandal

DIFFERENT PV TECHNOLOGIES AND THEIR STATE OF ART

Faculty of Information Technology and Communication Sciences
Master's Degree Program in Electrical Engineering
Master of Science Thesis
First examiner: Prof. Seppo Valkealahti
Second Examiner: Kari Lappalainen
March 2022

ABSTRACT

Shriya Mandal: Different PV technologies and their state of the art
Master of Science Thesis
Tampere University
Master's Degree in Electrical Engineering – Smart Grids
March 2022

Due to the rising demands of energy and decarbonization of the energy sector, use of renewable energy is on the rise. In fact, renewable energy is the future because use of conventional sources of energy does not assure clean environment and we do not have unlimited supply of coal, gas, or petroleum. Among the other renewable sources of energy, solar energy is quite popular and has been proven to be reliable in most of the countries.

Photovoltaics (PV) technology has been the most popular technology used to convert solar radiations into usable form of energy. In my thesis, we get a brief overview of the operating principle behind solar PV technology and its history of evolution. The main characteristics involved when the development of PV technologies need to be considered have been discussed. The different PV technologies that exist today have been explained in brief. Different PV technologies have different efficiency rates, and each has its own advantages and disadvantages. The state of the art of the commercially mature PV technologies will be discussed elaborately. In the end, the challenges of PV technologies have been discussed.

Keywords: Renewable energy, solar power, PV

PREFACE

I would like to express my gratitude towards the primary examiner of my thesis, Professor Seppo Valkealahti, who helped me create the structure for the thesis with his valuable feedbacks and comments during this entire time of writing the thesis. I would also like to thank my second examiner Kari Lappalainen for his support. Finally, I thank my parents and my friends who have been there with me in this entire journey and have supported me in various ways to motivate me during this entire time.

Tampere, March 2022

Shriya Mandal

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

c-Si	Crystalline Silicon
a-Si	Amorphous Silicon
PV	Photovoltaics
µc- Si	Microcrystalline Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium diSelenide
NREL	the National Renewable Energy Laboratory
IEA	International energy agency
Fig.	Figure
ITRPV	International Technology Roadmap for Photovoltaic
DSSC	Dye-sensitised solar cells
OPV	Organic photovoltaics
PCE	Photo conversion efficiency
CO2eq	Carbon dioxide equivalent
ARC	Antireflection coating
BSF	Back surface field
CVD	Chemical vapour deposition
SPS	Serial-parallel-serial
EVA	Ethyl vinyl acetate
PID	Potential induced degradation
HJT	Hetero-junction technology
PEVCD	Plasma enhanced chemical vapour deposition
TCO	Transparent conducting oxide
RF	Radio Frequency
PVD	Physical Vapor Deposition

SWE	Staebler-Wronski effect
HRT	High resistance transparent
CBD	Chemical Bath Deposition
CSS	Close-Spaced Sublimation
MOCVD	Metal-organic chemical vapour deposition
VTD	Vapor transport deposition
SAS	Sulfurization after selenization

1 INTRODUCTION

In recent times, it is very difficult to imagine living a comfortable life without energy. Due to the growing world population and its demand for comfort and developments, the consumption of energy has been rising every year. To meet these demands, fossil fuels such as coal, petroleum and gas have been the primary resources of energy. However, these primary resources of energy are available in limited quantities and take quite a long time to replenish. Environmental pollution caused due to the use of fossil fuels has raised serious concerns. To meet the global energy demands and to save the environment, the use of renewable sources of energy is of huge potential. Unlike non-renewable sources of energy, most renewable sources of energy are referred to as “clean” energy in terms of the neutral or positive impacts on the environment. While non-renewable sources of energy may take millions of years to get replenished, most renewable sources of energy are replenished within the human lifespan. In fact, some forms of renewable energy sources are replenished almost constantly.

The five most common types of renewable sources of energy are solar, wind, hydro, geothermal and, biomass. Among other renewable sources of energy, solar energy has been quite popular and has been proven to be quite reliable in most countries. The most used technology used to convert solar radiations into a usable form of energy is photovoltaics technology.

According to IEA, in Q1(first quarter) 2020 use of renewable sources of energy increased by about 1.5% as compared to Q1 2019. Renewable sources of energy have been resilient to a great extent to all lockdown measures during the covid-19 pandemic. The share of renewable energy sources in global electricity generation rose from 26% in the year 2019 to 28% in the year 2020. [3]

Owing to the strict lockdown measures during the pandemic there were considerable curtailments of mobility and global economic activities which resulted in pushing down the global energy demand by 3.8% during the first quarter of 2020. In China, the energy demand fell by 7%. In the US, it fell by 6% and in European Union it fell by 5%. However, in India the energy demand increased by 0.3%. [1]

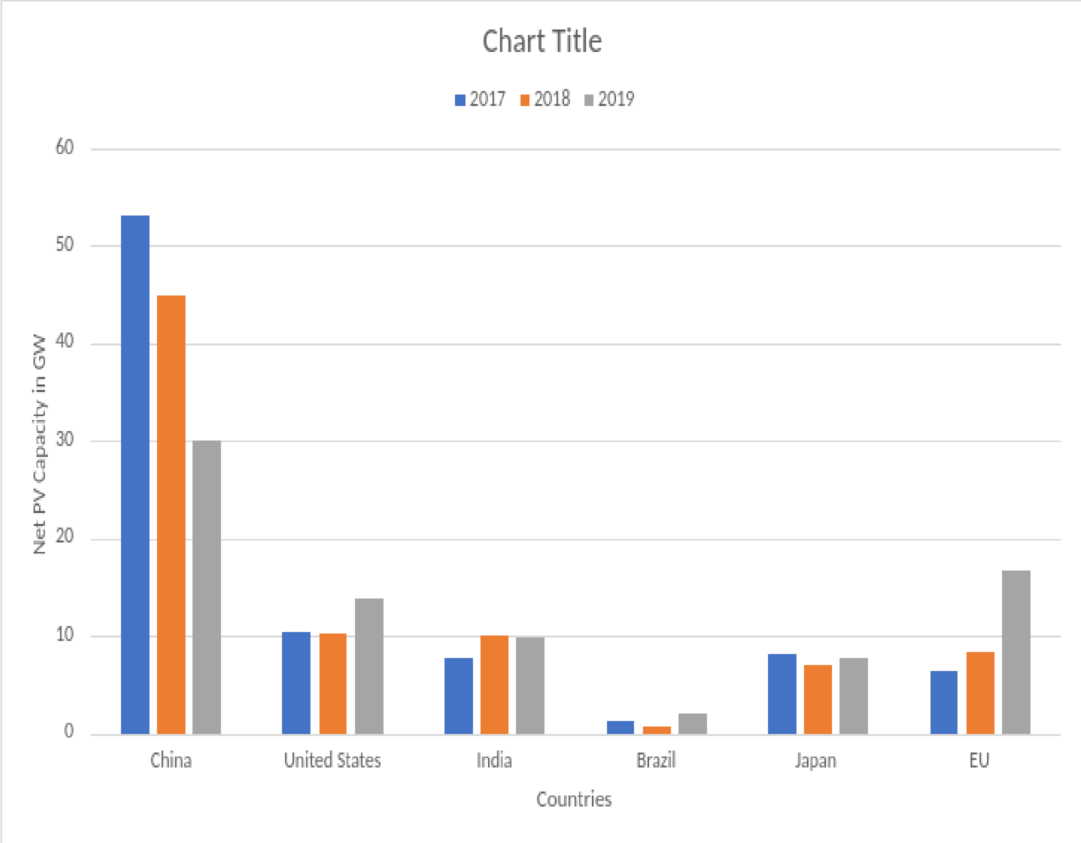

Figure1: Net solar PV capacity additions for the period 2017-2019.[1]

Fig. 1 shows the change in net capacity addictions of solar PV in selected few countries from the year 2017 to 2019. The solar PV capacity additions in China slowed down from 53.1GW in the year 2017 to 30.1GW in the year 2019. However, there was a stable growth of PV installations in the United States as seen from the graph.

Due to the Paris agreement, there is much pressure to bring down the energy related CO_2 emissions by 3.5% within the year 2050. An increased use of renewable sources of energy in the year 2020 was caused by an increase in renewable electricity generation of about 3% after completion of more than 100GW of solar PV and about 60GW of wind power projects in the year 2019. [16]

Solar PV power generation increased by 22% in 2019 resulting to about 720 TWh. Solar PV generation rose steeply in South East Asia due to new capacity in Vietnam (from 0.1GW to 5.4GW). The slowdown of PV power generation in China was compensated by the increase in capacity additions in the European Union, the Middle East, Latin America, the United States, India, and Africa.

China (Mainland) led the PV module production in 2019 with a share of 66% while Rest of Asia-Pacific and Central Asia (ROAP/CA) with 18% followed by Europe with 3% and United States with 4%. Europe's contribution to the total cumulative PV installations was 24% in 2019 (as against 25% in 2018). However, installations in China remained the same which is about 36%. Share of Silicon based PV technology amounted to about 95% of the total production in 2019. Mono crystalline technology accounted for about 66% of the total production.

Development of different PV technologies in the last five years have been remarkable. In my thesis I have tried to explain about the operating principle and about materials and main characteristics involved in PV technologies in the second chapter. The worldwide status of PV technology has also been discussed there. In the third chapter the state of the art of various PV technologies have been discussed which are mainly used commercially in the market. And finally, conclusion has been made about the challenges and prospects involved in the PV technologies.

2 SOLAR PV TECHNOLOGIES

2.1 History of photovoltaics

The term photovoltaics (PV) comes from the photovoltaic effect which is the process of converting light to electricity. The photovoltaic effect was discovered by Alexandre-Edmond Becquerel in 1839. In the year 1954, scientists at Bell laboratory used this phenomenon to make silicon based solar cells which when exposed to solar radiations generated electricity.

2.2 Working Principle of Solar Photovoltaics Technologies

The working principle of solar PV cell revolves around the photovoltaic effect that is exhibited by semiconducting materials on exposure to solar radiations. An individual PV cell is made up of layers of semiconducting materials. In these semiconducting materials when exposed to sunlight, electric field is generated across the layers causing electricity to flow. The magnitude of this current that gets generated in the PV cell depends on the intensity and wavelength of the solar radiations. Therefore, to ensure maximum absorption of radiation the PV cells are coated with an anti-reflective material. The working of a typical PV cell has been shown in fig. 2.

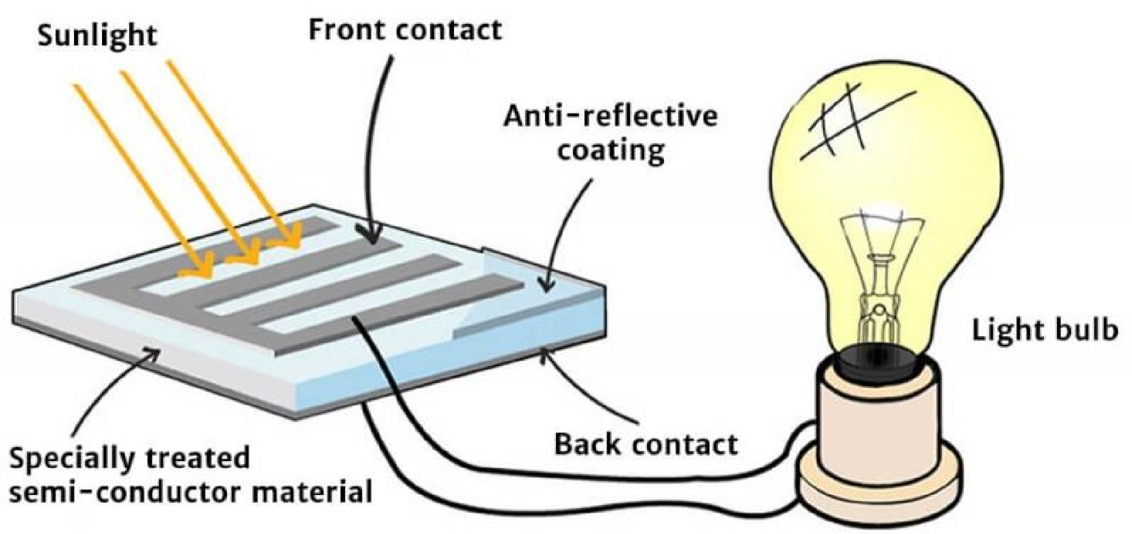

Figure 2: Working of a typical PV cell [2]

Usually, several PV cells are connected together to form PV modules or panels. These PV modules when connected form arrays. Fig. 3 shows how large solar PV panels look like.

Figure 3: Solar PV panels [3]

2.3 Important Characteristics

PV technology has been widely popular and considerable developments have taken place since its invention. Three main characteristics that usually are taken into consideration when development of PV technology has been discussed below.

2.3.1 Cost

Cost of manufacturing of PV device is a vital characteristic which includes cost of materials used, manufacturing costs and the cost of components. It is always the aim to make manufacturing cost economic. The industries suggest two methods to reduce the manufacturing cost. One of the methods being bulk production of PV modules and the other being use of low cost materials. The price of the PV module itself represents almost 50-60 percent of the total cost of an installed solar PV system.

2.3.2 Efficiency

The efficiency of a PV device in terms of power conversion is an important characteristic as it concerns the percentage of incident solar power that gets converted to electricity. So, in case, a PV device with low efficiency is used, then larger area coverage is necessary to generate the required power. Table 1 consists of the laboratory measured efficiencies of some of the popular solar PV technology cells.

Semiconductor material	Power conversion efficiency (%)	Technology
Mono-crystalline silicon	20 – 27.6	Crystalline
Poly-crystalline silicon	13 – 21.1	Thick and thin film
Gallium arsenide	20 – 29.1	Crystalline
Amorphous silicon	8 – 14	Thin-film
CdTe	10 – 22.1	Thin-film
CIGS	10 – 23.4	Thin-film
Dye sensitised (dye, TiO2)	13	Thin-film
Organic photovoltaic	6 – 25.5	Thin-film

Table 1: Research Cell efficiencies [5]

2.3.3 Lifespan

While deciding the commercialisation potential of any specific PV technology, the lifespan of a PV device becomes an important characteristic.

Research on PV technology focuses on - high efficiency, low cost, reliable solar cells. Electricity generation from solar cells have risen and therefore large-scale PV system are employed to support the grid system.

2.4 Materials

A brief overview of categorisation of PV technologies based on materials used is given in figure 4. PV technologies are categorised into three generations based on the materials used. In first generation PV cells wafer-based crystalline silicon is used which is either monocrystalline or polycrystalline. Second generation PV systems are based on thin film solar cells which are made of thin layers of semiconductor materials such as cadmium telluride (CdTe) or copper indium gallium diselenide (CIGS). Mostly the first generation and, second generation PV systems are available for commercial use. Third generation solar PV cells are next generation solar cells that are made from polymer-based materials aiming to be flexible, light-weight and inexpensive. Several new technologies fall under this category such as organic PV cells, quantum dots and hybrid cells.

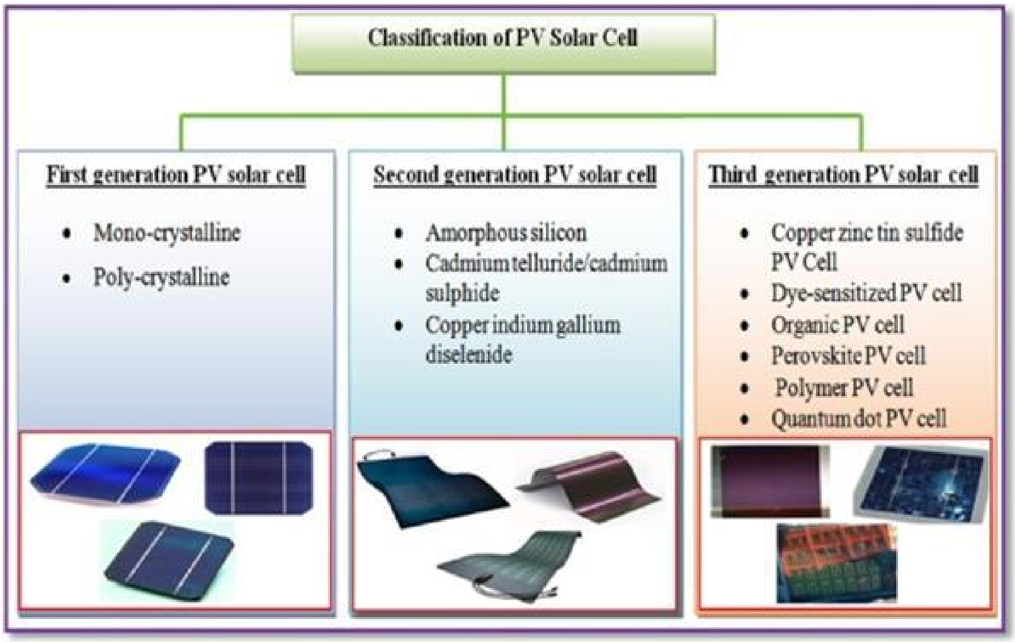

Figure4: Classification of solar PV cells based on material used [6]

2.4.1 Silicon solar cells

Due to the easy availability of silicon in nature, a vast majority of solar cells are made of silicon. Crystalline silicon cells provide highest efficiency among other materials available. Crystalline silicon cells consist of silicon atoms connected to each other forming a crystal lattice structure which helps in efficient conversion of light to electricity.

2.4.2 Thin Film Solar Cells

Thin film solar cells are so called because thin layers of semi conducting material such as cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) are used. The thickness of these layers is about a few micrometers only. CdTe being the second most popular PV material used after silicon. Although they are of low cost, but they have lower efficiencies than silicon cells.

2.4.3 Organic cells

Organic PV cells fall under the third generation PV systems. Therefore, this is comparatively a new and an emerging technology which promises to improve cell efficiency, increase performance lifetime, lower costs, and ease manufacturing process. Organic photovoltaics use variety of organic materials for the absorber, interfaces, and acceptor. Organic photovoltaics (OPV) have proven to be as efficient as 18.2% with small area modules used. This technology is appealing to the building integrated PV market due to the use of various absorbers to build efficient transparent or coloured OPV devices. A simple representation of operating mechanism of an OPV is given in figure 4. However, OPV is still not commercially mature to be used widely in the market.

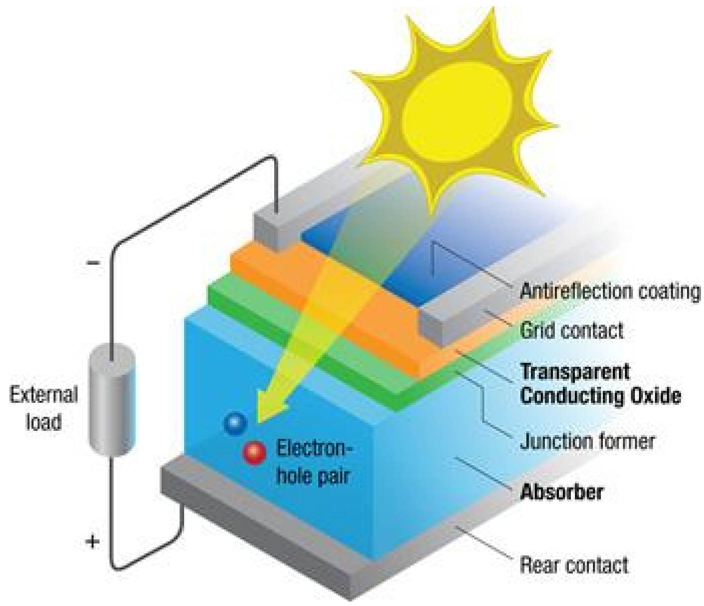

Figure 4: Basic mechanism of OPV technology [7]

2.4.4 Quantum dots

They have huge potential to increase the efficiency rate because unlike standard silicon cells, the quantum dots generate more than one exciton (bound electron-hole pair) per incoming photons. The quantum dot panels use tiny spheres of semiconductor material whose size can be adjusted to effectively respond to different wavelengths of light. Initially lead sulfide was used in quantum dot solar cells which had an efficiency of 2.9% [NREL]. However, the latest quantum dot solar cells use cesium lead triiodide (CsPbI3). Currently this technology is still in developing stages and much work needs to be done in terms of efficiency, costs, manufacturing process to become commercially mature.

2.4.5 Hybrid solar cells

In hybrid solar cells, both organic and inorganic semiconductor materials are used. In first generation PV cells, inorganic materials such as silicon has been used mainly which have high efficiency rate but high manufacturing costs. The third generation PV cells have used organic materials whose efficiency rate is lower than silicon, but they have low manufacturing costs. So, hybrid PV cells make use of the advantages of both of the above mentioned technologies.

2.4.6 Perovskite Cells

The perovskite solar cell is a hybrid organic-inorganic solar cell which is an emerging technology in the PV family. This technology makes use of the advantages offered by the perovskite materials such as high charge carrier mobility, excellent light absorption and lifespan delivering high efficiency with low manufacturing cost. There are concerns related to the stability and environmental compatibility of the technology. But once when these above mentioned issues are taken care of, perovskite based technology has huge potential to deploy terawatt scale levels of solar energy.

2.4.7 Dye-sensitised solar cell

Among the third generation PV technologies, dye-sensitised solar cells (DSSC) gained much popularity among the researchers due to their low cost, ease of manufacturing and low toxicity. Composition of a typical DSSC includes a photoanode, a cathode, a photosensitizer and an electrolyte. In DSSC, dye is the most important part which is the source of photoexcited electrons. Recent photo conversion efficiency (PCE) as certified by NREL is 12.3%

2.5 Worldwide status of PV technology

In the year 2019, the market size of solar PV panels was valued at 115.2 billion USD. Despite the slowdown of the Chinese market, Asia continues to dominate the global PV market.

Fig. 5 shows an overview of the global PV market as of the year 2020. After China, the European Union came second with annual PV installations with around 16 GW.

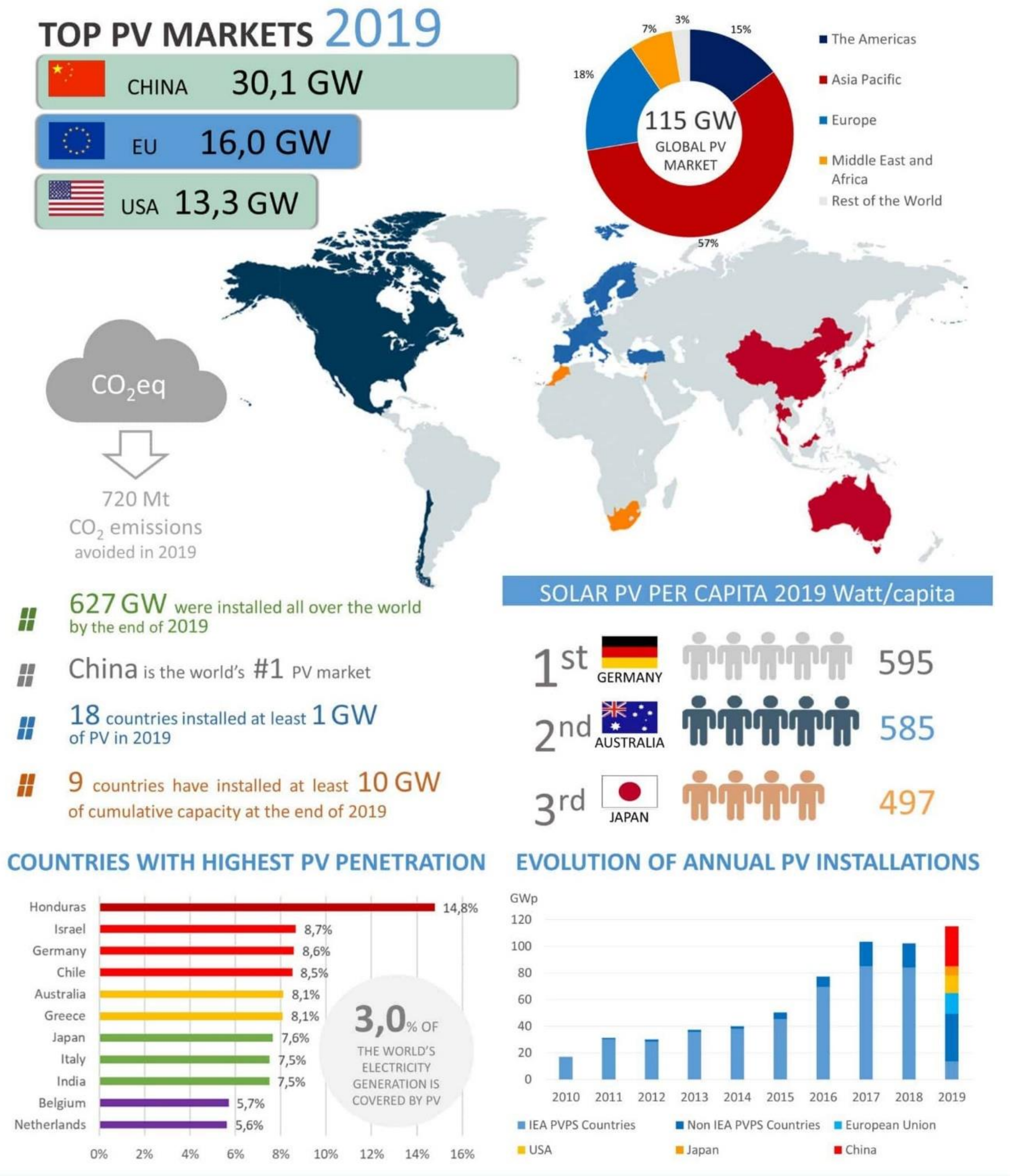

Figure 5: A snapshot of global PV markets-2020 [8]

In the year 2020, China reported 48.2 GW PV installations and that represents 35% of global market. European Union reported 19.6 GW of PV installations in the year 2020 followed by US with 19.2 GW PV installation. However, India reported a major fall of PV installation to around 5 GW due to the pandemic and all the uncertainties related to the pandemic. [8]

Countries such as Honduras, Israel, Germany, Chile, Australia, Greece, Japan, Italy, India, Belgium, Netherlands, Spain, and Turkey now have enough PV capacity to generate their annual electricity demand by 5% with PV theoretically. Among the global electricity demand, PV represents around 3.7%. In the year 2020, PV has been successful to save about 875 million tons of Carbon dioxide equivalent (C02eq) which in 2019 was 720 million tons. So, there is definite progress towards decarbonizing the energy mix by PV. [8]

In the year 2020, 95% of the c-Si PV module production came from Asia with China (mainland) being the leading producer with a share of 67%. Share of Europe and USA/CAN in the PV module production was 3% and 2% respectively. In 2020, Si wafer based PV technology accounted for around 95% of the total production among which share of monocrystalline technology accounted for 84% of the total c-Si production. However, in the year 2019, the share of monocrystalline technology accounted for 66% of the total c-Si production. Fig. 6 shows the annual global thin film technology based PV production where the production of a-Si technology based PV modules have decreased. But the production of CdTe and CIGS technology based PV module production has increased.

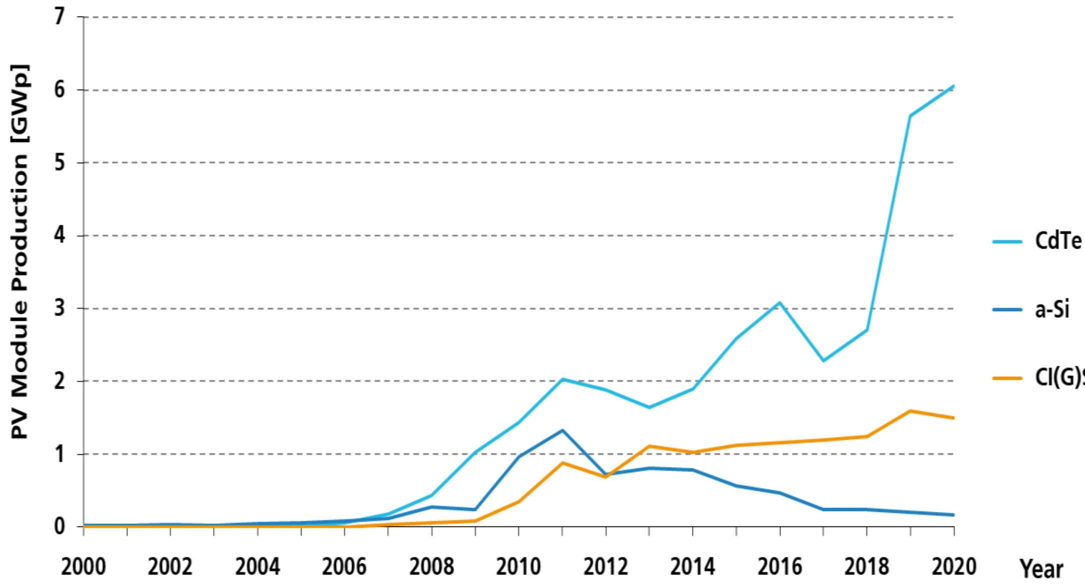

Figure 6: Annual global thin film technology based PV module production [35]

Figure 7 shows development of laboratory solar cell efficiency from the year 1993 to 2021. These record efficiencies illustrate the potential for further increase in efficiencies of the PV modules at the production level.

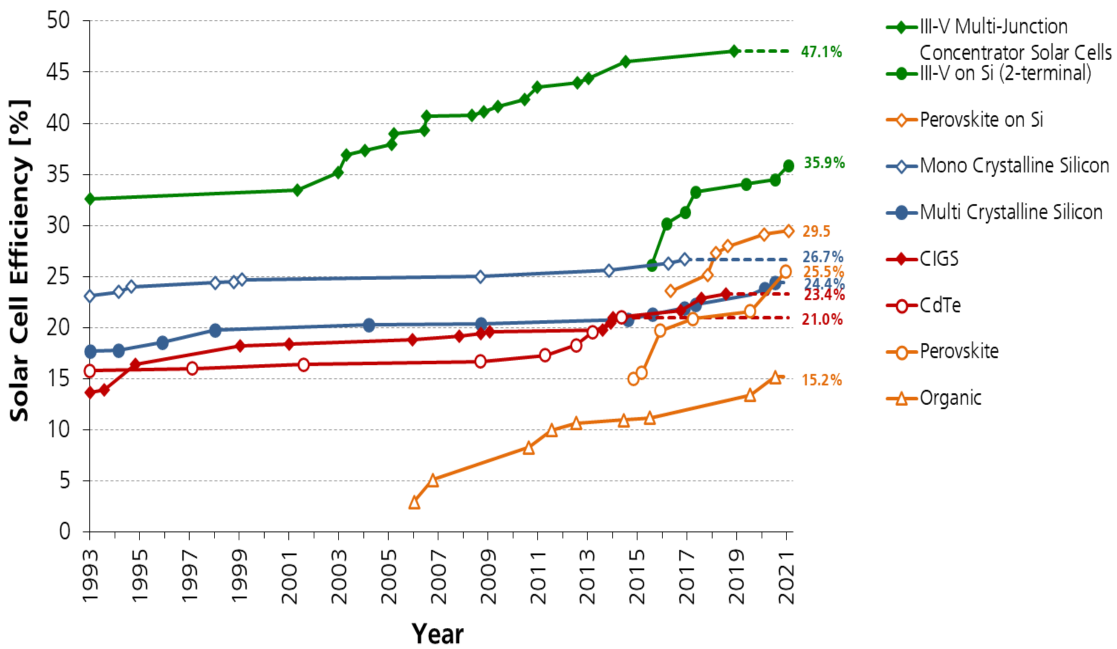

Figure 7: Development of laboratory solar cell efficiencies [35]

The record lab cell efficiency of multi junction concentrator solar cells is 47.1% in the year 2019. The record lab cell efficiency for monocrystalline silicon solar cell is 26.7% and for polycrystalline silicon solar sell is 24.4%. The OPV cells with lab efficiency less than 5% initially, made good progress to attain a 15.2% lab efficiency in the year 2021. Perovskite have record lab cell efficiency of 25.5% as of 2021 data.

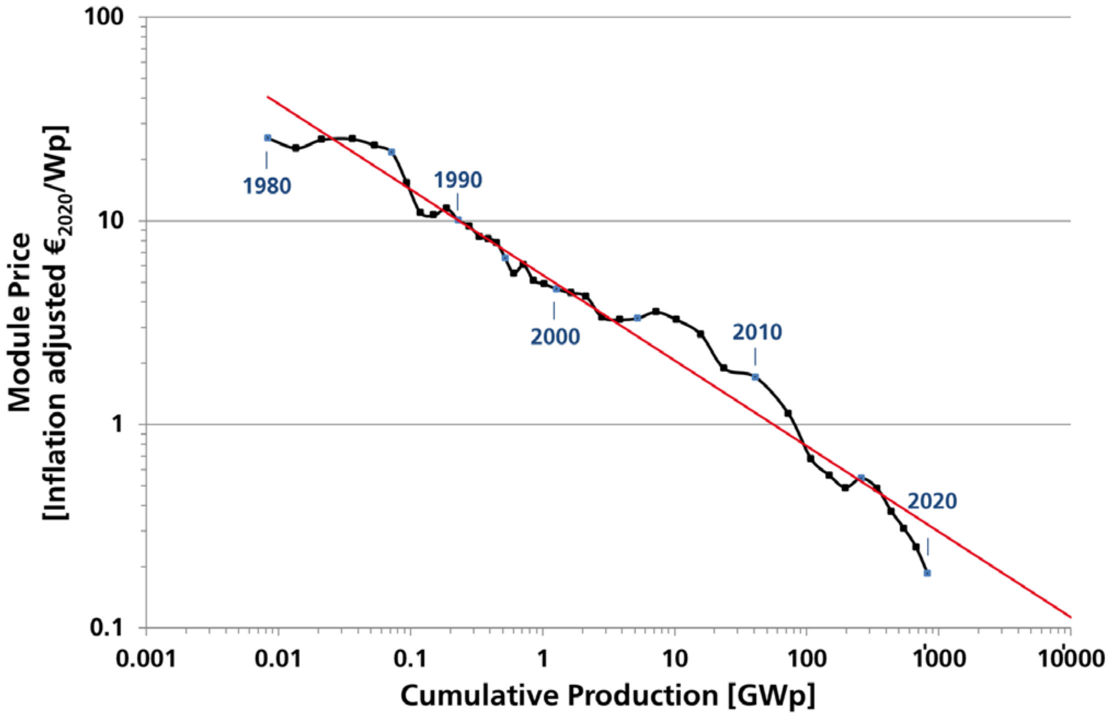

Figure 8: Price learning curve including all commercially available PV technologies [35]

Fig. 8 shows the price learning curve of the commercially available PV technologies. The learning curve, also called the experience curve shows that the price of PV modules decreased by 26% every time the cumulative module production doubled, in the last forty years. With technological improvements and economies of scale, the overall cost decreases.

3 CRYSTALLINE SILICON TECHNOLOGIES

Crystalline based silicon solar cells have the highest efficiency so far and with silicon being the second most abundant element after oxygen makes it easily available for manufacturing of PV technologies. The state of the art of various crystalline silicon technologies have been discussed below

3.1 Monocrystalline Silicon Technology

These cells are made of pure silicon and their efficiency rate is about 15-22% which is still highest among other technologies used. The efficiency rate depends on the manufacturing process.

Monocrystalline silicon cells have single crystalline silicon wafers, majority of which are developed by the Czochralski process. This process required material purity of 99.999% but the electrical conduction of silicon in its pure state is low. Therefore, a small quantity of some different material such as boron or phosphorus, are added to improve the electrical conductivity capacity of the material. Whether the silicon becomes p-type of n-type, it depends on the material added to the mixture.

The colour of a monocrystalline solar cell is usually dark blue or black depending on the anti-reflexive treatment that it receives. Fig. 9 shows how a typical monocrystalline solar cell and panel look like.

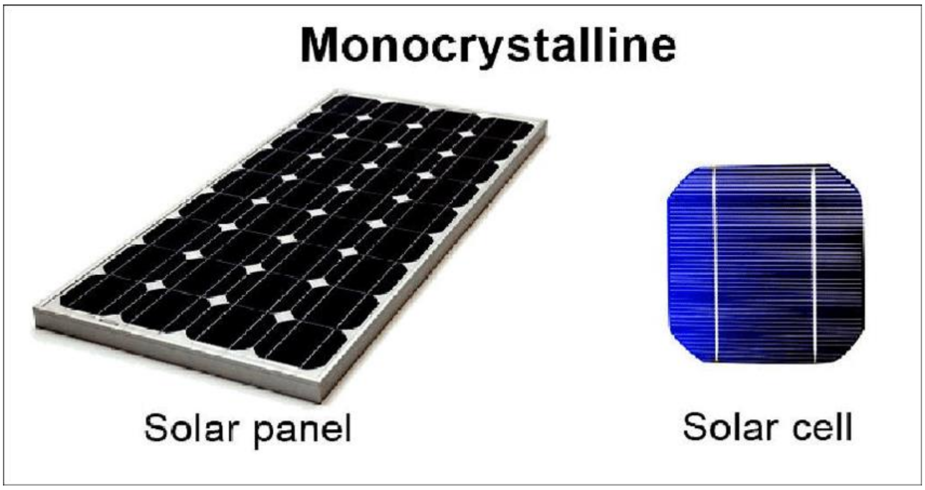

Figure 9: A monocrystalline solar PV panel(left) and a solar cell(right) [46]

A typical woking solar cell consists of the following three elements

- There is an absorber for absorbing the incoming photons and to convert that energy into a charged carrier's excited state. Usually, a semiconductor material such as silicon is used as absorber. During the absorption process, an electron gets transferred into the conduction band thereby leaving a hole in the valence bond.
- Existence of a membrane that forbids any kind of recombination of an excited carrier to its ground state. In the current technology there is a p-n junction which gets formed by adjacent areas of p and n semiconducting layers.
- There are contacts that makes collection of carriers and interconnection with other solar cells or a load possible.

Fig. 10 shows the structure of a monocrystalline solar PV cell. The blue coloured pyramid shaped structures represent the antireflection coating (ARC) layer whose function is to lessen the reflection of light thereby increasing the absorption of those incoming photons into the absorber and increasing the length of path of those incoming photons inside the absorber layer. For the formation of this ARC layer, often silicon nitride (SiN_X) or titanium dioxide (TiO_2), is used. The top layer doped with phosphorous forms n-type layer and a p-n junction is formed. At the front surface, there is a layer of sintered silver (Ag) paste that punches through the ARC layer. This silver layer ensures transportation of carrier efficiently and low shading. There are bus bars and contact fingers used. The main function of the bus bar is to collect current from the contact fingers. The contact fingers are located perpendicular to the busbars. These contact fingers offer low contact resistance to the underlying n-type Si surface. It also offers great lateral conductivity for transportation of carrier efficiently. The posterior side is usually fully metalised. A small portion of this metal posterior end is used as contact pads which is composed of thick Ag paste. Their main function is to collect current from the metalised part and to facilitate for a high conducting electrode. The remaining area of the posterior side includes a multi-layer area which is surrounded by a non metalised area. The metalised area in the posterior end which has Si surface is doped with Al and on top of this layer is a eutectic layer. On top of this eutectic layer there is sintered Al paste layer with diffusion of Si. This area mainly helps to reduce contact and lateral resistance and by implementing a back surface field (BSF) it helps in passivation of the posterior side.

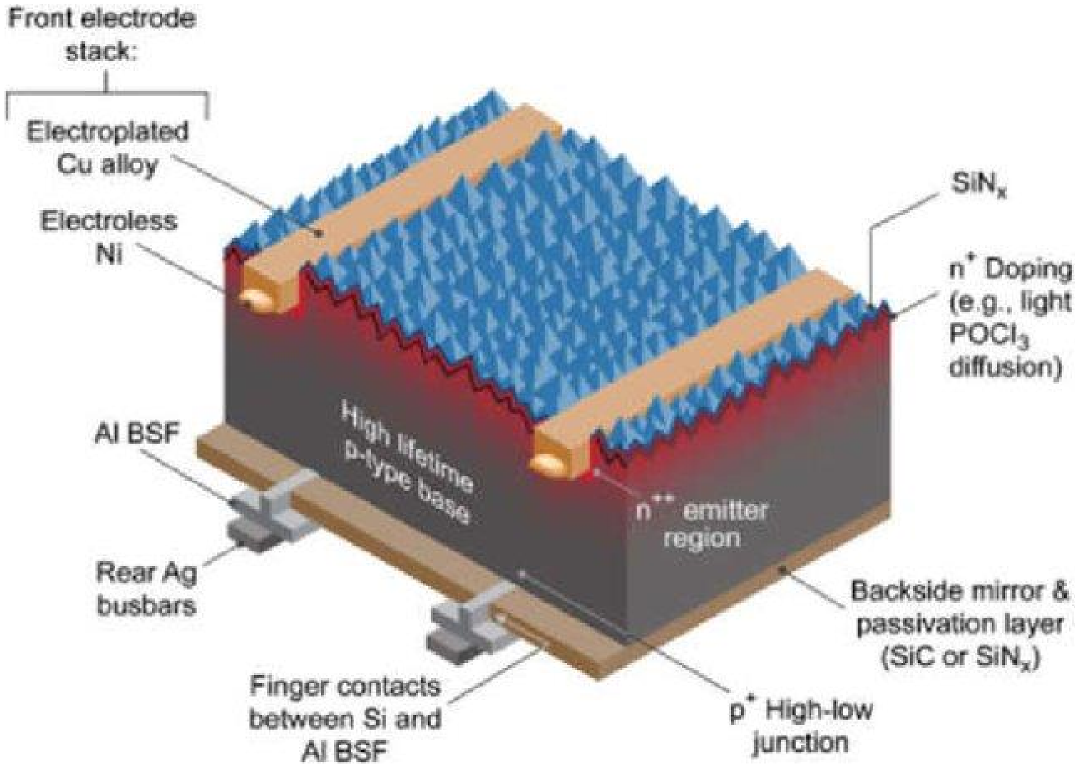

Figure 10: Structure of a monocrystalline solar PV cell [48]

The efficiency of monocrystalline solar cells is dependent on optical losses and carrier losses. Less absorption of the incident light results into optical losses.

The ways to reduce the optical losses are as follows

- Having ARC layer
- Having a back surface mirror or reflector
- Texturizing of surface

All the above stated methods help in reducing optical losses. Fig. 11 shows a comparison of the surface reflection from a silicon solar cell with and without using anti-reflection coating. As seen from the graph the bare silicon has surface reflection of over 30%. ARC on solar cells consist of a thin layer of dielectric material whose thickness is chosen so as the wavelength of the dielectric material remains one quarter the wavelength of the incoming wave.

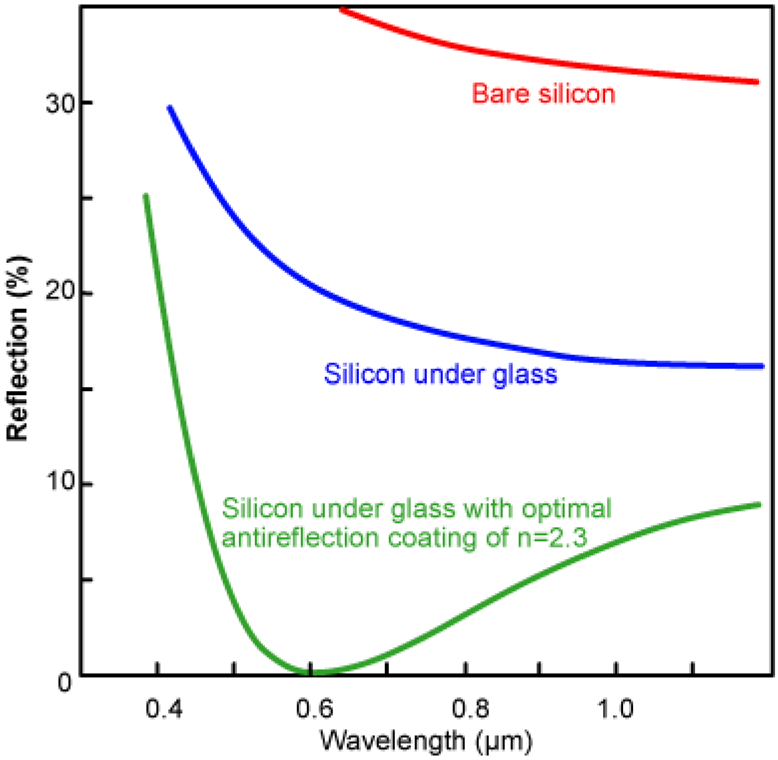

Figure 11: Comparison of surface reflection from silicon solar cells with and without anti reflection coating [50]

The efficiency of a solar cell is affected by losses of carrier recombination. So, for the p-n junction of the solar cell to trap all the photo generated carriers, losses due to surface and bulk recombination should be minimised. The carrier should be generated within a diffusion length of the p-n junction of the solar cell so that it can diffuse to the junction before recombining

The quantum efficiency of a solar cell is shows in the fig. 12. The quantum efficiency of a solar cell measures the recombination effect on the current generated by the incident light. Due to the losses by carrier recombination, the short circuit current and open circuit voltage is perturbed.

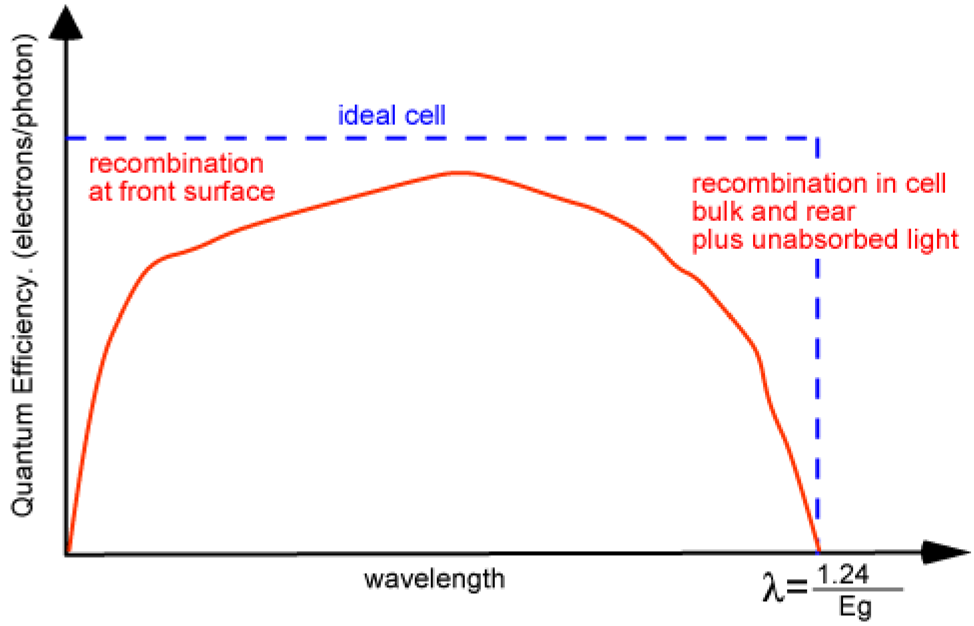

Figure 12: Comparison of quantum efficiency in an ideal and an actual solar cell [50]

By reducing the cost of manufacturing and by increasing the efficiency of the solar cell, the cost of the solar modules can be reduced. To increase efficiency of a solar cell, the BSF is used and the wafer thickness along with the properties of the emitter is taken into consideration. The thickness of the silicon wafer is the reason behind making solar cells so expensive. The efficiency of monocrystalline solar cells is increased by decreasing the thickness of the silicon wafers used.

3.2 Polycrystalline Technology

As compared to the monocrystalline technology, the efficiency levels are low in case of polycrystalline technology. However, the manufacturing costs of polycrystalline cells are lower than monocrystalline cells. Polycrystalline cells have the ideal geometry during the production process; therefore, they use the space in the module better. Typical polycrystalline module is blue in colour but then again it depends on the anti-reflexive method what the shade would be. Fig. 13 shows what a typical polycrystalline module in the left and polycrystalline cell in the right would look like.

Figure 13: Picture of a polycrystalline module(left) and a cell(right) [51]

Refining of crystalline silicon using carbon based reducing agents form metallurgical grade silicon. This metallurgical grade silicon gets processed further either by the Siemens process which involves decomposition of trichlorosilane by chemical vapour deposition (CVD) technique using a fluidized bed reactor or by chemical refinement process to obtain polycrystalline silicon. Different types of crystalline silicon ingots can be produced from the polycrystalline silicon. Polycrystalline silicon ingots are a less expensive alternative but with structural defects, residues, and impurities they have lower efficiency rate.

The polycrystalline silicon ingots have defects entering them through different ways. During crystallisation, there is higher concentration of impurities at the top of the silicon ingot. There is higher concentration of impurities at the edges of the ingot when the system cools down. During crystallisation and the cool-down, structural defects such as dislocation clusters and grain boundaries are also formed. The structural defects can be controlled by grain engineering. This results in reduction of dislocation growth thereby improving cell performance.

With the cell efficiencies increasing above 20% significantly, the demand of low-cost polycrystalline silicon wafers shifted towards high quality monocrystalline silicon wafers. Therefore, the market share of silicon wafers for polycrystalline silicon has fallen from 60% in the year 2017 to about 32% in the year 2019.

3.3 Half-cell Technology

Half cells are produced by cutting monocrystalline or polycrystalline solar cells exactly in the centre by laser. Fig. 14 shows the difference between a half cell and a full cell.

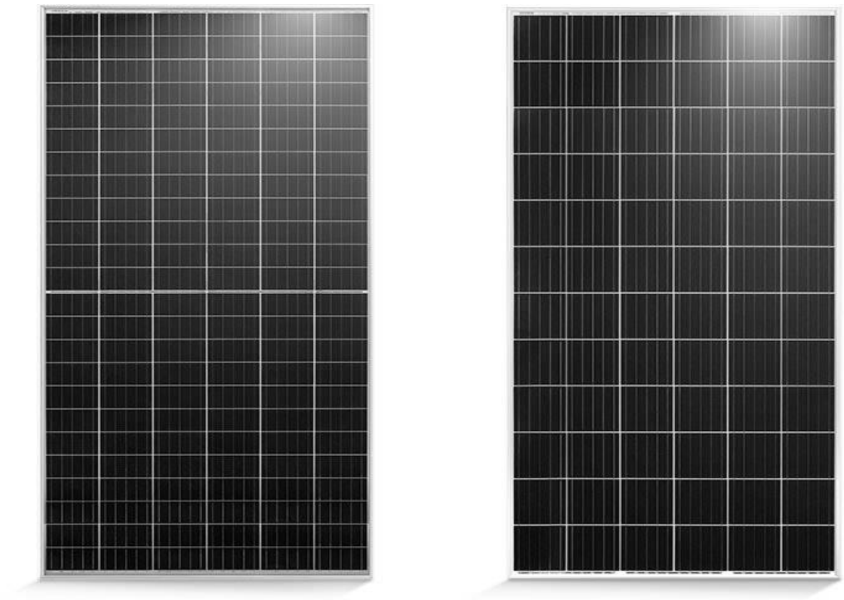

Figure 14: Picture of a half cell (left) and a full-sized cell (right) [54]

In this technology, the internal losses have been reduced by using half cells. So, with usage of half cells, the flow of current in each bus bar is also halved. Now the relation between current and electrical loss goes like one in below,

Electrical Losses = I^2 *R

So, from this relation, since the current gets halved so that results in making the internal losses get 1/4th of a full cell module. This automatically increases the efficiency of half-cell modules. Another advantage of half cells over complete cell being less prone to cracks caused by mechanical stress owing to their small area. The half-cell modules use serial-parallel-serial (SPS) connections which allow them to respond better to shading since one half of the module is not affected by the other.

Fig. 15 shows the arrangement of a half cell module in rows. In general, there are three rows of cells in typical solar panels. In serial connection, when a single cell in a row experiences shading then the row containing the entire shaded cell stops producing power. So, in general, with three rows of cell the productivity will decrease by one third. In case of half cells, cutting of cells in the centre results into a doubling of the number of solar cells on the solar panel which in turn leads to doubling of the number of rows. So instead of three rows there are six rows in a half cell module. Shading of one cell from one of the six rows decrease the productivity by one sixth.

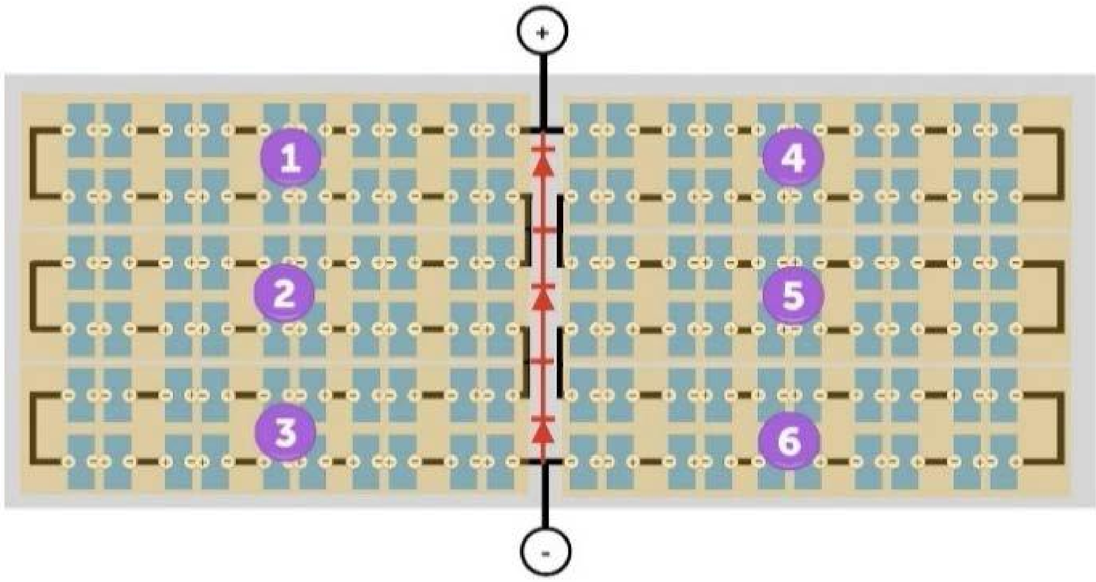

Figure 15: Connection arrangement of a half cell module [55]

It is usually not considered a good idea to have half of connected cells serial as in normal cell panels due to uneven voltage generation by the plate. However, for a functioning of a half cell plate the connection must be done such that instead of connecting 120 cells in a row, the plate gets divided into two groups and each group consists of 60 cells each. Each of these groups operate at a voltage of 30 V. The plate voltage is same as the voltage value of one group which is 30 V because of the two groups being connected to the branch.

3.4 Double glass Technology

It is a frameless solar module which has a solar cell layer in between two heat strengthened glasses instead of the traditional polymer back-sheet. This way of designing allows more sunlight to pass through thereby decreasing moisture hazards such as delamination, ethyl vinyl acetate (EVA) encapsulant degradation thereby increasing the mechanical strength and durability of the module. The frameless design reduces the risk of any potential induced degradation (PID). Fig. 16 represents the structure of a typical double glass PV panel.

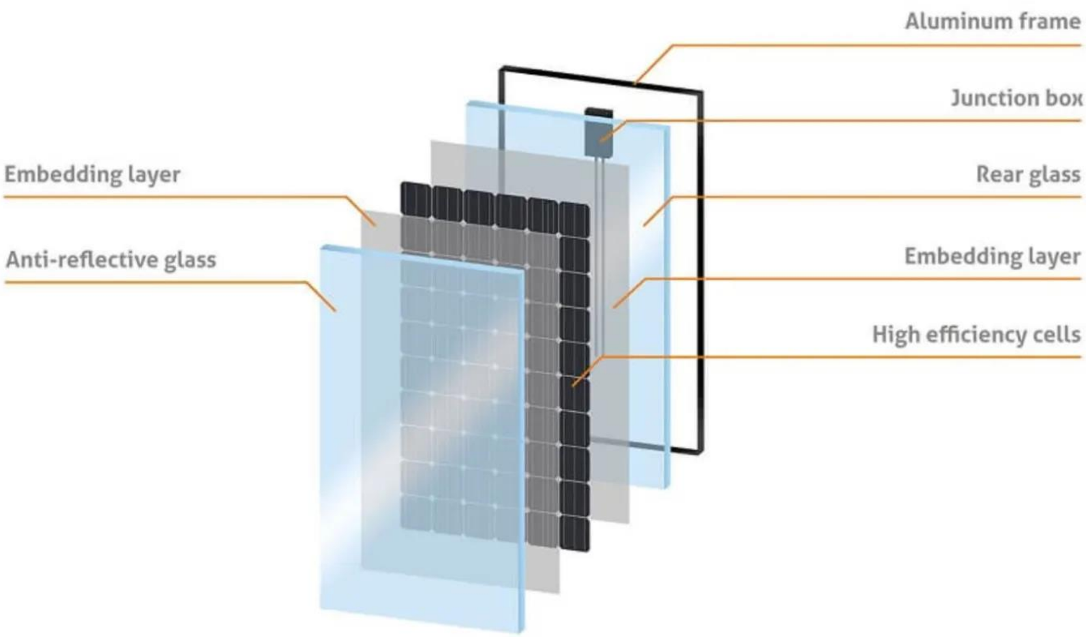

Figure 16: Structure of a double glass PV panel [56]

Using double glass material makes it heavier and more expensive than the traditional polymer back sheet yet the advantages of the technology outweigh the disadvantages. Fig. 17 shows the world's market share of double glass versus other materials used as cover materials in the PV modules. As per ITRPV's predictions, the world's market share of using double glass material will increase up to 30% by 2029.

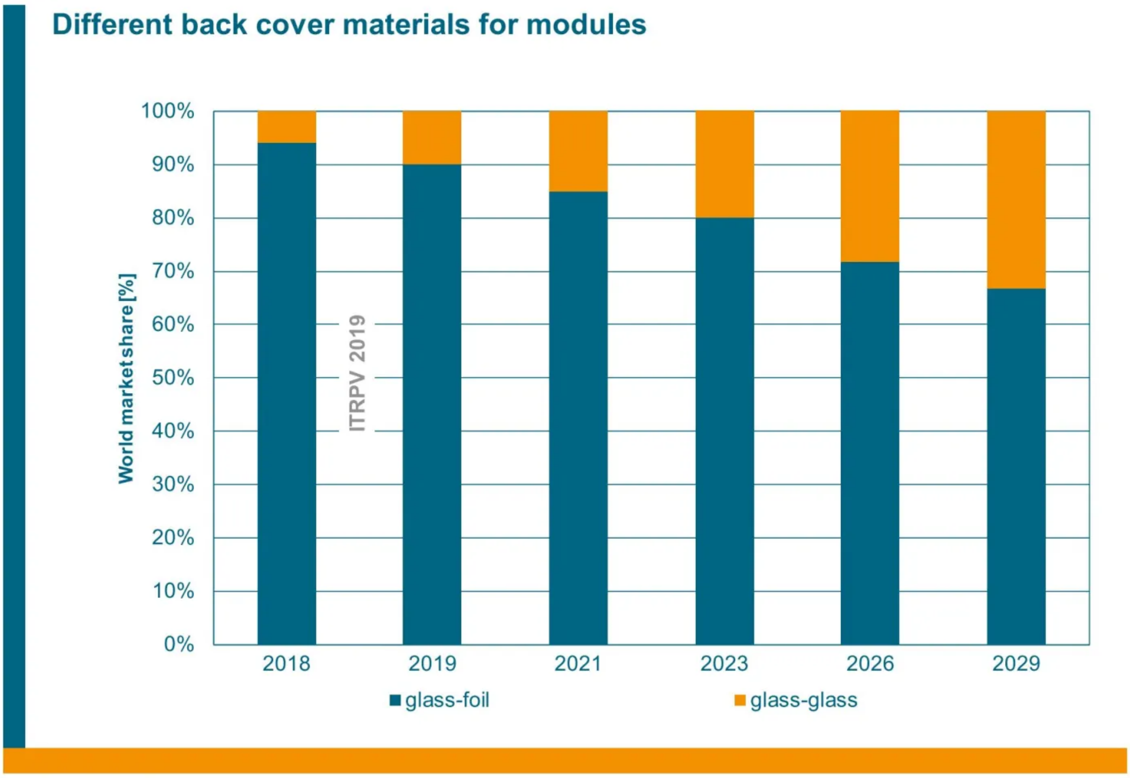

Figure 17: World's market share of double glass versus other materials as back cover materials for modules [56]

Double glass PV technology is suitable for utility scale PV projects because they offer greater resistance to humidity, UV conditions and higher temperatures. They also offer great mechanical stability thereby ensuring greater lifetime of modules. Usually, the glass used for double glass modules have thickness around 2mm and are as heavy as standard panels. The durability of these glass sheets is quite high and does not get dented when hit with a hammer. Fig. 18 shows market share of different front glass thicknesses used for PV modules. Majoring of the front glass used for modules have thickness of more than 3mm. Use of thin glass is still not commercially mature.

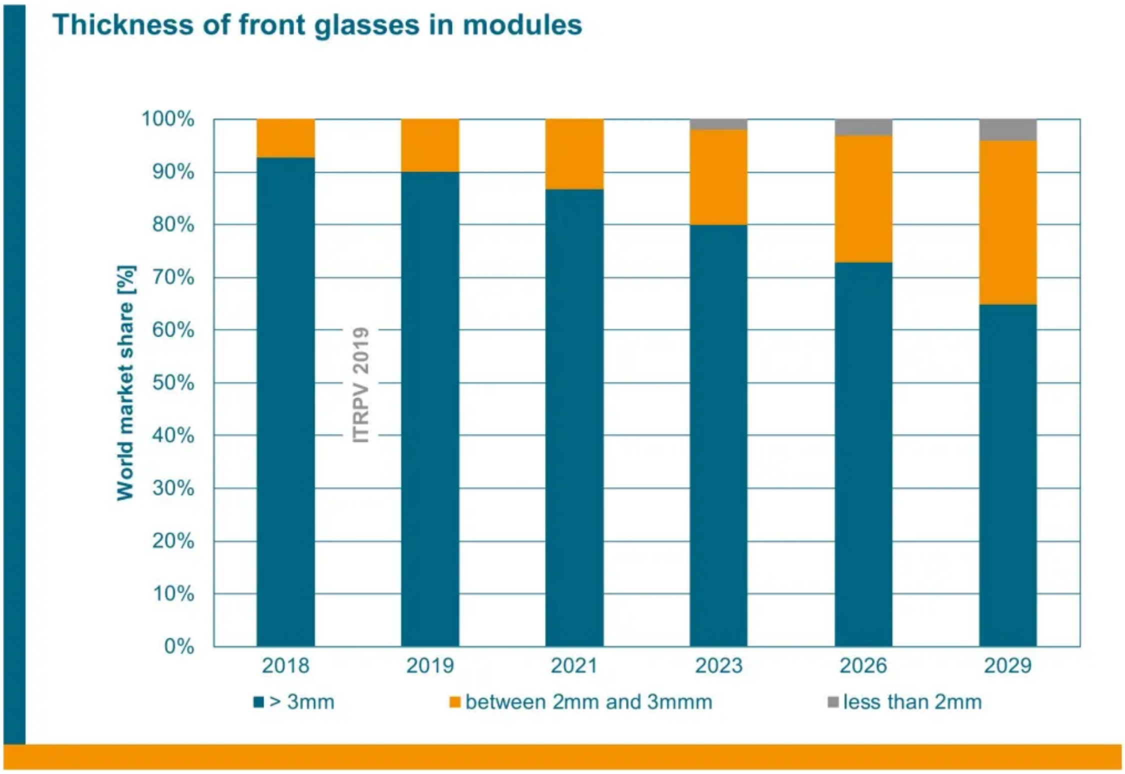

Figure 18: World market share of different front glass thicknesses for PV modules [56]

In double glass technology, polyolefins are used as an encapsulant instead of EVA. During cross linking process of EVA, free radicals are produced which can enter from sides of double glass module. Moisture also can enter and get trapped inside the double glass modules. So double glass is non-permeable to such degrading factors unlike the traditional polymer back sheet which is permeable. Problem of free radical is solved using polyolefins, but the issue of moisture stands as a major argument against using double glass PV technology.

3.5 Bifacial Technology

While conventional PV modules are designed with a non-transparent sheet at their rear end, bifacial PV modules have transparent sheet and use bifacial solar cells. So, while conventional PV modules are only capable of absorbing solar irradiance only from the front side, the bifacial PV modules are capable of absorbing solar irradiance from both sides and harvesting energy from ground reflections. Fig. 19 represents the difference between conventional PV modules and bifacial PV modules. A very important characteristics influencing the performance of bifacial PV module is the reflectivity of the ground which is measured as albedo. Using bifacial PV technology is very useful in areas experiencing significant snowfall due to increased albedo during those periods.

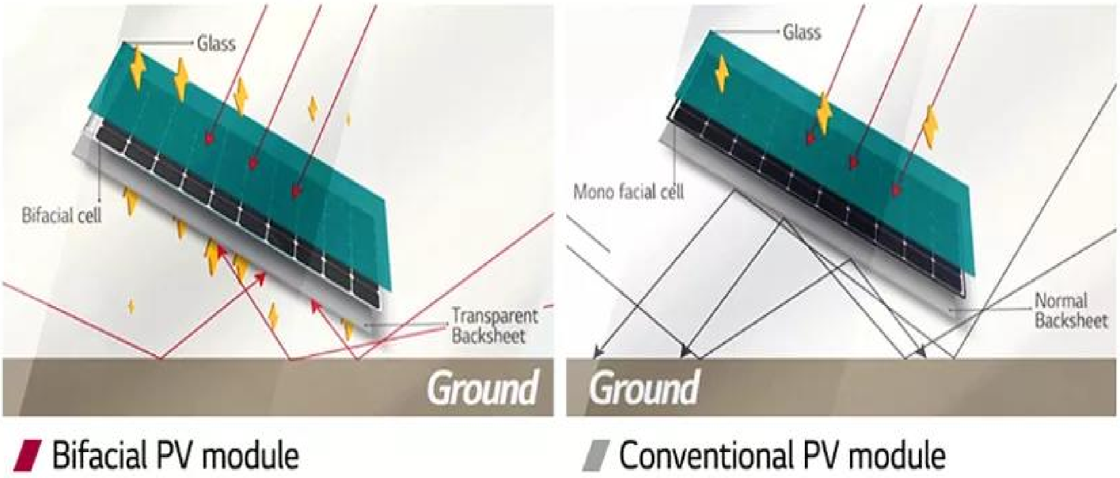

Figure 19: Design difference in a bifacial PV module and a conventional PV module [59]

Albedo is the measure of the fraction of incident sunlight that gets reflected from a surface. Value of albedo is not constant for a given surface since it depends on the angular and spectral distribution of sunlight. Surface conditions such as surface roughness, etc also influences the albedo.

Bifacial gain is also an important terminology in bifacial PV system. Bifacial gain is the extra energy produced by a bifacial PV system compared to monofacial system of similar orientation and size.

Currently, 90% of the bifacial PV modules are glass-glass or double glass modules. Due to breakage of glass, the frameless double glass modules changed to the ones with frames.

According to ITRPV, world PV cell market share of bifacial cells as of 2020 is about 20% which is predicted to increase to 70% by 2030. Due to an increase in the demand of bifacial PV modules in the market, new strategies are being developed to improve the performance without compromising the reliability or increasing the manufacturing cost. One such strategy is pairing of bifacial PV cells with a white reflective back encapsulant. As compared to backsheets or transparent encapsulants, white encapsulants have higher reflectivity and a shorter reflection pathway.

However, bifacial cells and modules can experience light and elevated temperature induced degradation (LeTID). Rear side potential induced degradation may occur when the ARC gets exposed to the back side of bifacial modules. [58]

Bifacial cells come in various forms such as PERT, PERC, HIT, etc.

3.6 Passivated Emitter Rear Cell Technology

With passivated emitter rear cell (PERC) technology the problem of wastage of solar irradiance gets solved to some extent. In a conventional crystalline solar cell, all the radiation that's incident is not absorbed by the silicon cell. Some of the radiation passes the silicon layer and goes all the way till they reach the polymer backsheet in the end of the cell. To reduce this wastage of energy, a dielectric layer is coated which remains in between the silicon and the backsheet. This dielectric layer reflects any irradiance that may have surpassed the silicon layer thereby increasing the efficiency of the cell. Fig. 20 shows the difference between a normal solar cell and a PERC cell.

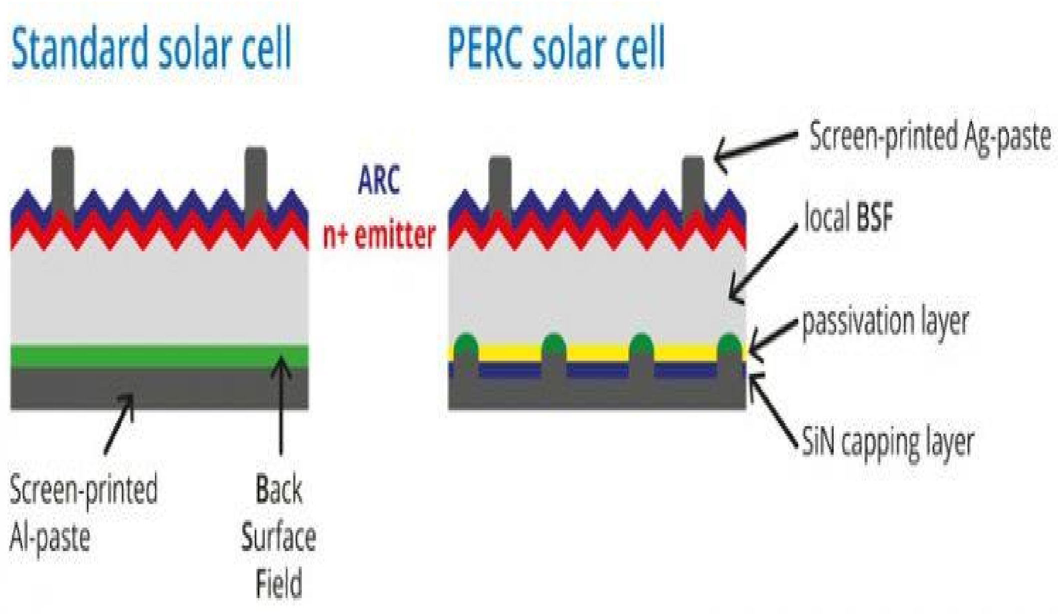

Figure 20: Represents the difference between a standard crystalline solar cell and a PERC solar cell [60]

According to ITRPV, 50% of the world PV market is PERC as per 2019 data. While monofacial PERC cells have their upper limit of efficiency around 22.5%, making PERC cells bifacial ($PERC_+$) helps to improve the power output. To convert a monofacial PERC cell into a bifacial $PERC_+$, the rear Al screen-print area needs to be replaced with Al finger grid screen design. Fig. 21 shows how a bifacial $PERC_+$ cell differ from monofacial PERC cell. There is a reduced screen print metallisation at the rear end of bifacial $PERC_+$.

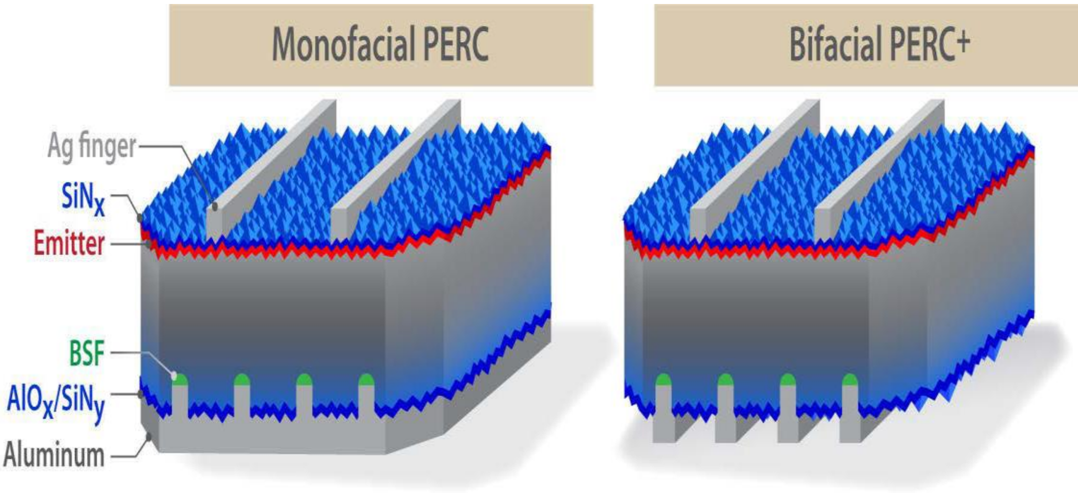

Figure 21: Difference between a monofacial PERC and bifacial PERC+ [61]

3.7 Hetero-Junction Technology

Fig. 22 shows the basic structure of a hetero-junction technology (HJT) cell. In general, HJT cells have n-type mono-Si wafers because HJT cell production does not involve high temperature treatment that would help in impurities gettering and boron-oxygen defects deactivating. In HJT cell structure, intrinsic a-Si provides surface passivation which is deposited on both sides of the wafer with plasma-enhanced chemical vapour. It also provides for carrier selectivity on top. n and p type doped intrinsic amorphous silicon layers when applied to opposite sides of the wafer, adds electrical connections to the electron-hole pair in the wafer. By using carrier-selective passivating contacts, the re-combination related losses in conventional solar cells are reduced using HJT. These carrier-selective passivating contact structures also offer carrier selectivity and surface passivation in areas of high recombination active direct contact between the metallization and the silicon absorber.

The concept of HJT has been developed and patented as hetero junction with intrinsic thin layer (HIT) by Panasonic Corporation.

HJT technology has the following advantages

- Low temperature coefficient
- Reduced costs due to compatibility with thin wafers
- High bifaciality potential (above 92%)

A significant limitation of HJT technology being the parasitic optical absorption in the intrinsic a-Si layers and in the transparent conductive oxide layers that presents a compromise between J_{sc} and V_{oc} of cells.

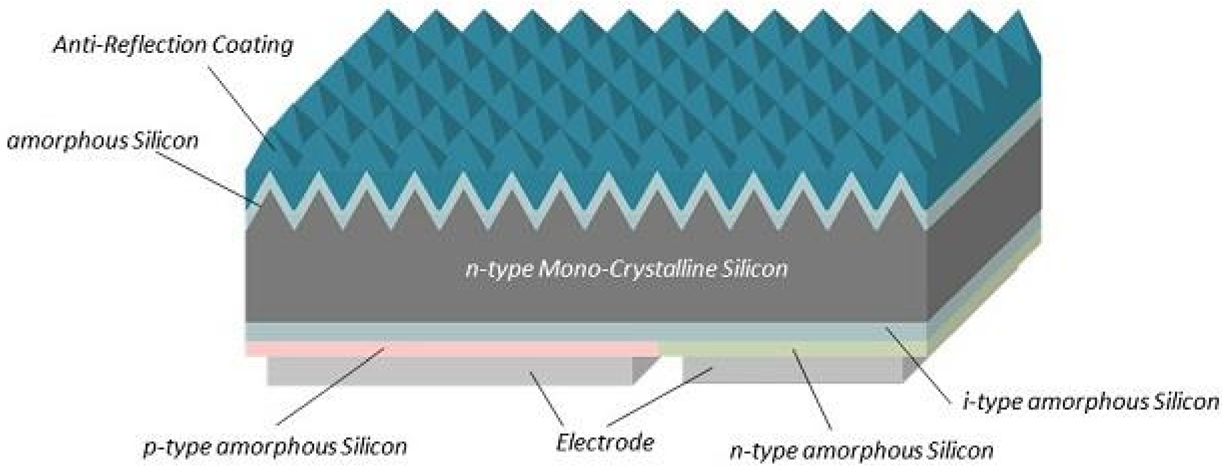

Figure 22: Structure of HJT cells [62]

4. THIN FILM TECHNOLOGIES

Thin film technologies involve flexible pairing of PV materials. It is a second generation technology that involves single or multiple layers of PV elements on a metal substrate, glass, or plastic. The basic difference between thin film solar cells and c-Si cells can be discussed as follows

- Thin film collar cells are cheaper than the mature c-Si solar cells.
- Thin film solar cells are easier to handle as compared to the c-Si solar cells.
- c-Si solar cells have higher efficiency than thin film solar cells.
- There is dissimilarity between thin film solar cells and the c-Si cells in terms of flexible pairing of PV materials.

In thin film PV cells, mostly the following absorber materials are used: a combination of a-Si and µc- Si, a compound semiconductor made of CdTe, a compound semiconductor made of CIGS which are only a few micrometres thick. Since those PV cells made with the above-mentioned materials are only a few micrometres thick, they are called as thin film PV cells. The manufacture of c-Si modules differs fundamentally from the thin film PV modules. The so-called absorbers in thin film PV modules, get deposited on substrates. The substrate mostly constitutes of glass panes. So unlike silicon wafers, these absorbers in thin film PV modules are not self-supporting. The difference between thin film PV module structure and c-Si module structure has been portrayed in fig. 23. In thin film solar PV modules, instead of individual cells, the already connected interconnected cells are processed. The absorber with the surfaces in contact and all the additional in-between layers are placed on vast glass panes in an integrated manner and then all the layers get laminated under a second glass pane forming a complete solar PV module.

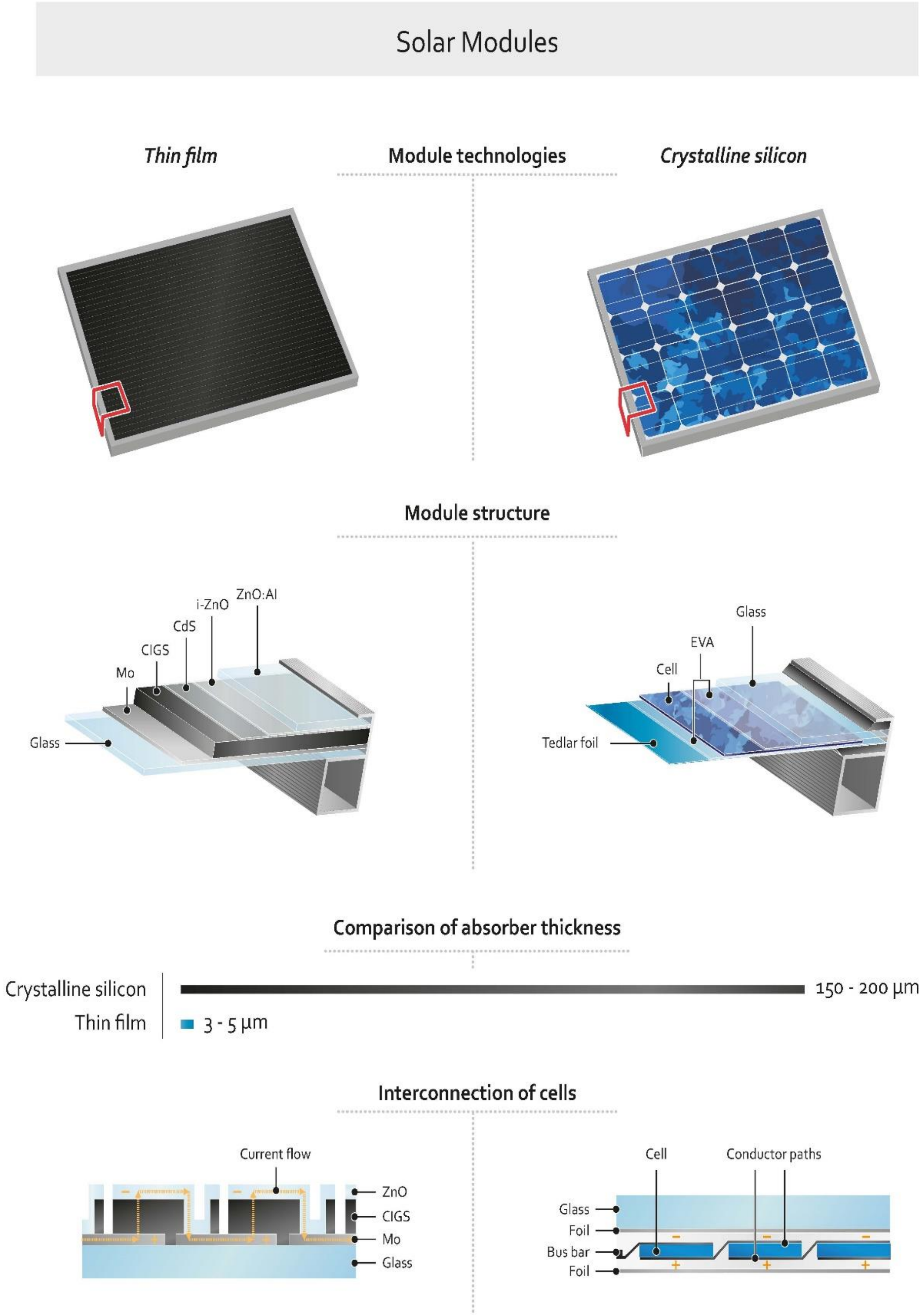

Figure 23: Comparison of solar module structures made from wafer based c-Si and thin film technology [63]

Three main thin film PV technologies that are commercially mature are a-Si, Cadmium Telluride (CdTe) and Copper Indium Gallium diSelenide (CIGS).

3.8 Amorphous Silicon Technology

During the 1980s, a-Si was the only thin film technology used. Amorphous silicon is the non-crystalline form of silicon which has a very high optical absorption coefficient in the visible spectrum range as compared to the crystalline silicon. It has a high band gap of 1.7 eV which makes high absorption of light possible. Among other thin film cells, a-Si PV cells use the least quantity of materials but it also has the least efficiency rate.

Hydrogenated a-Si [a-Si:H] started getting used as semiconductor material during 1970s. To reduce the recombination losses, a-Si:H solar cells use the p-i-n structure, but an n-i-p structure can be fabricated as well. This p-i-n structure consists of a p-type doped thin layer, then a photovoltaically active central intrinsic i-type layer and then a p-type doped thin layer. Fig. 24 shows the layout of a triple junction a-Si:H/uc-Si:H/uc-Si:H solar cell.

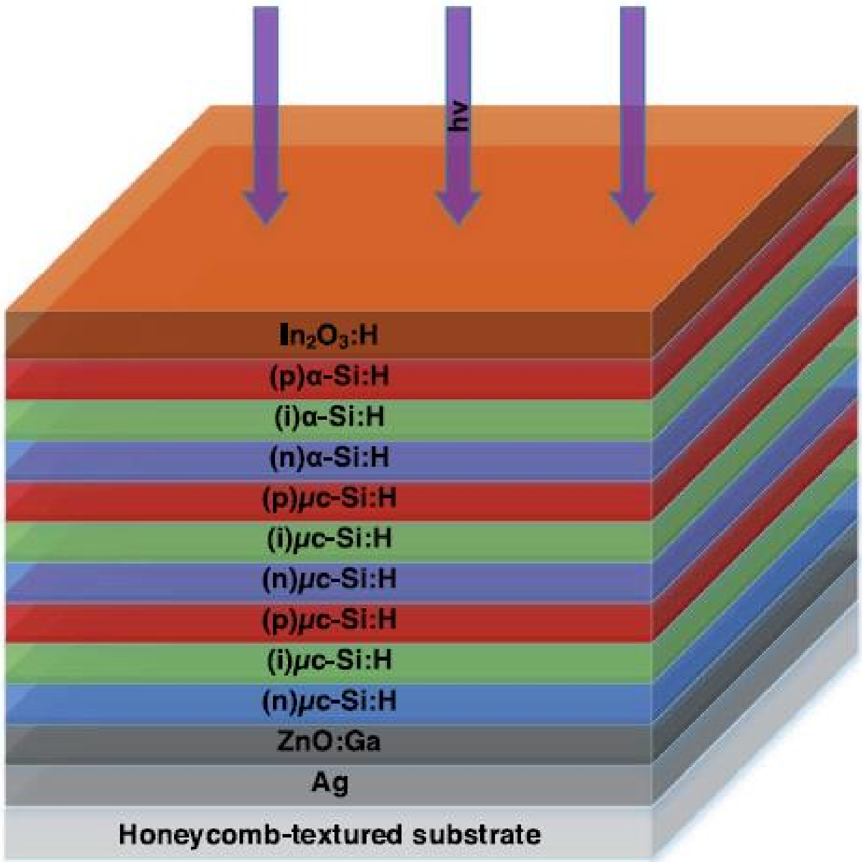

Figure 24: State of the art of a triple junction a-Si:H/uc-Si:H/uc-Si:H p-i-n solar cell [64]

For single junction usually a random crystal structure gets developed on fluorine doped tin oxide [SnO_2:F] glass substrate or then for micromorph tandem structure on honeycomb textured substrate [HTS]. Usually, to increase conductivity and reduce reflective loss, Ag and Ga doped Zinc oxide coatings are applied successively on the substrate. The a-Si layers get deposited in the solar cells by the PECVD. So, the hydrogenated a-Si [a-Si:H] gets deposited by plasma enhanced chemical vapour deposition (PECVD) with dopant gases such as H_2, SiH_4, PH_3, CO_2, B_2H_6. Next step involves depositing transparent conducting oxide (TCO) film by radio frequency (RF) magnetron sputtering. This TCO coating remains in the front and is made of Indium tin oxide [In_2O_3:Sn] or hydrogenated indium oxide [In_2O_3:H][IOH]. Ag can be positioned as the grid electrode and to improve the cell's performance an ARC coating can be placed.

The laboratory efficiency of single junction and multi-junction a-Si cells has been marked in fig. 25. During the early 1976, the efficiency of single junction a-Si cell was recorded to be 2.4%. There has been much progress ever since and in the year 2015, the reported cell efficiency for single junction a-Si in the laboratory was around 10.22%. The efficiency of multi-junction a-SI cell in the laboratory was reported to be around 11% in the year 1992. Laboratory efficiency of multi-junction a-Si cells were reported to be about 14.04% around the year 2016. [64]

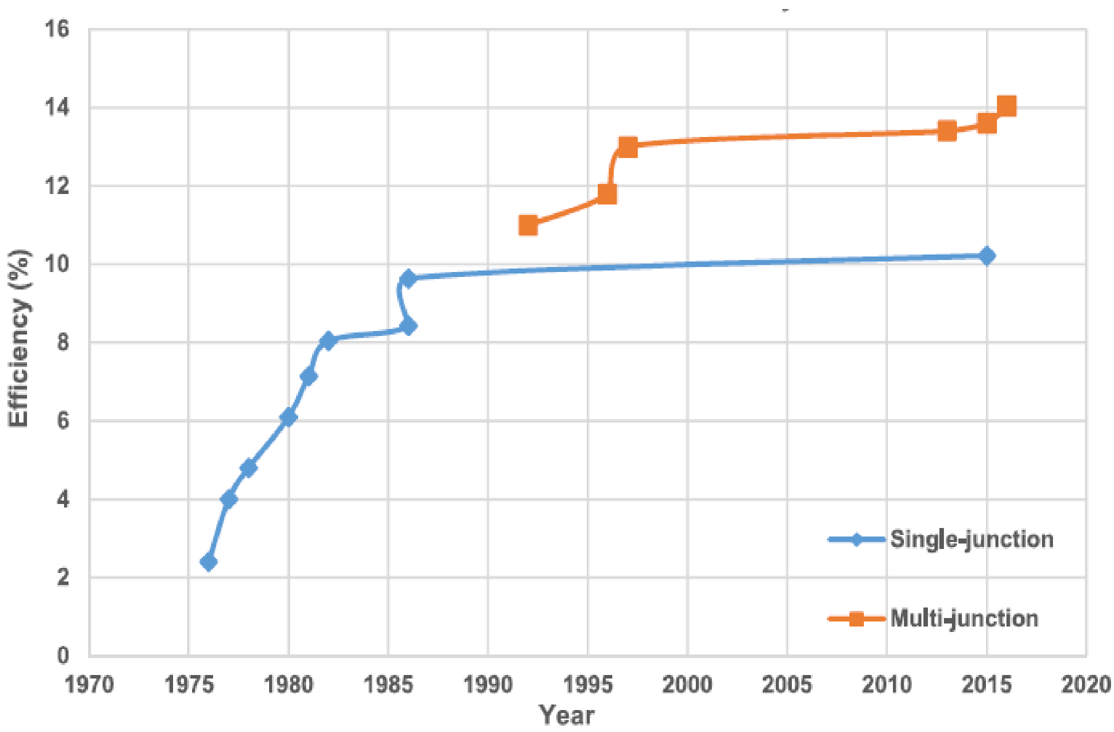

Figure 25: Laboratory efficiency of single and multi-junction a-Si cells [64]

Even though, using PECVD allows for deposition of large areas but for large scale manufacturing for commercial purposes the deposition rate is low resulting in high deposition time.

The optoelectronic properties of the front TCO component needs to be improved to resolve the light scattering properties.

The efficiency of a-Si cells is low. One of the main reasons of the low efficiency of a-Si modules being the Staebler-Wronski effect (SWE) which refers to light induced degradation resulting in decreasing efficiency to a steadied but low value after approximately 1000 hours of illumination. The effects of SWE can be reduced to some extent by diluting the SiH_4 gas during the a-Si deposition using PECVD method by H_2. This SWE is due to formation of new defects. An electron-hole pair is formed in the intrinsic layer by an absorbed photon. Due to the induced electric field across the intrinsic layer, there is drifting of electrons to n layer and holes to p layer. So thinner intrinsic layer could be employed to reduce the additional defects.

3.9 Cadmium Telluride (CdTe) Technology:

After c-Si PV technology, CdTe is the second most popular PV technology in the world. Due to the ability of the CdTe based solar cells to get manufactured easily and inexpensively, they provide the lower cost alternative to the c-Si based PV technologies.

In the beginning, CdTe based solar cells had substrate configuration but in the latest technology, superstrate configuration is the best for higher efficiency.

The structure of a standard CdTe solar PV cell in superstrate configuration has been shown in fig. 26. So, this structure is developed on glass substrates. Heat strengthened SLG is preferably used as substrate in the front. The layer that coats the substrate is the TCO layer which works like a window or buffer layer. This TCO layer is often a SnO_2:F(FTO), ZnO:Al (AZO), Cd_2SnO_4 (CTO), In_2O_3:Sn(ITO). Intrinsic oxides are deposited on TCO and CdS as high resistance transparent (HRT) layers to ensure optimization in the alignment of the energy bands and to avoid shunting of the device. Tin Oxide (TO) and Zinc Oxide (ZO) are the most commonly used HRTs. The n-type CdS layer which works as the buffer layer can be deposited by a number of ways such as Chemical Bath Deposition (CBD), Close-Spaced Sublimation (CSS), Sputtering, Vacuum Evaporation. Then comes the p-type CdTe absorber layer which can be deposited by PVD, screen printing, Metal-organic chemical vapour deposition (MOCVD), Sputtering etc.

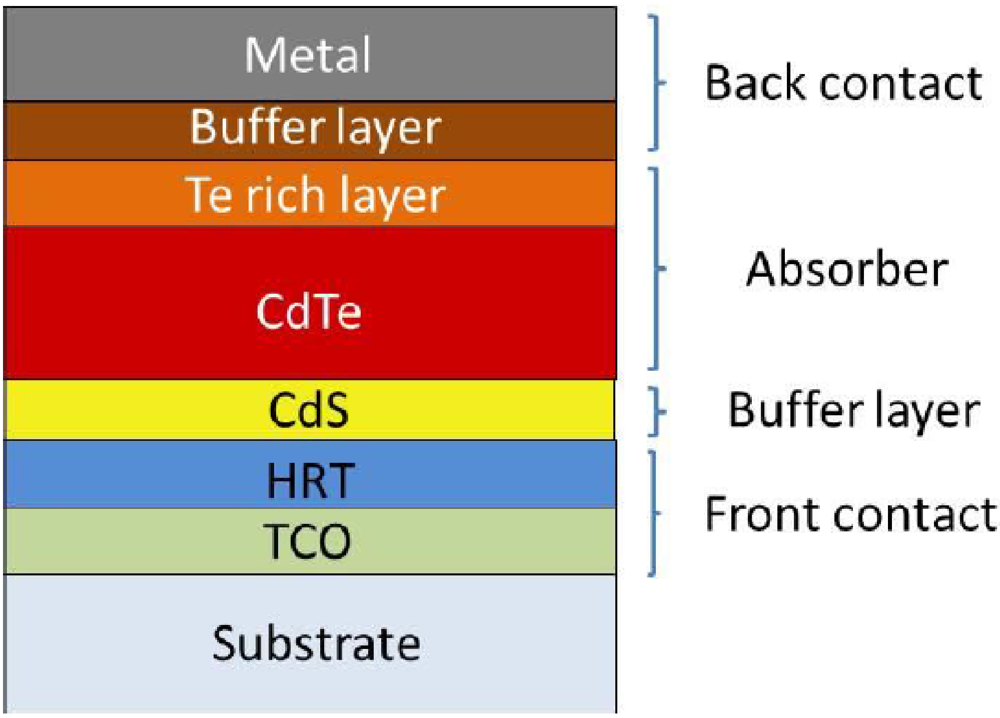

Figure 26: Structure of CdTe solar PV cell in standard superstrate configuration [67]

In the latest technology, the CdTe PV technology based solar cell is laminated between two glass layers which is shown in fig. 27. Among the two glass layers, the second glass layer is usually a heat tempered back SLG. To ensure protection from delamination due to chemical degradation these layers are further coated by EVA which acts as a transparent encapsulate sheet. Then the metal contact is employed which is usually copper doped zinc telluride (ZnTe:Cu). The CdTe layer gets deposited using CSS and undergoes cadmium chloride $CdCl_2$ treatment. Then, the CdS layer get fabricated by vapor transport deposition (VTD).

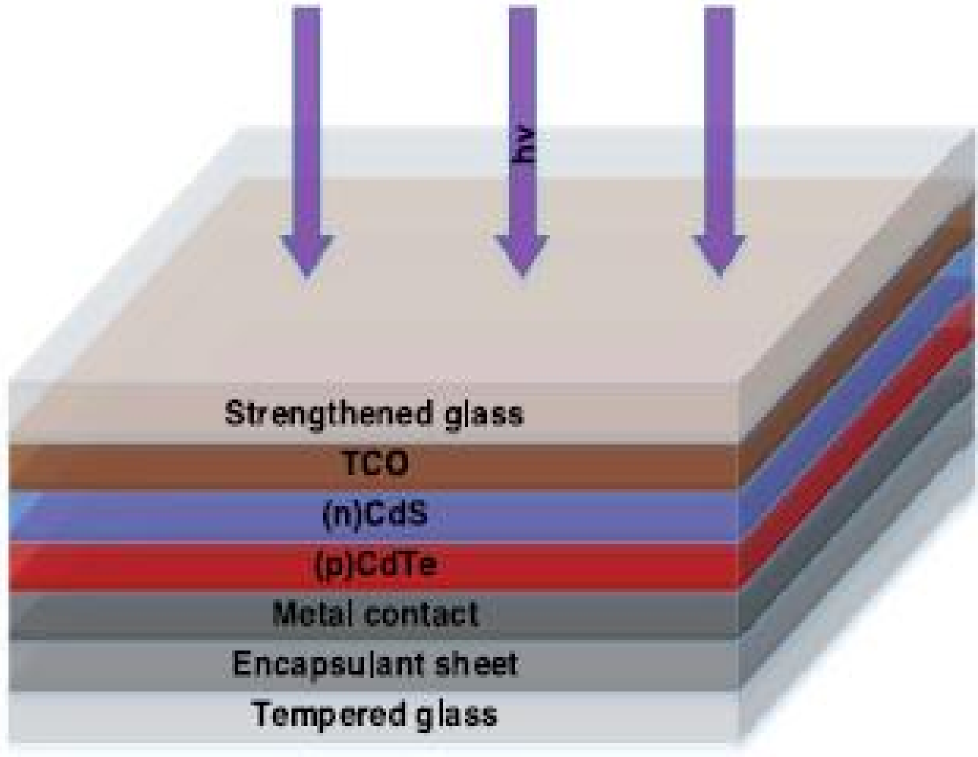

Figure 27: Structure of a superstrate glass-glass CdTe/CdS solar cell [64]

Due to low carrier concentration and short lifetime, achieving high efficiency is a problem using CdTe based PV technology. Even though the CdTe band gap is such that delivering more than 1 Volt is possible but usually the open circuit voltage value of CdTe base solar cells is in the range of 900 mV as confirmed in the very best cases.

There is a problem of material shortage as well. Cd is obtained in abundance when it is produced as a by product of Zn refining. However, Te is obtained as a rare element as a by product of Cu refining. Therefore, there is a shortage of material.

Cd is toxic and carcinogenic. So, it is considered environmentally hazardous. Even though, CdTe as a compound is considered less toxic.

The laboratory efficiency of CdTe solar cells over the years have been shown in fig. 28. Laboratory efficiencies of both superstrate and substrate configuration has been given. During 1972, the first CdTe/CdS solar cell in its substrate configuration reported a laboratory efficiency of 6%. 1976 onwards, the reported efficiency for CdTe solar cell in superstrate configuration ranged from 8.1% to about 22.1% around 2016. [64]

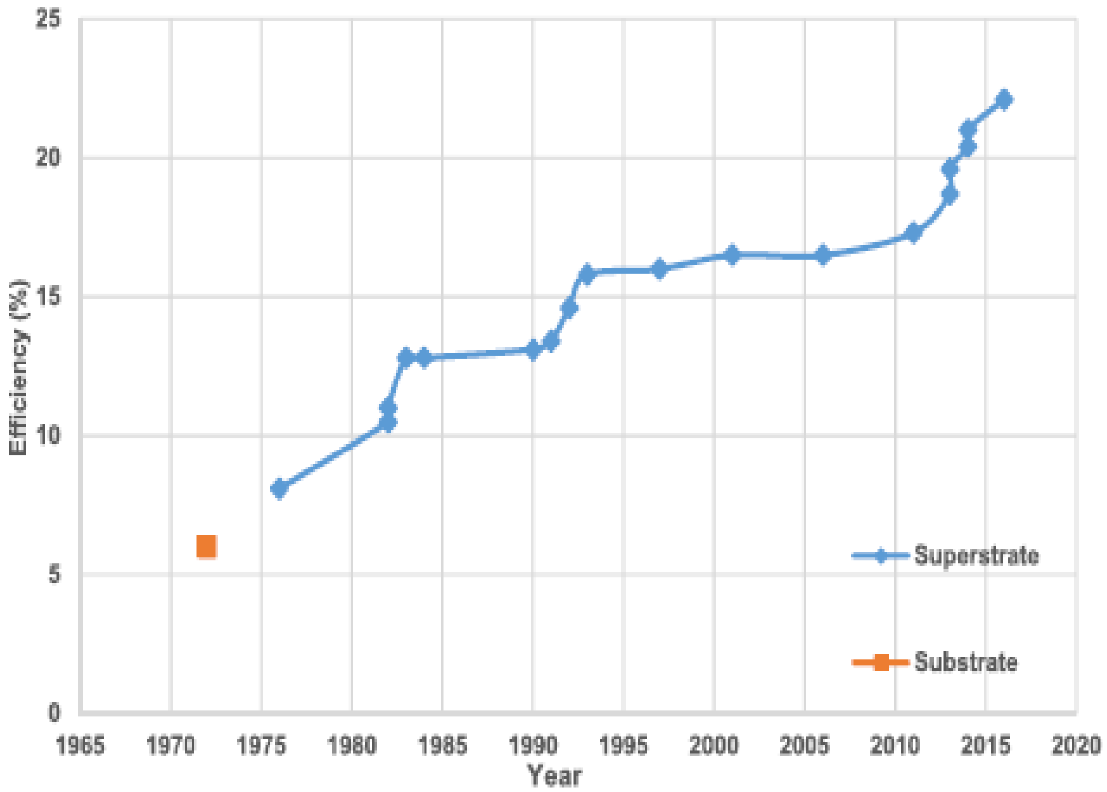

Figure 28: Laboratory efficiencies of CdTe solar cells [64]

3.10 Copper Indium Gallium Selenide (CIGS) Technology

For large scale commercial solar modules, CIGS PV technology based solar modules serve as a high efficiency alternative. CIGS can be deposited on substrates made of polymers, glass, and metal foils. Use of metal foils and polymers make it possible to use applications that needs light weight modules.

Solar cells based on CIGS PV technology has a chalcopyrite crystal structure developed on glass, polymer or metal foils based substrates. As a back contact and reflector, Mo is used which is sputtered on the SLG glass. Next comes the absorber layer which is fabricated with the popular “three stage process”. The absorber layer that is CIGS or $Cu(In,Ga)(Se,S)_2$ which is approximately 2um thick and gets fabricated by PVD. The layers behind the CIGS layers get treated with sulfurization after selenization (SAS) by hydrogen selenide (H_2Se) gas that leads to development of $Mo(S,Se)_x$ film between the back contact and the absorber layer. Sometimes, the absorber layer gets Cs treatment with thermally evaporated CsF and then the buffer layer or the CdS layer gets developed through CBD. In the latest technology in order to improve performance, a second buffer layer of ZnO:Mg which is approximately 50nm thick gets fabricated by atomic layer deposition (ALD) gets fabricated on the first buffer layer which could be CdS or Cd free $Zn(O,S,OH)_x$. Fig. 29 demonstrates the state of the art of a double buffer CIGSSe solar PV cell. For the TCO layer, B-doped ZnO (ZnO:B) gets deposited using MOCVD technique. When Al-doped ZnO (ZnO:Al) is used as TCO layer on the CdS layer then CVD method is used to avoid any external damage. For making the electrode and the ARC, the Al and magnesium fluoride ($MgFl_2$) gets evaporated by using electron beam evaporation method.

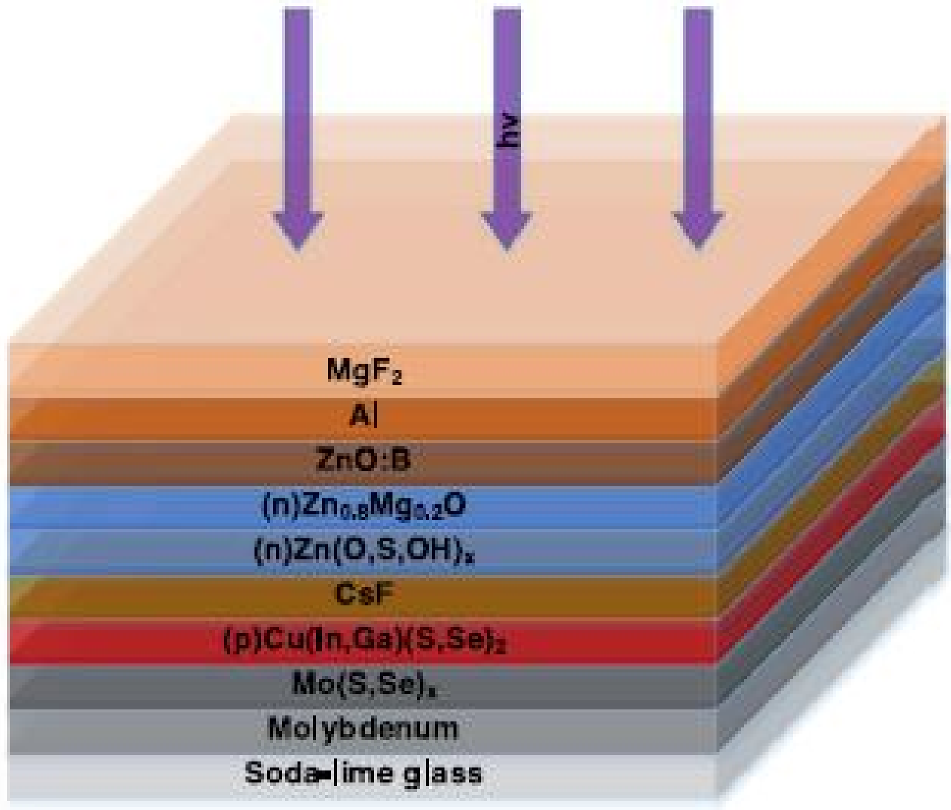

Figure 29: Structure of a double buffer CIGSSe solar cell [64]

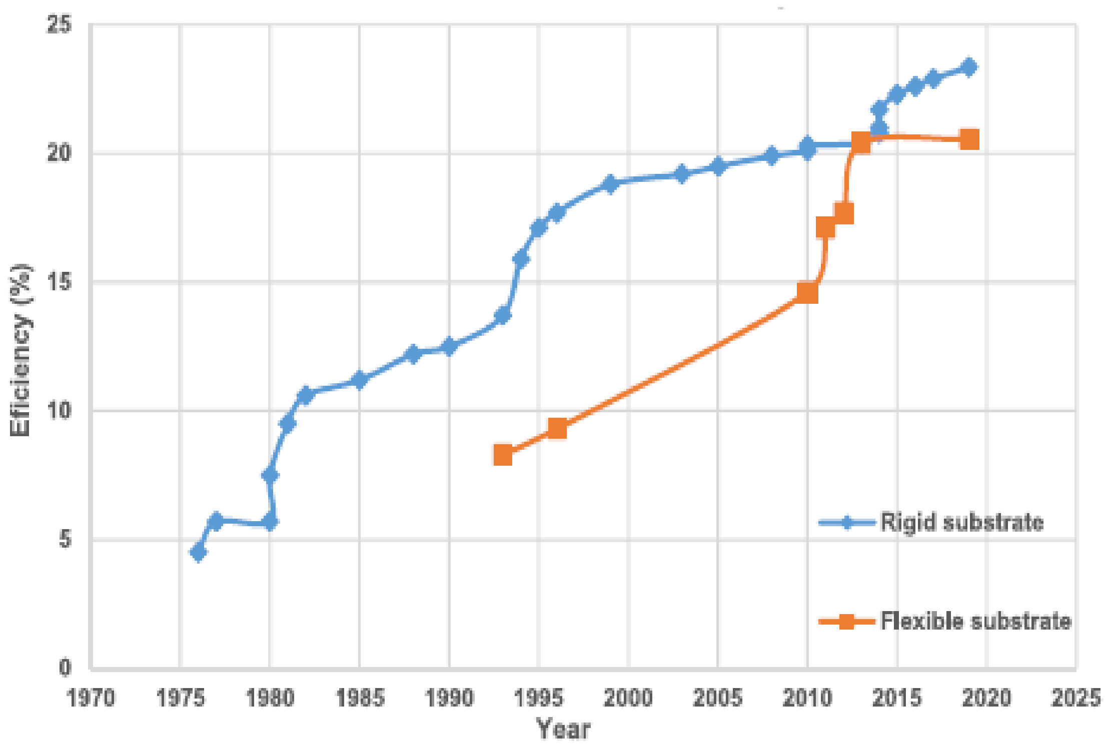

Figure 30: Laboratory efficiencies of CIGS PV solar cell [64]

The laboratory efficiencies of CIGS based PV cells have been shown in fig. 30 where both rigid substrate and flexible substrate has been taken into consideration. Clearly the rigid substrate was developed and early during 1976-1977 the efficiency rate of CIGS cells was around 4.5%. Using flexible substrate in CIGS cells came later and from 8.3% efficiency rate in the year 1993 it went upto 17.1% around 2011-2012. Over the years labs such as NREL have made advances in developing the “three stage process” for the fabrication of the absorption layer of CIGS cells. This three stage process turns out to be an important step to demonstrate high conversion efficiency.

Even though most of the materials required for developing CIGS cells are available in abundance but Indium is scarcely available. So, this makes you look for an alternative.

Like most other thin film technologies, developing CIGS cells leave behind toxic wastes that are not good for the environment.

4 CONCLUSION

Recent IEA report says that there has been an increase in the energy demand by 5% during the year 2022. Even though use of renewables is increasing, and many countries have adopted the use of renewables to meet the growing energy demand yet more than half of this increase is met by fossil fuels and coal. Among the renewables, solar PV technology is quite popular and in this thesis the state of the art of various PV technologies have been discussed specifically those which are commercially mature. The following points could be concluded

- C-Si still dominates in the market of PV technologies.
- The laboratory efficiency of mono crystalline cell being maximum is 26.7% and then comes poly crystalline cells with cell efficiency to be 24.2% and then in thin films technology CIGS achieve to have the highest cell lab efficiency of 23.4% followed by CDTE cells with 21% cell lab efficiency.

The cost of PV modules still is high and with more use of them the cost could come down. Renowned laboratories such as NREL, IEA, Fraunhofer, etc are carrying on research to fix problems in the current technologies. Thin film technologies have scope of being commercially more popular however in their fabrication process, the toxic waste disposal needs to be taken care of and also c-Si PV modules continue to be cheap in terms of materials used.

5 REFERENCES

[1] Net solar PV capacity additions, 2017-2019, IEA, Paris, Available: https://www.iea.org/data-and-statistics/charts/net-solar-pv-capacity-additions-2017-2019

[2] How a PV Cell Works - Knowledge Bank - Solar Schools, Available: https://www.solarschools.net/knowledge-bank/renewable-energy/solar/how-a-pv-cell-works

[3] Renewables 2020 – Analysis – IEA, Available: https://www.iea.org/reports/renewables-2020

[4] IEA, Share of renewables in power generation in the Sustainable Development Scenario,2000-2030,IEA,Paris,Available:https://www.iea.org/data-and-statistics/charts/share-of-renewables-in-power-generation-in-the-sustainable-development-scenario-2000-2030

[5] Best Research-Cell Efficiency Chart | Photovoltaic Research | NREL, Available: https://www.nrel.gov/pv/cell-efficiency.html

[6] SunPowerSource · SunPowerSource types of solar panels, Available: https://www.sunpowersource.com/types-of-solar-panels/

[7] Organic Photovoltaic Solar Cells | Photovoltaic Research | NREL, Available: https://www.nrel.gov/pv/organic-photovoltaic-solar-cells.html

[8] A. Detollenaere , Becquerel Institute, Snapshot of Global PV Markets 2020 PVPS Task 1 Strategic PV Analysis and Outreach, Available: https://www.researchgate.net/publication/341051533_Snapshot_of_Global_PV_Markets_2020_PVPS_Task_1_Strategic_PV_Analysis_and_Outreach#fullTextFileContent

[9] K. Eber, Quantum Dots Promise to Significantly Boost Photovoltaic Efficiencies, Available: https://www.nrel.gov/docs/fy13osti/59015.pdf

[10] Why perovskite photovoltaics? | Oxford PV, Available: https://www.oxfordpv.com/perovskite-pv-transform-global-solar-market

[11] Organic Photovoltaics Research | Department of Energy, Available: https://www.energy.gov/eere/solar/organic-photovoltaics-research

[12] International Energy Agency, Data and Statistics, CO2 emissions by energy source, 2020, Available: https://www.iea.org/data-and-statistics?country=WORLD&fuel=CO2%20emissions&indicator=CO2%20emissions%20by%20energy%20source

[13] A Study of Materials for Solar PV Technology and Challenges, Available: https://www.researchgate.net/publication/322159344_A_Study_of_Materials_for_Solar_PV_Technology_and_Challenges

[14] What is a heterojunction solar cell, Available: https://www.thesolarnerd.com/blog/what-is-heterojunction-solar-panel/

[15] Innovative PV modules and PERC technology, Available: https://www.vpsolar.com/en/innovative-pv-modules-perc-technology/

[16] International Renewable Energy Agency, FUTURE OF SOLAR PHOTOVOLTAIC Deployment, investment, technology, grid integration and socio-economic aspects A Global Energy Transformation paper About IRENA. 2019. Available: www.irena.org/publications

[17] M. Woodhouse, B. Smith, A. Ramdas, and R. Margolis, Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reduction Road Map, 2017, Available: https://www.nrel.gov/docs/fy19osti/72134.pdf

[18] Bifacial PV technology: technical considerations, Available: https://www.dnv.com/article/bifacial-pv-technology-technical-considerations-186095

[19] Why use Double Glass Panels? – SREL, Available: http://www.srel.net/index.php/why-use-double-glass-panels/

[20] S. Riepe *et al.*, CAST-MONO SILICON WAFERS FOR A SUSTAINABLE PV MARKET GROWTH, Available: https://www.eupvsec-proceedings.com/proceedings?paper=49612

[21] Evolution of solar PV module cost by data source, 1970-2020 – Charts – Data & Statistics – IEA, Available: https://www.iea.org/data-and-statistics/charts/evolution-of-solar-pv-module-cost-by-data-source-1970-2020

[22] D. D. B. Mesquita, J. Lucas De Silva, H. S. Moreira, M. Kitayama, and M. G. Villalva, A review and analysis of technologies applied in PV modules, Available: https://www.researchgate.net/publication/337195909_A_review_and_analysis_of_technologies_applied_in_PV_modules

[23] Evolution of solar PV module cost by data source, 1970-2020 – Charts – Data & Statistics – IEA, Available: https://www.iea.org/data-and-statistics/charts/evolution-of-solar-pv-module-cost-by-data-source-1970-2020

[24] P. K. Nayak, S. Mahesh, H. J. Snaith, and D. Cahen, Photovoltaic solar cell technologies: analysing the state of the art

[25] D. D. B. Mesquita, J. Lucas De Silva, H. S. Moreira, M. Kitayama, and M. G. Villalva, A review and analysis of technologies applied in PV modules

[26] Fraunhofer ISE, "Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems," *Agora Energiewende*, no. February, p. 82, 2015. Available: http://www.fvee.de/fileadmin/publikationen/weitere_publikationen/15_AgoraEnergiewende-ISE_Current_and_Future_Cost_of_PV.pdf

[27] Silicon Material TEChnology research center (SIMTEC) - Fraunhofer ISE, Available: https://www.ise.fraunhofer.de/en/business-areas/photovoltaics/silicon-photovoltaics/feedstock-crystallization-and-wafering/simtec.html

[28] Renewable energy market update – Analysis – IEA, Available: https://www.iea.org/reports/renewable-energy-market-update

[29] Solar PV – Analysis – IEA, Available: https://www.iea.org/reports/solar-pv

[30] J. Logan *et al.*, "Electricity Generation Baseline Report, 2015, Available: www.nrel.gov/publications

[31] Renewables – Global Energy Review 2020 – Analysis - IEA., Available: https://www.iea.org/reports/global-energy-review-2020/renewables

[32] Renewables 2019 Global Status Report, Available: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf

[33] Study: Levelized Cost of Electricity - Renewable Energy Technologies - Fraunhofer ISE, Available: https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html

[34] A. W. Bett and F. Ise, Photovoltaics and Climate Change, 2020.

[35] F. Ise, Photovoltaics Report, Available: www.ise.fraunhofer.de

[36] Materials and Devices | Photovoltaic Research | NREL, Available: https://www.nrel.gov/pv/materials-devices.html

[37] High-Efficiency Crystalline Photovoltaics | Photovoltaic Research | NREL, Available: https://www.nrel.gov/pv/high-efficiency-crystalline-photovoltaics.html

[38] Joseph von Fraunhofer Prize 2016: Changes in Solar Cell Technology, Available: https://www.fraunhofer.de/en/about-fraunhofer/excellence-in-research/archive/2016/joseph-von-fraunhofer-prize-2016-changes-in-solar-cell-technology.html

[39] Fraunhofer ISE Sets Two Records for the Efficiency of Silicon-Based Monolithic Triple-Junction Solar Cells - Fraunhofer ISE, Available: https://www.ise.fraunhofer.de/en/press-media/press-releases/2019/fraunhofer-ise-sets-two-records-for-the-efficiency-of-silicon-based-monolithic-triple-junction-solar-cells.html

[40] Fraunhofer Technologies for the Herkulean Energy Transition Project ‘Energiewende, Available: https://www.fraunhofer.de/en/research/current-research/fraunhofer-technologies-for-the-energy-transition.html

[41] SUNRISE - Fraunhofer IGB, Available: https://www.igb.fraunhofer.de/en/press-media/press-releases/2019/sunrise.html

[42] Renewable Energy, Available: https://www.fraunhofer.de/en/research/fields-of-research/energy-resources/renewable-energy.html

[43] Energy and Resources, Available: https://www.fraunhofer.de/en/research/fields-of-research/energy-resources.html

[44] H. Zsiborács, B. Pályi, H. N. Baranyai, M. Veszelka, I. Farkas, and G. Pintér, Energy performance of the cooled amorphous silicon photovoltaic (PV) technology, *Idojaras*, vol. 120, no. 4, pp. 415–430, 2016.

[45] V. V. Tyagi, N. A. A. Rahim, N. A. Rahim, and J. A. L. Selvaraj, Progress in solar PV technology: Research and achievement, *Renew. Sustain. Energy Rev.*, vol. 20, no. April 2020, pp. 443–461, 2013.

[46] Design & Estimation of Rooftop Grid-tied Solar Photovoltaic System, Available: https://www.researchgate.net/publication/318654444_Design_Estimation_of_Rooftop_Grid-tied_Solar_Photovoltaic_System

[47] Crystalline Silicon Photovoltaics Research | Department of Energy, Available: https://www.energy.gov/eere/solar/crystalline-silicon-photovoltaics-research

[48] DYE SENSITIZED SOLAR CELLS-A REVIEW, Available: https://www.researchgate.net/publication/320345931_DYE_SENSITIZED_SOLAR_CELLS-A_REVIEW

[49] Light and Materials - J.A. Woollam, Available: https://www.jawoollam.com/resources/ellipsometry-tutorial/light-and-materials

[50] Anti-Reflection Coatings | PVEducation, Available: https://www.pveducation.org/pvcdrom/design-of-silicon-cells/anti-reflection-coatings

[51] A review and analysis of technologies applied in PV modules, Available: https://www.researchgate.net/publication/337195909_A_review_and_analysis_of_technologies_applied_in_PV_modules

[52] AURA: Temperature coefficients and crystal defects in multicrystalline silicon solar cells, Available: https://uia.brage.unit.no/uia-xmlui/handle/11250/2690259

[53] New processes for the production of solar-grade polycrystalline silicon: A review, Available:https://www.researchgate.net/publication/222273561_New_processes_for_the_production_of_solar-grade_polycrystalline_silicon_A_review#fullTextFileContent

[54] Jinko Solar-半片技术, Available: https://www.jinkosolar.com/en/site/halfslice

[55] Q. A. Alabdali, A. M. Bajawi, and A. M. Nahhas, Review of Recent Advances of Shading Effect on PV Solar Cells Generation

[56] PV-Manufacturing.org, Available: https://pv-manufacturing.org/glass-glass-modules/

[57] Double Glass Solar Panels, Available: https://sinovoltaics.com/learning-center/solar-panels/double-glass-solar-panels/

[58] I. PVPS Task, Bifacial Photovoltaic Modules and Systems: Experience and Results from International Research and Pilot Applications 2021 Task 13 Performance, Operation and Reliability of Photovoltaic Systems PVPS, Available: https://iea-pvps.org/wp-content/uploads/2021/04/IEA-PVPS-T13-14_2021-Bifacial-Photovoltaic-Modules-and-Systems-report.pdf

[59] Bifacial photovoltaic panels: the new mainstream? - Blog - Super PV, Available: https://www.superpv.eu/blog/Bifacial-photovoltaic-panels-the-new-mainstream/

[60] Innovative PV modules and PERC technology, Available: https://www.vpsolar.com/en/innovative-pv-modules-perc-technology/

[61] C. Deline, S. Ayala Peláez, B. Marion, B. Sekulic, M. Woodhouse, and J. Stein, Bifacial PV System Performance: Separating Fact from Fiction, Available: https://www.nrel.gov/docs/fy19osti/74090.pdf

[62] Sharp hits 25.09% efficiency on full size HJT cell – pv magazine International, Available: https://www.pv-magazine.com/2018/03/27/sharp-hits-25-09-efficiency-on-full-size-hjt-cell/

[63] ZSW: Thin-film solar cells and modules, Available: https://www.zsw-bw.de/en/research/photovoltaics/topics/thin-film-solar-cells-and-modules

[64] Z. Wang *et al.*, Engineering Research Express TOPICAL REVIEW, Available: https://doi.org/10.1088/2631-8695/ac2353

[65] Photovoltaic Technology: The Case for Thin-Film Solar Cells, Available: https://www.researchgate.net/publication/12872592_Photovoltaic_Technology_The_Case_for_Thin-Film_Solar_Cells

[66] Best Research-Cell Efficiency Chart | Photovoltaic Research | NREL, Available: https://www.nrel.gov/pv/cell-efficiency.html

[67] Alessandro Romeo, Elisa Artegiani, CdTe-Based Thin Film Solar Cells: Past, Present and Future