LONG TERM PERFORMANCE AND DEGRADATION RATES OF PV MODULES IN CENTRAL ANATOLIA

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ABSTRACT

LONG TERM PERFORMANCE AND DEGRADATION RATES OF PV MODULES IN CENTRAL ANATOLIA

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Outdoor tests of photovoltaic modules are crucial for the market, and technological development. It is vital for manufacturers and researchers to conduct tests not only in the long term but also in different climatic conditions. In this thesis, 12 modules are tested in Middle Anatolia climate conditions for nine years in three different module groups, which are mono-crystalline (Mono-Si-1 & 2 & 3, Bifi-Mono-Si, HIT), poly-crystalline (Poly-Si-1 & 2), and thin films (CIS-1 & 2, CIGS-1 & 2, μSi/a-Si). We analyzed the efficiencies of solar PV modules with nine years of data collected from Middle Anatolia. The most effective module is the Bifi-Mono-Si with 16.47 % as expected and the second effective module is HIT with 14.82 % efficiency. In addition to efficiencies, performance ratios are investigated and Mono-Si-1 has the highest performance ratio on average. Furthermore, we analyzed the weather corrected performance ratio of 5 modules (CIS-1 & 2, μSi/a-Si, HIT, Poly-Si-2) and the HIT module obtains the best corrected performance ratio on average. Finally, we utilized efficiencies and performances ratio values to estimate the degradation rates of solar PV modules. We found the following degradation rates for modules: 0.80 %/year for

Mono-Si modules, 1.95%/year for CIS modules, 0.68 %/year for a-Si, 1.42 %/year for Poly-Si, and 1.09 %/year for HIT module. Considering all results, Mono-Si is the best option for long-term usage and development.

Keywords: Photovoltaic modules, Long term outdoor testing, Degradation rates, Initial power rating, Weather corrected performance rate

ÖZ

ORTA ANADOLU'DAKİ PV MODÜLLERİNİN UZUN VADELİ PERFORMANS VE BOZULMA ORANLARI

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Fotovoltaik modüllerin açık hava testi, şirketler ve teknolojik gelişme için çok önemlidir. Testlerin sadece uzun vadede değil, farklı iklim koşullarında da yapılması üreticiler ve araştırmacılar için hayati önem taşımaktadır. Bu tez çalışmasında 12 modül monokristal (Mono-Si-1 & 2 & 3, Bifi-Mono-Si, HIT), polikristal (Poly-Si-1 & 2) ve ince filmler (CIS-1 & 2, CIGS-1 & 2, μSi/a-Si) olmak üzere üç farklı grup modül kullanılarak yaklaşık dokuz yıl boyunca Orta Anadolu iklim koşullarında test edilmiştir. Güneş PV modüllerinin verimliliklerini Orta Anadolu'dan toplanan dokuz yıllık verilerle analiz ettik. En verimli modül beklendiği gibi % 16,47 ile Bifi-Mono-Si ve ikinci verimli modül ise %14,82 verimlilik ile HIT'dir. Verimliliklerin yanı sıra performans oranlarını araştırdık ve Mono-Si-1 ortalama olarak en yüksek performans oranına sahip olduğu tespit ettik. Ayrıca, 5 modülün (CIS-1 & 2, μSi/a-Si, HIT, Poly-Si-2) hava koşullarına göre düzeltilmiş performans oranını analiz ettik ve HIT modülü ortalama olarak en iyi düzeltilmiş performans oranına sahip oldu. Son olarak, güneş PV modüllerinin bozulma oranlarını tahmin etmek için verimlilik ve performans oranı değerlerini kullandık. Modüller için şu bozulma oranlarını bulduk: Mono-Si modülleri için 0,80 %/yıl, CIS modülleri için 1,95%/yıl, a-Si için 0,68 %/yıl, Poly-Si için 1,42 %/yıl ve HIT modülü için 1,09 %/yıl. Tüm sonuçlar göz önüne alındığında Mono-Si, uzun süreli kullanım ve geliştirme için en iyi seçenek olarak karşımıza çıkmaktadır.

Anahtar Kelimeler: Fotovoltaik modüller, Uzun süreli dış mekan testi, Bozulma oranları, İlk güç derecelendirmesi, Fotovoltaik verimlilik belirsizliği, Hava koşullarına göre düzeltilmiş performans oranı

To my precious and lovely husband Dr. Deniz Cantürk and my kids Feyza and Asaf

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CHAPTER 1

INTRODUCTION

Throughout human history around the world, people seek energy to provide for their needs. Firstly, humans discover the fire and they use wood to gain the fire. With the industrial revolution, coal came into our life. The development in science bring about electricity and it began to play a vital role for humanity. The population of the world is increasing significantly and energy demand is increasing day to day. Since the most using energy resources such as coal or natural gases are limited [1], it will no longer provide the energy demand of humanity. In addition to this energy demand, fossil-fuel resources bring about global warming, greenhouse effect and so climate change [2]. Both global warming and decreasing the sources of fossil fuel have canalized renewable energy to generate electricity.

According to the arrangement of "The Kyoto Protocol to the United Nations Framework Convention on Climate Change", countries took an action and, they aimed to reduce the greenhouse emissions by at least 5 % below 1990 levels until 2012. After the Paris Agreement at 2015, it is aimed to keep the global temperature under $2°C$ by 2030 (UNFCCC, 2015). All these agreements are a significant step to keep the environment and to avoid climate change by using renewable energy.

Renewable means energy resources that is able to replenish at the same rate as they are used (Armstrong & Hamrin, 2000). Such kinds of renewable energy are wind power, hydro-power, solar energy. At that point, solar energy has gained importance with the development of photovoltaics (PV) technologies. According to IEA, the generation of electricity by solar energy increased %22 in 2019, and the generation energy value reach 720 TWh [3]. Also, according to IRENA's annual Renewable Capacity Statistics 2021, the capacity of solar energy generation in the world is reported as 2799 GW

[4]. In 2050, it is predicted about %15-%20 that total energy demand of the world will be supplied by solar energy [5].

1.1 Solar Energy

The sun is the center of our solar system. We can say that it is the source of life on the earth. The sun [6] is a yellow dwarf star, and it is like a fireball including severe gases inside. According to NASA [7], the distance between earth and sun is 149,600,000 km. The temperature of the surface of the sun is about 5800 K.

Inside the sun, there are several nuclear reactions. The most important reaction is hydrogen fusion reactions to transform helium. Since helium nucleus has less energy than hydrogen nucleus, the extra energy is released in this reaction from sunlight into the space. The power-release the sun is 3.9×10^{26} Watt and the solar irradiance is $H_{sun} = 64 \times 10^6\ W/m^2$ and the solar radiation releasing from the sun to the surface of the Earth is $1366.1\ W/m^2$ [8]. The amount of solar energy that reaches the earth's surface is sufficient to supply the energy demand of the world for one day. However, converting solar energy to electricity is a complicated process and it can do in two ways which are thermal and PV technology.

The thermal way is based on the heating fluid by using sunlight and it uses at homes as hot water. This technology, solar thermal panels are used for boiler, collector, and immersion heater. A collector is used to transform heat into a fluid (or water). This warm water is pumped to a heat exchanger and then it heats the water inside the cylinder.

PV means sunlight generates electricity directly. Photons, which are particle of light, stimulate the electrons if it has enough energy and electrons become free inside the semiconductor. The energy band for semiconductor materials has a valance band and conduction band. The bandgap energy is required for electrons to absorb photon's energy and it jumps from valance band to conduction band. If the coming photon energy is less than the bandgap, an electron can not jump and a photon passes throughout inside the material without any interaction. only one photon can be absorbed by only one electron. This is a crucial thing relating to solar energy amount and power.

In PV technologies, material doped and p and n-type semiconductors are created and a p-n junction is formed to create a voltage difference. On the n-type side, there are some non-bonding electrons. On the p-type side, there are holes which means that there is a vacation to make a bond with an electron in the atom. Excess electrons in the n-type move to the p-type side with the drift current. The holes in the p-type side diffuse to n-type and a current occurs (Neamen, 2006).

1.2 Solar Geometry

Generally, coming beam is measured with a pyronometer but in this study at the beginning, this couldn't be done. If we have a data about bright sun shine hour or total horizontal irradiation, the total tilted irradiation can be estimated by using isotropic and an-isotropic models.

Isotropic model was driven by Liu et all [9] at 1963. According to isotropic model, the sun light com into the earth surface with three ways. These are described as beam, diffuse and ground reflecting. The beam is the energy directly coming from the Sun without scattering. Diffuse parts are the scattered due to atmosphere and reflected back from the ground. Considering isotropic sky the equation for the solar irradiation incident on tilted surface is written as [10]:

$$I_T = I_b R_b + I_d(\frac{1 + cos\beta}{2}) + I\rho_g(\frac{1 - cos\beta}{2}) \tag{11}$$

Here, I_T is represents the total irradiation incident to the module surface. I_b represents direct beam, I_d represents diffuse radiation from the light and R_b represents the ratio of beam radiation on the tilted surface to the horizontal surface. β is the tilted angle, which is between module and horizontal surface of the ground and ρ_g is a constant value that represents the coefficient of reflectance of ground. According to Liu et all [9], the average value of ρ_g is taken as 0.20 for all months during which the ground is free of snow [11].

The other model is an-isotropic model. In this model, it was included circumsolar diffuse and horizon brightening. This model is released by Hay and Davies [12].

Reindl et all [13] modified this model by adding horizon brightening term. Duffie and Beckman give the name to this model as HDKR model [10]. This equation is given as:

$$I_t = (I_b + I_d A_i)_b + I_d(1 - A_i)(\frac{1 + cos\beta}{2})[1 + f sin^3(\frac{\beta}{2})] + I\rho_g(\frac{1 - cos\beta}{2}) \quad (12)$$

The different terms from isotropic model are A_i and f and they represent an anisotropic index and the modulation factor respectively.

Perez et al. [14] studied a model on irradiance components from direct and global irradiance based on the three diffuse components by analyzing with more detail. This equation is given as:

$$I_{d,T} = I_d \left[(1 - F_1)(\frac{1 + cos\beta}{2}) + F_1\frac{a}{b} + F_2 sin\beta)\right] \quad (13)$$

In this equation, F_1 and F_2 are circumsolar and horizon brightness coefficients and a and b are represents the con and sin function of the angles of incidence of the cone of circumsolar radiation on the tilted and horizontal surfaces. In the circumsolar radiation, the sun is assumed as the point source and this is written as:

$$a = max(0, cos\theta), b = max(cos85, cos\theta_z) \quad (14)$$

1.3 Photovoltaics

While atoms make a bond with each other to form a solid or liquid, their potential energy change. According to Bloch Theorem (1928), their energy levels split. In the solids many atoms make boon each other and their energy level overlap and it cause the formation of energy band structure. Energy bands splits with a forbidden energy gap and this gap is called energy gap (E_g). Electrons in the valance band can be transformed to the conduction band in case of excitation and such a material is called semiconductor. If the band gab is too large and the electron transform cannot occur, this solid is called insulator. In the conductors, valance band and conduction band overlap and electrons in the valance band can move easily to the conduction band without any excitation and therefore electrons can move easily under applied electric field [15].

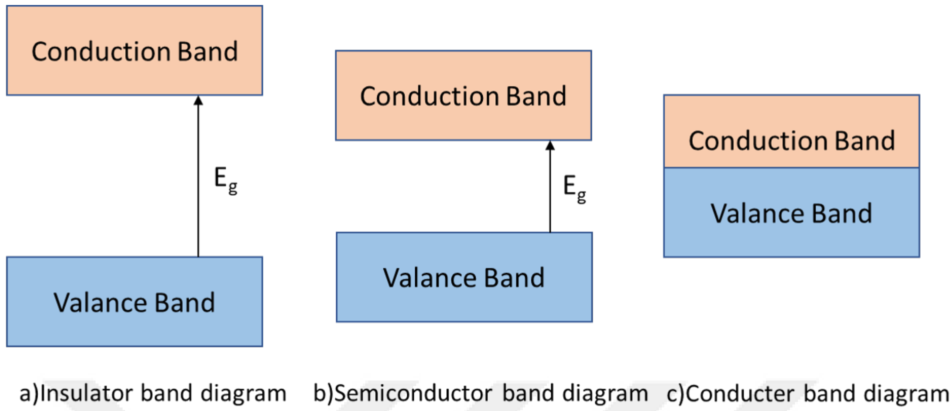


Figure 1.1: The band diagrams of these three types of materials.

In semiconductors, when an electron excites to the conduction band, electron hole pair (EHP) is generated. To increase the charge carrier density in the semiconductors, doping with other materials can be applied. For example, if the material is doped with boron (B), this material has more holes in the valance band and this material is named as p - type semiconductor. For phosphorus (P), there are more electrons in the conduction band, this material is named as n-type. If any doped process is not done, this semiconductor is named as intrinsic.

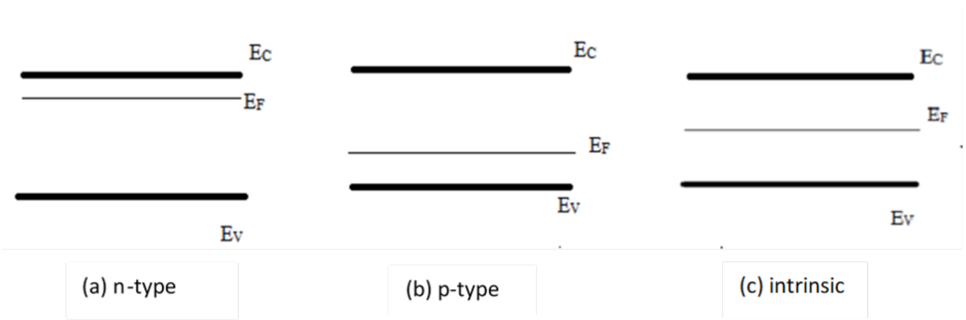


Figure 1.2: Fermi level in semiconductor according to their doping

If p-type and n-type semiconductor is connected, the p-n junction is created and this is called diode. A solar cell is actually a diode. When p and n type semiconductor connected, electrons and hole exert a force to each other and their potential energy levels are changed and a voltage difference is created as shown in the figure 1.3 [16]. Electrons in n side draft to the p side and the holes in the p side diffuse to n side. In this way, the depletion region occur between p-type and n-type side in the junction. In the n side of depletion region charges are positive and in the p side charges are negative.

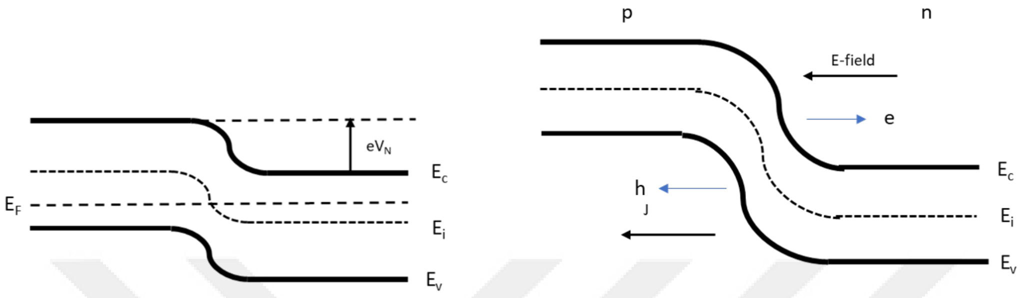


Figure 1.3: Energy-band diagram of a p-n junction in thermal equilibrium and when illuminated a reversed current occurs.

In the illuminated p-n junction, photons cause a formation of EHP in the n side. This excited electrons move to p type side again and voltage difference between p and n type side increase so the current occurs. As a results of this process, incident solar energy is transformed to electricity [16].

1.4 Solid Structure for Semiconductors (Cell Structures)

When atoms form a solid material, the atoms bond each other in different types. This bonding forms randomly as well as periodically. The first one is amorphous structure and the other one is crystalline structure. In amorphous or non-crystalline materials the atoms in the solid have not long order periodicity. The nearest atoms stay like crystalline but in the long of distance, this periodic structure are not maintained, and large deviations occur [17]. In the crystalline structure the atoms are periodically arranged and this can occur in different types. So, some the crystal structure cannot generate exactly.

In this study, thin films modules that is amorphous structure and crystalline structure photovoltaic modules are experimentally analyzed in the long term. In the following some information on these structures is given.

1.4.1 Thin Films

Thin film is obtain by deposition method layer by layer on a substrate such glass or plastic. Thin film can have different values of thickness from a few nanometers to micrometers. A thin film solar cell consists of two materials that are dissimilar from each other electrically, separated by a thin electronic barrier.To be efficient, devices must convert solar photons and collect excited charge carriers with high conversion efficiencies. It is possible for junctions to be abrupt, stepped, buried, heterofacial, etc., involving materials of diverse conductivity [18]. In this study Cupper Indium Gallium Selenide (CIGS) ,Cupper Indium Selenide (CIS), Amorphous silicon(μc-Si / a-Si), ve Heterojunction with Intrinsic Thin layer (HIT) thin films modules are investigated.

- Cupper Indium Gallium Selenide (CIGS)

  CIGS modules are the most common use in the PV technologies. CIGS solar cell has a direct band gab with high absorption coefficient. In 1988, Arco Solar began selling commercially available CIGS cell . In this type of solar cell, the active layer is a poly-crystalline film with the chalcopyrite crystal structure. p-type is the absorber layer and its contact is n-type CdS layer. By controlling the copper concentration, it is created coper deficient phase near the CdS interface [19]. In the figure 1.4, the CIGS solar cell structure is shown and the soda lime glass is used for substrate commonly.

- Cupper Indium Selenide (CIS)

  The most commonly used thin film solar cell is CIS due to its properties of hight absorption of light. CIS base material is grown under copper excess. Also addictive element such as sodium or gallium is not strictly necessary [20]. CIS solar cell is produced with the method of deposition of copper, indium and selenium on a substrate. This substrate can be plastic, glass backing. Because of the high absorption of light for this type cells, they have high absorption coefficient.(Figure 1.4).

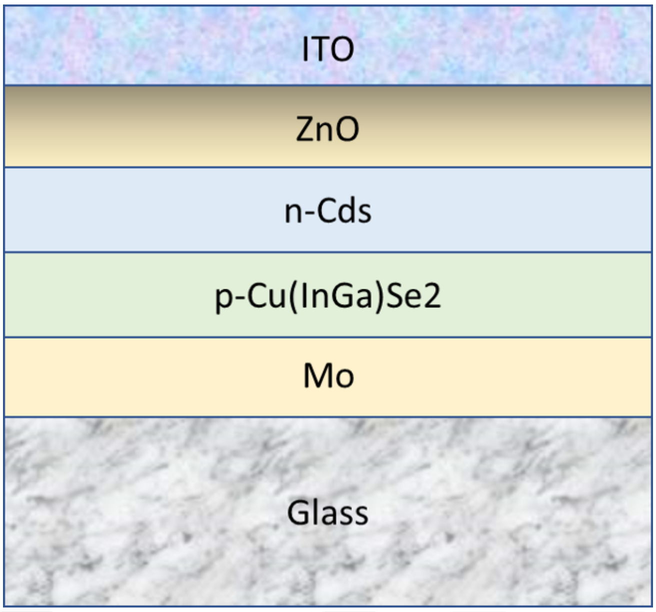


Figure 1.4: CIGS Solar Cell Structure

- Cadmium Telluride (CdTe)

  CdTe solar cells are the most commonly used one all over the world for generating energy from PV. The advantage of this type of cells is that it can be produced easily and it is cost friendly.Also it has direct bang gap with 1.4eV-1.5 eV which is in optimum range to generate electricity from the sunlight via a single junction. The technology of this type cell is p-n heterojunction structure. Firstly transparent conductive oxide (TCO) layer is deposited on a glass superstrate. Commonly, borosilicate glass is used because of durability to high temperature. For this layer generally, ITO and SnO_2 are used. After that an n-doped CdS or magnesium zinc oxide (MZO) window layer and a p-doped CdTe layer are deposited. CdS diffusion during the process decrease the lattice midmatch between CdTe and CdS. For contact, Al-Ni layer is deposited [21][18](Figure 1.5.

- Amorphous silicon(a-Si)

  a-Si solar cell is widely used for PV technologies because it is abundant matter on Earth. Low temperature process and low cost substrate are needed and it provides solar module to produce as flexible. Also, the large area deposition can be done easily and with less material, effective cell can be obtain. This

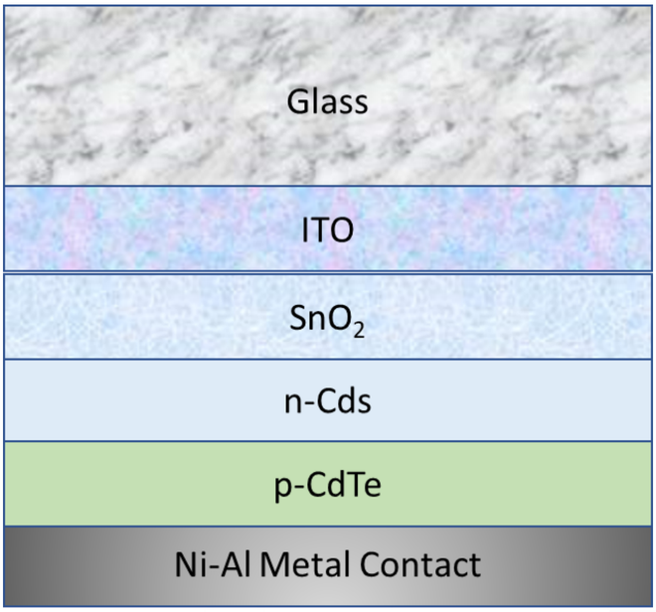


Figure 1.5: CdTe Solar Cell Structure

type of cells are obtained by depositing amorphous silicon on glass substrate. Commonly using method for deposition is plasma enhanced chemical vapor deposition (PECVD) [17].

- Tandem Cell Based on μc-Si / a-Si

  Tandem cell occurs when two layers of p-n junction are combined. The advantages of this technology are firstly the possibility of combining different materials having different band gaps. Also, higher open circuit voltage can be obtained with lower current densities. This reduces the series resistance problems. Finally, by using thin amorphous top cells, light-induced degradation can be reduced [20][22].

- Organic Solar Cell

  Organic solar cells are formed by using organic semiconductor. Organic semiconductor can be doped by introducing foreign atoms or molecules or with electrochemical oxidation/reduction processes. This technology is used because of its inexpensive production. Also, changing and adjusting the length or functional group of polymers, the band gap can be changed so that electronic tunability can be produced. However, organic solar cell have stability problem and it has low efficiency and low strength [18].

- Perovskite Solar Cell

  Porevskite solar cell is formed perovskite structure. In this structure, the hybrid of organic and inorganic or tin halide-based materials are included. The production of this metarials are cheap and simple. This cell is called "Perovskite" because of ABX3 crytal structure of the absorber materials. A ans B refer to cations and X refers to anion. Although they have sufficient efficiency with precious band gab structure, in long term usage, the efficiency reduce highly because of high degradation rates.

1.4.2 Crystalline Structure

Crystalline structure is the atoms bonding to each other in regular arrangements. Semiconductor materials bond each other with covalent bonding. The structure type change with pressure, temperature, or motion. There are three types of crystal structure in PV technologies.

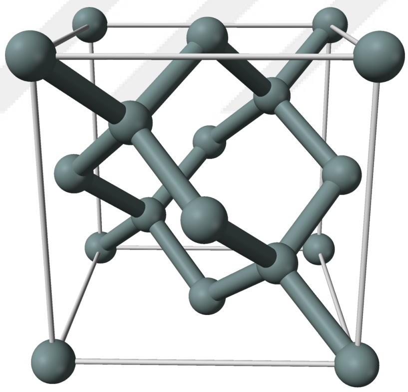


Figure 1.6: Diamond Crystalline unit Cell Structure

- Mono-crystalline:

  Mono-crystalline means that the material has the same repeating structure periodically. Silicon is in the 4A group as mentioned previously, and it forms as a diamond crystalline structure. Diamond cubic structure is based on face-centered cubic (FCC) arrangement. In the diamond unit cell, there are two FCC unit cells intertwined. This structure is very strong.

- Poly-crystalline:

  In the poly-crystalline structure the material there are many mono-crystal sites and no periodical adjustment. These mono-crystal formations results in a poly-crystal structure. The surface between mono-crystal regions is called Grain Boundary.

- Heterojunction with Intrinsic Thin layer (HIT)

  HIT cell structure is shown in the figure 1.7. The crystalline silicon is used as a substrate. In the both front and back side of substrate intrinsic a-Si, doped a-Si layers (p and n type respectively front and back side) and finally transparent conducting oxide layers are deposited. So a HIT cell has a symmetrical structure. The motivation of this type cell is that it is a stress free cell structure[23].

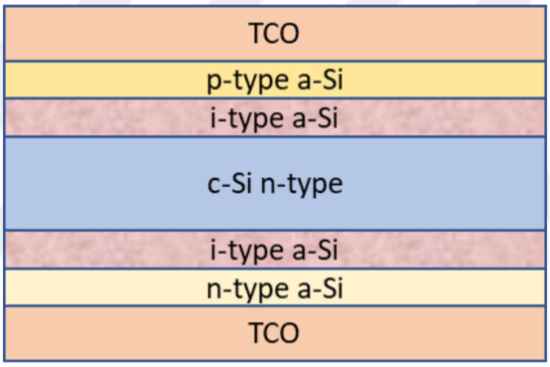


Figure 1.7: HIT Solar Cell Structure

1.4.3 Module Structure

In the fabrication process, modules are produced from rear to front side is ordered as the back sheet, encapsulated material, cell string, encapsulated material, and glass as shown in the figure 1.8. This module is called as mono-facial. The absorption of the sunlight by this type of module is only by the front side.

In the bi-facial modules, as shown in the figure 1.8, there is glass instead of a back sheet on the rear side so so the sunlight reflected from the ground is absorbed by the back surface. Therefore the electrical energy can be both by the front and rear side.

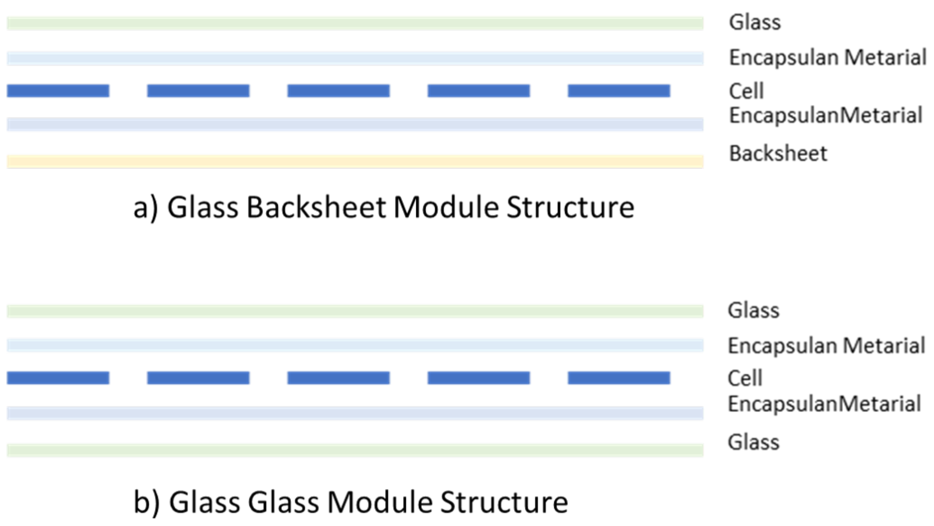
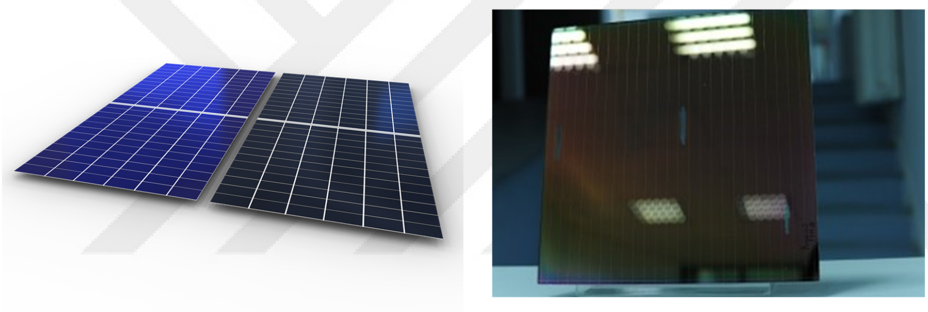


Figure 1.8: a)Glass-Backsheet and b)Glass-Glass Module Structure



a)Solar Module based on Mono-Si Cell
https://kalyonpv.com/teknolojimiz.html

b)Solar Module based on Thin Film
http://gunam.metu.edu.tr/facilities/thin-film-pv-lab/

Figure 1.9: Solar Modules based on a) Mono-Si and b) Thin Film Cell Structure

As shown figure 1.9, solar modules based on thin film are formed one or a few pieces while modules based on crystalline structure cells contain very many solar cells (today 72).

1.5 Thesis Motivation

The purpose of this thesis is to identify degradation rates of different types of PV Modules via long term outdoor tests for the region of Middle Anatolia. Around the world, PV companies, focus on increasing efficiency of cells or modules in the industry. Because of weather or nature condition, PV modules are subject to rain, snow, wind, soiling, etc. They deteriorate because of not only weather conditions but also due to solar irradiation and due to of course entropy.

Identifying the degradation rates helps to develop module technologies. Cost-effective fabrication is the most important matter for mass production. Both short term and long term information about the degradation and performances of these modules and cells are needed for investigating of pros and cons. Within this perspective, the testing of solar modules at various climates comes into prominence for companies and researchers.

In this thesis, efficiencies, performance rates, corrected performance rates, and degradation rates of 12 different solar modules are calculated and the results are analyzed via 12 years of data.

CHAPTER 2

LITERATURE REVIEW

Ishii et all [24] tested 14 different modules under moderate climate conditions for 4 years. The results of degradation rates are between 0.64 %/year and 0.92 %/year for mono-crystalline silicon modules while 0.4 %/year for poly-crystalline silicon modules at the same time interval. Besides, the degradation rate for amorphous silicon modules is higher than 1.45 %/year.

Makrides et al. [25] studied on 11 solar modules under the Mediterranean climate in Cyprus region for the period June 2006 – June 2009 including 5 kind modules which are mono-crystalline, poly-crystalline, amorphous silicon, Cadmium Telluride (CdTe), and Cupper Indium Gallium Selenide (CIGS) . They found that degradation rates are around 0.10 %/year for mono-crystalline modules, changes between 0.001 %/year and 0.11 %/year for poly-crystalline, 0.26 %/year for CIGS modules, 0.32 %/year for CdTe Modules and 0.23 %/year for amorphous silicon modules.

Bogdanski et all [26] studied on the influence of the climate conditions on the solar modules in four different regions. The studied climates are warm moderate climate (Cologne, Germany), tropical climate (Serpong, Indonesia), cold high mountain climate (Zugspitze, Germany) and arid conditions (Sede Boqer, Israel). According to the results of this study, the climate is very effective on degradation rates. The highest degradation rate belong cold high mountain climate because of high snowfall and wind stress. Because of high temperature and irradiation, in the desert and tropical climate, degradation is observed. In Israel and Indonesia, the contamination with sand were observed and this results in high of decrease the generating power.

Eke [27] carried out four different types of modules which are mono-crystalline silicon (Mono-Si), poly-crystalline silicon (Poly-Si), amorphous silicon (a-Si) and cadmium telluride (CdTe), for one year in Mugla whose climate is humid Mediterranean climate according to Köppen climate definition. This study reported the efficiencies are 8.8 % for Mono-Si, 9.2 % for Poly-Si, 5.4 % for a-Si and 3.5 % for CdTe at noon, and the max temperature reaching the modules is nearly $61°C$.

Quansah et al [28] studied on 29 crystalline solar module at six different locations in Ghana. They found the degradation rate in a range from 0.8 %/year to 6.5 %/year. In addition to I-V investigations, they observed some mechanical degradation such as broken glass, delimitation, yellowing encapsulate materials and bubbles.

Savvakis at al [29] work out a grid-connected system with 2.18 kWp. micro crystalline based amorphous silicon (μc-Si / a-Si) thin-film modules are observed for two years located in island of Crete in Mediterranean and using monthly average data. Also their study included module temperature to clarify the PV operating temperature. This group found the performance ratio as 85.1 % the efficiency as 7.25 %.

Tabatabaei et al [30] studied on degradation rates of 23 PV modules intalled on a roof o a family house in Netherlands. The interval gaining data is from May 2013 to January 2017 and PV panels installed in 6 different groups in terms of location and orientation. And they set the data to Seasonal and Trend decomposition using Loess technique. According to this study, panels at the same location and orientation have the same degradation rates and the average degradation rate of modules in this system is 0.923 %/year.

Limmanee et al [31] presented a study about degradation rates analysis of 73 different PV modules of 4 different module types: multi c,Si, heterojunction Si, thin film Si and CIGS on Thailan Science Park with 4 years data from 2012 to 2016. According to this study, performance rates of some thin film Si modules were having low efficiencies and they degraded seriously. Except that these modules, the degradation rates of other modules are in a range between 0.3 %/year and 1.9 %/year. Standard deviation is a measure of the level of mismatch between modules in the same array, indicating the array's performance. Also the levelized cost of electricity (LCOE) is studied and it was found in a range 4.1 baht/kWh and 14 baht/kWh and these values were related to their performance rates and their module types. As a result, LCOE for solar PV electricity in Thailand could be comparable to the retail price without a reduction of costs when degradation rate is less than 0.2%/year for the present PV technology.

Singh et al [32] released a study at 2020 about field analysis of three different PV system technologies. Analysis included monthly average performance rates, weather corrected performance rate series resistance and effective peak power of HIT, poly-crystalline and a-Si solar modules of three years data. Also degradation ratios were calculated by using three methods which were linear regression, classical seasonal decomposition (CSD), and locally weighted scatter plot smoothing (LOESS) via performance rate and normalized efficiency. The degradation rates were found as 1.24 %/year, 1.16 %/year and 1.16 %/year for a-si modules, 0.14 %/year, 0.56 %/year and 0.11 %/year for HIT modules and 1.50 %/year, 0.82 %/year and 1.46 %/year for poly-si modules using linear regression, CSD and LOESS analysis respectively. The average efficiency is found to be 5.17 % for a-si, 15.40 % for HIT and 10.78% of poly-si modules.

Frick et al [33], at 2020, presented a unified methodology to calculate degradation rate of PV systems accurately and prove this calculation is location dependent. The PV systems were installed at different climatic locations by using different c-Si PV modules to compare long term degradation rates. After 7 years, the degradation rate results showed convergence between time series analytical methods applied and degradation results from the indoor standardized procedures.Hence the multi crystalline silicon systems at the warm climatic locations had more degradation rate in comparison with the system in moderate climatic location.

Dhimish at al [34] presented a study calculating degradation rates with 10 years of data (from 2008 to 2017) in U.K. and Australia. The degradation rates are changing from 1.05 %/year to 1.16 %/year and from 1.35 %/year to 1.46 %/year for the system in the U.K and Australia respectively. In the Australia, because of rapidly changing ambient temperature and nonuniform irradiance, multiple faulty bypass diodes were found while, in U.K., damaged diodes were not observed. Also, performance rate of PV systems were calculated as 88.81 % and 86.35 % in U.K and Australia respectively.

Dag at al [35], at 2020, studied on the degradation rates and performance characteristic of poly-crystalline and hetero-junction with intrinsic thin layer PV modules for half and a two years. They install the system roof in the region of Central Anatolia (Konya). In this study, take into account temperature and the calculation of degradation rates were made by corrected performance rates. The results are lower than 0.1 %/year for thin film and within a range of 0.67 %/year and 0.83 %/year poly-crystalline.

Kurtz and Jordan from NREL [36], made an extensive analysis of degradation rates of PV modules and systems by using the results of outdoor measurements of five different types of modules and systems. To analyze degradation rates of PV modules, 2000 reported degradation rates in last 40 years before 2012 were worked out. The gaining value of average degradation rate for a-Si PV systems installed before the year 2000 was around 1.8 %/year, and after the year 2000 the average rate was about 1 %/year. For CdTe thin film PV systems, however, their reported values of average degradation rates were about 2 %/year for pre-2000 and about 0.6 %/year for post-2000. Finally, for Mono-Si arrays, the reported values were 0.7 %/year and 0.6 %/year for pre- and post-2000, respectively.

In addition to these studies, two of the system, which is used in this thesis, was performed and analyzed about degradation rate and performance ratio for three years [37]. Three different systems under the same climatic conditions of central Anatolia were analyzed with 44 months data. As a result of this study, the degradation rates are 0.40 %/year, 1.88 %/year and 10.60 %/year for Mono-Si, a-Si and CdTe thin film modules, respectively. The yearly average efficiency of these modules are 11.86 %, 6.49 % and 5.30 %, respectively [38].

CHAPTER 3

MATERIALS AND METHOD

Nine years of data is obtained from solar modules on the roof of METU Physics Building. In this section, the measurements and the calculations are explained. Data collected via some devices which is PV analyzer, pyranometer etc. Collected data were filtered and transformed by using python code. After transforming and filtering data, they were transferred to an excel file. All other calculation were carried out using excel worksheets.

3.1 Testing Region

This thesis includes the outdoor testing in middle Anatolia, Ankara-Turkey. The geographic coordination of Ankara is Latitude $39.9°N$ and longitude $32.8°E$ and the elevation is $920m$. The climate in this region is semi-arid [39],[40]. While the average yearly temperature is $12°C$, minimum average temperature is $7.3°C$ and maximum is $18.4°C$. Between 1991 and 2020 the recorded [1] maximum temperature is $41°C$ on July and the recorded minimum temperature is $-25°C$ on January. The relative humidity of the last 50 years are between 62.8 % and 66.6%. In the recent 90 years' average value of precipitation depth are 387 mm.

3.2 Testing Modules

The solar modules are tested for nine years, are located on the roof of the building of physics department in METU. These solar modules are as follows:

[1] https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=H

- Cupper Indium Gallium Selenide (CIGS)
- Cupper Indium Selenide (CIS)
- Micro crystalline based amorphous silicon (μc-Si / a-Si)
- Mono-crystalline silicon (Mono-Si)
- Poly-crystalline silicon (Poly-Si)
- Heterojunction with Intrinsic Thin layer (HIT)
- Bifi Mono-Si Mono-crystalline silicon (Bifi Mono-Si)

In the testing area there are two CIGS solar modules with the same properties, two CIS solar modules with the same properties, one μc-Si / a-Si solar module, three Mono-Si, two Poly-Si and one HIT solar module. After April 2016 bifacial solar module is added to the facility. The outdoor instillation was carried out at April 2012. The data analyzed are from April 2012 to May 2021. In this process, measurements were stopped for Mono-Si-3 at November 2015 and for CIGS-1 and CIGS-2 at September 2018. In the following table, there are modules properties that are given by the company under standard test conditions (STC).

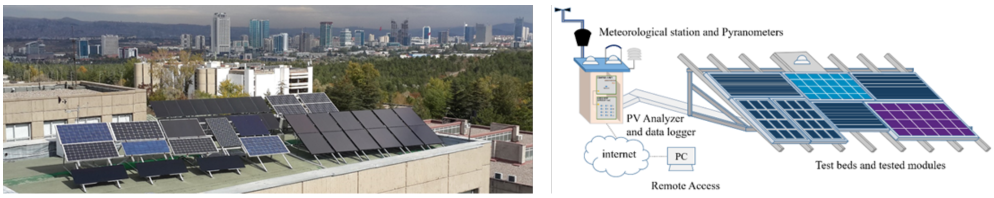


Figure 3.1: Testing Modules on the roof of the Physics Buildings at METU

As shown in table 3.1 CIGS-1 and CIGS-2 have the same properties. Also CIS-1 and CIS-2 and also Mono-Si-1 and Mono-Sİ-2 indicate the same properties.

3.3 Input Data

The measurement was carried out in the intervals of 10 minutes via measurement system. All incident irradiation and generated power were collected and reduced into

Table 3.1: Tested PV Modules Specifications (CIS, Mono-Si 1&2 are identical modules)

Module Type	P_{max} (W)	V_{oc} (V)	I_{sc} (A)	V_{mpp} (V)	I_{mpp} (A)	Area(m^2)	Start Date	End Date
CIGS-1	75	72.36	1.6	54.02	1.4	0.70	Jan, 2013	Sep, 2018
CIGS-2	75.5	74.10	1.6	56.71	1.3	0.70	Jan, 2013	Sep, 2018
μc-Si/a-Si	128	59.8	3.45	45.4	2.82	1.40	Apr, 2012	Continue
CIS-1	130	59.5	3.28	44.9	2.90	1.05	Oct, 2014	Continue
CIS-2	130	59.5	3.28	44.9	2.90	1.05	Oct, 2014	Continue
Mono-Si-1	160	43.7	5.06	35.3	4.58	1.28	Aug, 2012	Continue
Mono-Si-2	160	43.7	5.06	35.3	4.58	1.28	Apr, 2012	Continue
Mono-Si-3	240	37.1	8.45	30.3	7.94	1.66	July, 2012	Nov, 2015
Poly-Si-1	240	36.6	8.70	30.2	7.96	1.63	Apr, 2012	Continue
Poly-Si-2	130	21.71	8.18	17.8	7.30	1.02	May, 2012	Continue
HIT	230	42.3	7.22	34.3	6.71	1.39	Apr, 2012	Continue
Bifi Mono-Si	295	44.1	8.8	35.7	8.3	1.61	Apr, 2016	Continue

proper format. The most crucial estimations / measurements for this testing is the incoming energy from the sun. The incoming energy to the surface of the modules is called plane-of-modules irradiance. To measure this data pyranometers is used which is Kipp & Zonnen high precision secondary standard. Unfortunately, before April 2016, irradiance couldn't measured accurately because old silicon diode pyranometers was used. Their measurement were not meaningful and logical and they could not be used. Therefore, for this input, the data obtained by Turkish State Meteorological Service (TSMS) where it is located 20 km away from installed modules. The measured data is on horizontal surface therefore three different methods was used to estimate the plane-of modules irradiation and HDKR[41] was chosen the best option. In the following table 3.2 there are values estimated with HDKR model and also measured data and calculated errors.

After April 2016, a pyranometers is used which is Kipp&Zonnen high precision secondary standard. In the table 3.2, incident irradiation taken by the pyranometer after 2018 January is shown.

The incoming irradiation is given in $Watt/m^2$. To transform it to the daily data, first the transformation is done from power to energy density ($Watt.hour/m^2$). Then, the total irradiation was obtained by summing 10 minutely energy density in $Watt.hour/m^2$

Table 3.2: Monthly average daily values of solar irradiation incident on tilted modules as the input: Estimated using HDKR model, measured data

	Estimated with HDKR model					Measured					
Months	2012	2013	2014	2015	2016	2016	2017	2018	2019	2020	2021
January	—	65.68	62.37	75.53	71.08	—	70.44	80.97	94.30	97.26	81.41
February	—	104.20	135.23	90.63	111.07	—	117.85	91.83	103.58	94.16	148.48
March	—	141.32	159.05	140.81	140.23	—	147.04	131.89	182.31	158.28	140.89
April	176.42	181.51	182.26	177.73	200.35	201.12	169.35	206.23	157.50	186.52	147.62
May	179.50	214.84	189.36	200.29	186.63	170.07	173.69	177.20	169.76	201.26	215.67
June	223.15	221.20	202.37	166.99	213.83	211.35	194.70	208.06	193.73	197.38	—
July	226.67	226.97	233.51	238.24	236.88	235.91	219.77	225.58	272.59	235.73	—
August	225.35	227.51	229.43	223.14	222.29	215.90	215.99	222.72	216.88	235.01	—
September	221.59	199.74	180.08	201.52	202.33	191.70	198.06	189.87	198.09	200.66	—
October	157.94	168.44	142.15	138.66	168.35	153.29	148.54	156.40	169.68	164.60	—
November	89.21	114.84	74.25	117.57	116.64	113.61	101.49	107.92	121.95	133.03	—
December	71.11	81.16	57.58	86.25	83.79	83.37	118.39	83.37	62.25	86.19	

unit.

Another important data is the module temperature in this study. Temperature for each modules is used for weather corrected performance rates for each module. Also only 5 modules, which are CIS-1 & 2, HIT, a-Si, Poly-Si-2 could be taken into account in term of temperature since temperature coefficient of other modules couldn't be reached. In the appendix C.1, all monthly average temperature of 5 modules are shown.

3.4 Output Data

After solar module generated energy, power-meter measured output power in Watt unit, current in Amper unit, and voltage difference in Volt unit. As explained in section 3.5, only power parameters were used.

The data transformation from 10 minutely to monthly are done via python. Missing data are found and the unit of data is changed from $Watt$ to $Watt.hour$ so transformation to hourly, and daily are done via python. After these transform data again are transformed to monthly. In this section, the procedure explained. In figure 3.2, the flowchart of calculation is shown. To calculate output energy density ($Watt.hour/m^2$) generated by modules, the results was divided by the area of the modules individually. These values are given in the appendix D.1 As shown in the

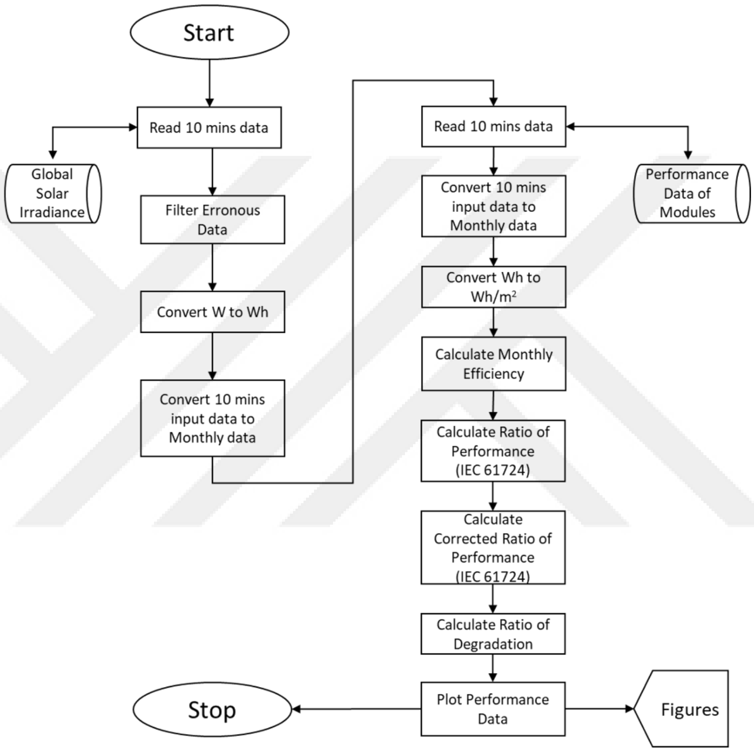


Figure 3.2: Flowchart of data integration

figure 3.3, there are the total yields of the modules in the year of 2017. This interval is chosen because 11 modules are available in this time. In the figure 3.4, last year of specific yield are plotted. CIGS-1 and CIGS-2 were uninstalled at September 2018, in this graph, there are 9 modules. In the appendix D.1, generated yield by all power modules are given.

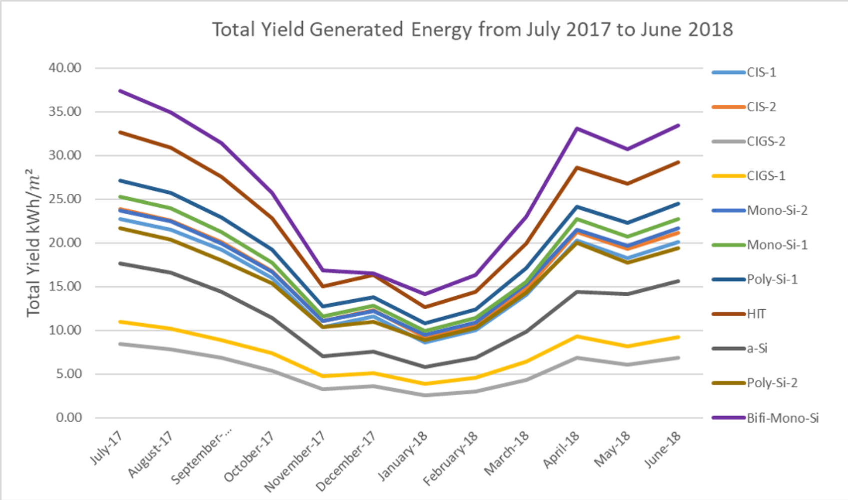


Figure 3.3: Total Yield Generated Energy During July 2017-June 2018

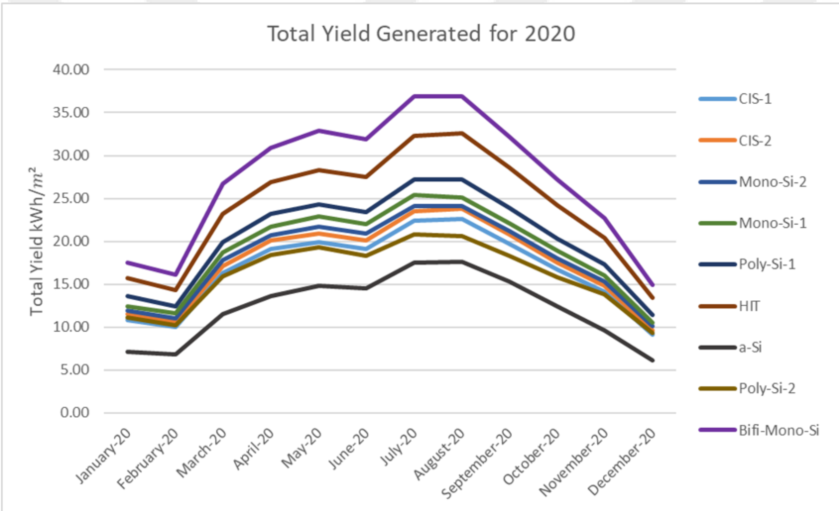


Figure 3.4: Total Yield Generated Energy During 2020

3.5 Data Integration

Reduction of the data to daily and monthly using the hourly averaged values was done. All calculations are mainly carried out with the monthly values.

Daily data exhibits the measured values of each day and the calculation code is given in the appendix A.2.

During the sunset and sunrise hours when the irradiance is less than $10W/m^2$ for all data, it is filtered and the power is assigned to be zero.Due to device failures data could not be measured for some of the days therefore they are denoted as "NaN". Also, when the missing data are fixed, if the data is absent almost during an hour, data insert as "NaN" and this hourly data is filtered. In addition, if total daily data is less than 1 Watt.hour, it is filtered and it is inserted as "NaN" again.

Temperatures are recorded by calculating the average values. The unit of the temperature is Celsius in the measurement and data. The temperature is taken to be, of course, different for day and night and for ambient and module temperature, average temperatures are taken into account. Firstly, hourly average temperatures are obtained and after daily temperatures are obtained as given in the appendix A.2.

In monthly data, for each month, there is one data and this data is the total energy generated in this month. Also for radiation, this data again is total energy reaching the surface of the solar modules. Temperature of module is the average temperature during that month. This code function is given in the appendix A.3.

Monthly power transformation is done from daily. Reading file in this part is daily data and it is read orderly all year and for each year, a file is produced. As in the transformation of daily data, again the total energy is found by adding daily data in a month. If a data for a day is "NaN", this data is assumed to be zero.

Monthly irradiation is carried out by summing the daily data . On the other hand, the filtering is also done, again, if total daily data is "NaN", it is recorded as zero but if the total daily data is less than $10Wh/m^2$. Also, if total monthly irradiation is less than $2Wh/m^2$, it is filtered again and it is written as "NaN".

For monthly temperature, the averages of the daily data are found and for each month, it is written. Filtering temperature for missing data it is written as "NaN" as in the power and irradiation. And for less than -50, all temperature data is filtered because -50 is not meaningful for Ankara.

3.6 Performance Calculation

Calculation of efficiencies, performance rates, corrected performance rates and degradation rates of solar modules are calculated via excel program. All transformed data, explained in the previous section, transpose to excel file and after that daily and monthly efficiencies and other calculations are carried out.

3.6.1 Efficiency

Efficiency means the rate of output energy to input energy to generate energy. The highest efficiency recorded in the PV technology is [42] 22.6% with a 400 W PV module. To do this, firstly generated energies are transformed to energy densities which is Wh/m^2 by dividing the data to areas of modules as given in the table 3.1. Then equation 31 is used and the efficiencies are obtained.

$$\eta = \frac{P_{in}}{P_{out}} => \eta = \frac{\sum_i^{day}(daily\ output)_i}{\sum_i^{day}(daily\ input)_i} \tag{31}$$

3.6.2 Performance Rate and Corrected Performance Rate

Another parameter to identify the module performance is the performance rate (R_p). R_p means a ratio of the final energy yield of the solar module (Y_f) to the reference yield according to supplier specification data sheets (Y_r). So, the performance rate is calculated as given in the eq.32.

$$R_p = \frac{Y_f}{Y_r} \tag{32}$$

Y_f is calculated from total energy yield by dividing to the output power of module measured STC.

$$Y_f = \frac{E_{out}}{P_{STC}} \tag{33}$$

In addition, Y_r is calculated from total incoming energy by dividing it to reference irradiance in STC which is 1000 W/m^2.

$$Y_r = \frac{E_{in}}{G_{STC}} \tag{34}$$

For corrected performance rate, the temperature of module is needed. Because the temperature is an important factor for conduction of semiconductors, the performance rate is needed as a correction. For this correction, Kurtz at al. [43] published a report. For this corrected performance rate, the temperature coefficient, in which specific properties of the module, and module temperature are needed. It is given in eq.35 and 36.

$$RP_{corr} = \frac{Y_f}{Y_r \times C_k} \tag{35}$$

$$C_k = 1 + \gamma \times (T_{mod} - 25°C) \tag{36}$$

Here γ is temperature coefficient written in the module data sheet, T_{mod} is measured module temperature. γ is always negative because of semiconductor materials.

3.7 Degradation Rate

Degradation rate is most important factor to identify the module performance especially in terms of long term yield. Degradation rate can be calculated using efficiency or performance rate. Firstly, a simple linear regression is applied [38] versus time series and after that the equation can be obtained as:

$$y = mt + n \tag{37}$$

As shown in the eq. 37, y refers to efficiency η or performance rate R_p, (it depends on researcher preference) t is time in term of month and n is the constant of the graph that we will use for degradation rate. For degradation rate, by using the graph constant n, percent calculation is done as eq. 38.

$$R_d = \left[\frac{n - y(N)}{n} \times \frac{12}{N}\right] \times 100 \tag{38}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Efficiencies and Total Yield of Modules

As explained in the Chapter 3, efficiencies are calculated via excel according to eq. 31. In the table 4.1, there are comparisons of efficiencies in STC and together with nine years of outdoor measurement. As expected, outdoor efficiencies are lower than STC values. Also as shown in the table, all panels areas are given. In the appendix A.3, there is a table showing all monthly efficiencies.

Table 4.1: Comparing of Efficiencies of Solar Modules According to Manufacturer and Average of Calculated Output

Module Type	Area(m^2)	Power(W)	Manual Efficiency(%)	Average Efficiency Calculated (%)
CIS-1	1.05	0.13	12.34	10.30
CIS-2	1.05	0.13	12.34	10.82
CIGS-1	0.67	0.08	11.25	6.73
CIGS-2	0.67	0.08	11.25	4.36
μSi/a-Si	1.40	0.13	9.14	7.44
Mono-Si-1	1.28	0.16	12.50	11.62
Mono-Si-2	1.28	0.16	12.50	11.22
Mono-Si-3	1.66	0.24	14.48	13.27
Bifi-Mono-Si-Si	1.61	0.30	18.32	16.47
HIT	1.39	0.23	16.59	14.82
Poly-Si-1	1.63	0.24	14.69	12.63
Poly-Si-2	1.02	0.13	12.75	10.32

Also, in the figure 4.1, it is shown a graph of all modules in the testing area from April 2012 to May 2021. Both table in the upper and in the graph, CIGS-1 and CIGS-2 modules works with low performances although their manual efficiencies are not too low. Because of this situation might be failures in CIGS's module due to older fabrication technology or unpredictable manufacturing problems. The most effective module is Bifi-Mono-Si Module. This module is the newest one in the testing area (installed on April 2016) and this module is the only bifacial module in the testing area. Hence, it is reasonable to have highest efficiency among all modules.

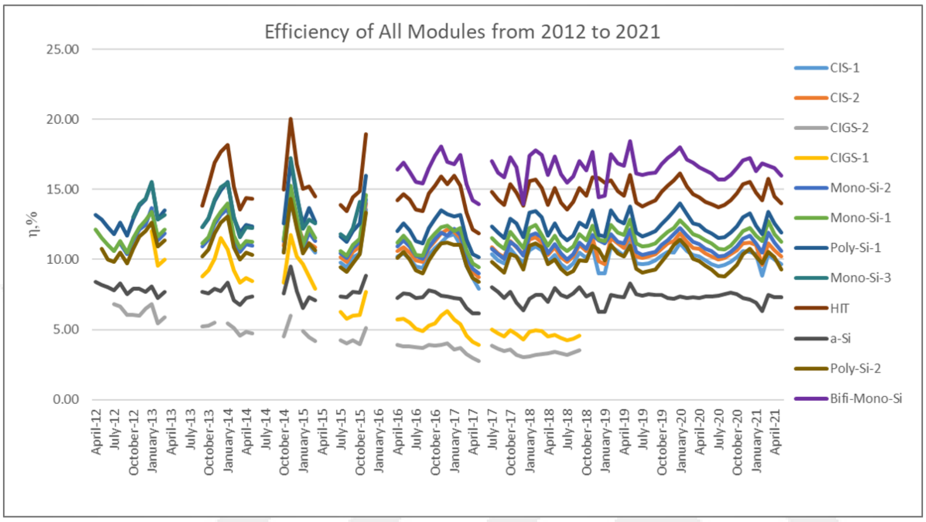


Figure 4.1: Efficiency of All Modules in the Testing Area from April 2012 to May 2021

In addition to that, from starting date of outdoor testing to until today, μSi/a-Si module are available and as seen in the graph, efficiency decreases slightly. When we check the manual efficiency and measured efficiency from table 4.1, there is no large difference. Due to it is not expecting to reach the efficiency at STM, this value is acceptable to be real efficiency.

When we investigate the efficiencies of modules in the interval May 2017-May 2018 and May 2020- May 2021 as shown in the figure 4.2.On the graph of May 2020- May 2021 the efficiencies slightly less than the efficiencies on the graph of May 2017-May 2018.

For example, the efficiency of "Bifi-Mono-Si" modules is almost 18% on 2017-2018 while roughly 17% on 2020-2021. The reason of this drop is because of degradation of the modules.

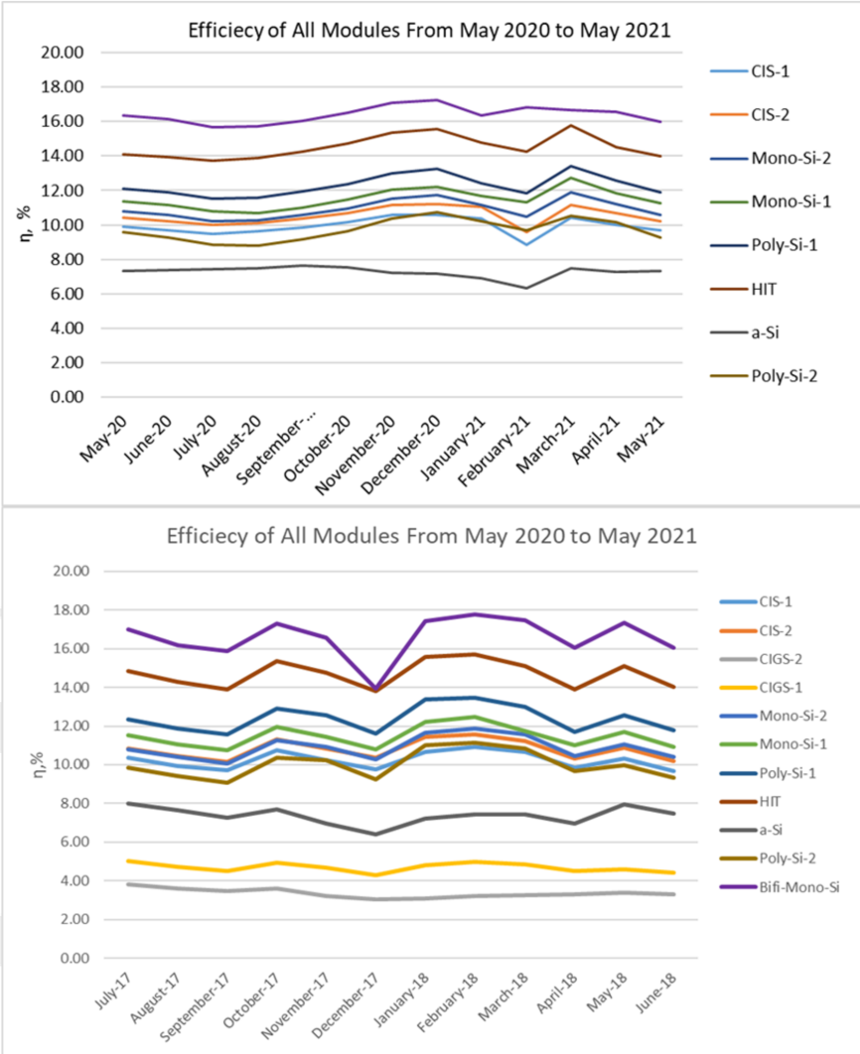


Figure 4.2: The compare of efficiencies of modules 2017-2018 with 2020-2021

4.2 Performance Rates and Corrected Performance Rates of Modules

4.2.1 Performance Rate without Temperature

Performance rates of modules are calculated according to eq.32. As shown in the figure 4.3 and 4.4, performance rates of modules at winter and summer months bit decrease in different ranges because of temperature difference. At the STC, the temperature is $25°C$ and when the temperatures of modules larger than $25°C$, performance rates decrease. In addition to that, temperature and conductivity in the semiconductor are inversely proportional. Therefore, in the summer,performance rates reduce noticeably. At the graph of 2017-2018, CIGS-1 and CIGS-2 have too low performance rates.

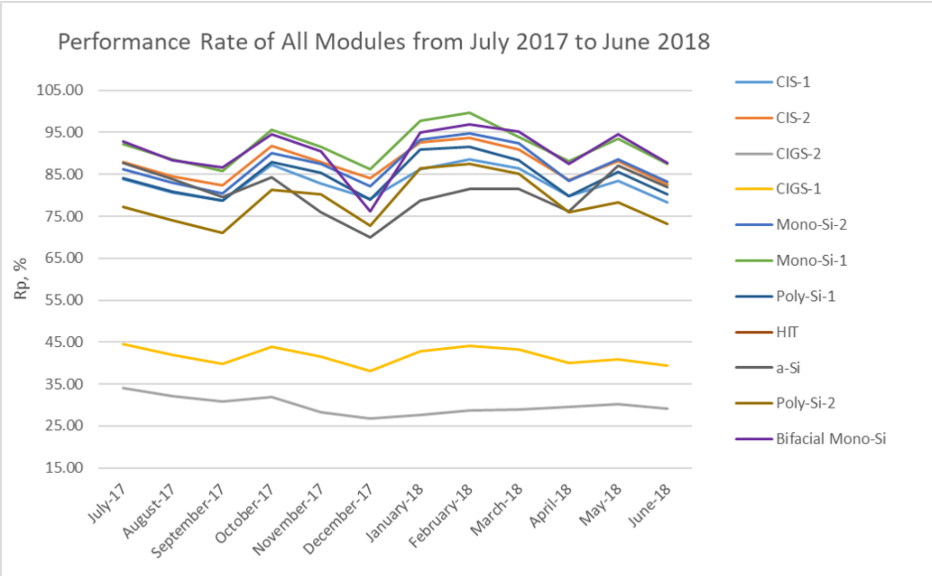


Figure 4.3: The performance Rate of Modules 2017-2018

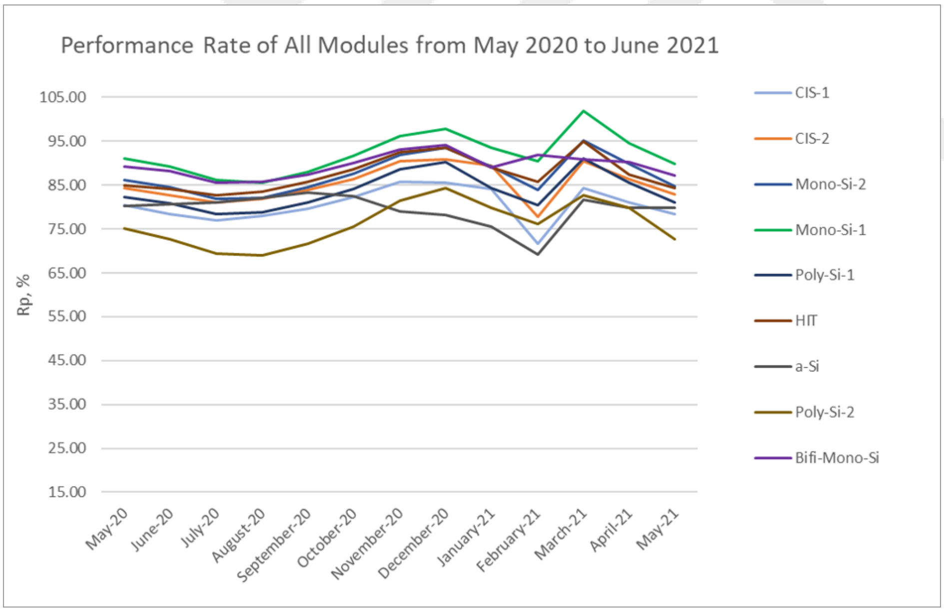


Figure 4.4: The performance Rate of Modules 2020-2021

When we look at the graph of 2020-2021 for performance rates of modules, it is observed that CIGS-1 and CIGS-2 modules were uninstalled and there are only 9 modules. Their performance rates are close to each other except μSi/a-Si. Their performances decreases February. This situations, both graphs are for degraded modules and some of them are available almost nine years. Performance rates.

In the both graphs, it is observed that performance rates for some modules exceeds over 100 and this doesn't look like logical and this is observed in the winter months and low temperature is responsible for this exceeding.

4.2.2 Temperature-corrected Performance Ratio

Table 4.2: The Values of Corrected Performance Rate and Performance Rates of Modules for 2020-2021 years

Month	CIS-1 Corrected	CIS-1	CIS-2 Corrected	CIS-2	HIT Corrected	HIT	μSi/a-Si Corrected	μSi/a-Si	Poly-Si-2 Corrected	Poly-Si-2
May-20	79.50	80.35	83.73	84.41	84.14	84.88	79.83	80.33	73.73	75.12
June-20	78.15	78.47	82.19	82.74	83.82	84.04	80.40	80.65	72.68	72.72
July-20	74.88	76.92	78.64	80.97	81.14	82.70	79.84	81.14	67.39	69.38
August-20	76.11	77.99	79.80	81.97	82.19	83.57	80.90	82.04	67.17	68.94
September-20	78.59	79.68	82.59	83.92	85.10	85.82	82.72	83.32	70.78	71.75
October-20	81.37	82.23	85.64	86.41	87.65	88.60	81.89	82.56	74.36	75.48
November-20	81.30	85.77	85.94	90.56	88.55	92.61	76.32	79.08	76.24	81.55
December-20	80.52	85.55	85.51	90.79	89.13	93.64	75.28	78.28	77.90	84.41
January-21	78.38	84.12	83.34	89.36	84.18	89.08	72.14	75.45	72.95	79.92
February-21	67.40	71.66	73.33	77.82	81.69	85.79	66.52	69.17	68.02	76.12
March-21	79.37	84.32	85.32	90.47	90.58	95.01	78.70	81.75	75.67	82.71
April-21	78.43	81.15	83.68	86.44	85.11	87.44	78.17	79.83	76.56	79.79
May-21	78.16	78.36	82.91	82.93	84.06	84.25	79.79	79.88	72.35	72.72

In the corrected performance rates, we can observe rather little decreasing for the module performance rates. The calculation of corrected performance rates could be done after April 2016, since before this time, the measurement of temperature of module could not be done. The temperature sensors were connected in 2016.

According to these results, the differences between corrected performance rates and performance rates increase during summer and winter while decrease during spring and autumn. Especially in the winter, the gap is growing. In the table 4.2, there are performance rates values and corrected ones are from May 2020 to May 2021.

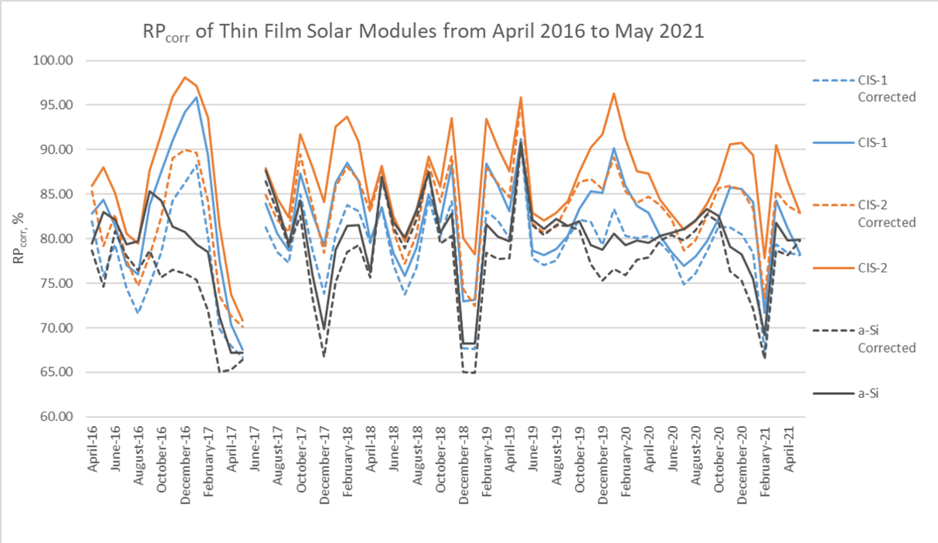


Figure 4.5: R_p and RP_{Corr} of Thin Film Modules from April 2016 to May 2021

In figure 4.5, there is a graph showing the (RP_{Corr}) and R_p of thin film modules, which are CIS-1 & 2 and μSi/a-Si, from April 2016 to May 2021. According to this graph, there is no degradation in the visual inspection. The dashed line represents the RP_{Corr} and the straight line represents R_p. While increasing the gap between RP_{Corr} and R_p in the winter and summer, in the spring and autumn months, they get closer to each other.

In figure 4.6, crystalline solar modules , which are HIT and Poly-Si-2 are shown. Similar to the thin film modules, RP_{Corr} and R_p are are different in the summer and winter months. The reason of that is the module temperature is increasing larger amount or decreasing too much during the summer and winter respectively.

4.3 Degradation Rates

Degradation rates can be calculated by using two methods. In the first one, efficiency is used in eq. 38 as "n". To find R_d, figure 4.1 is used. The following table shows the equation of the slope for all panels. At some months, the system failed and measurement could be done or meaningful data could not be obtained as seen in graph 4.1.

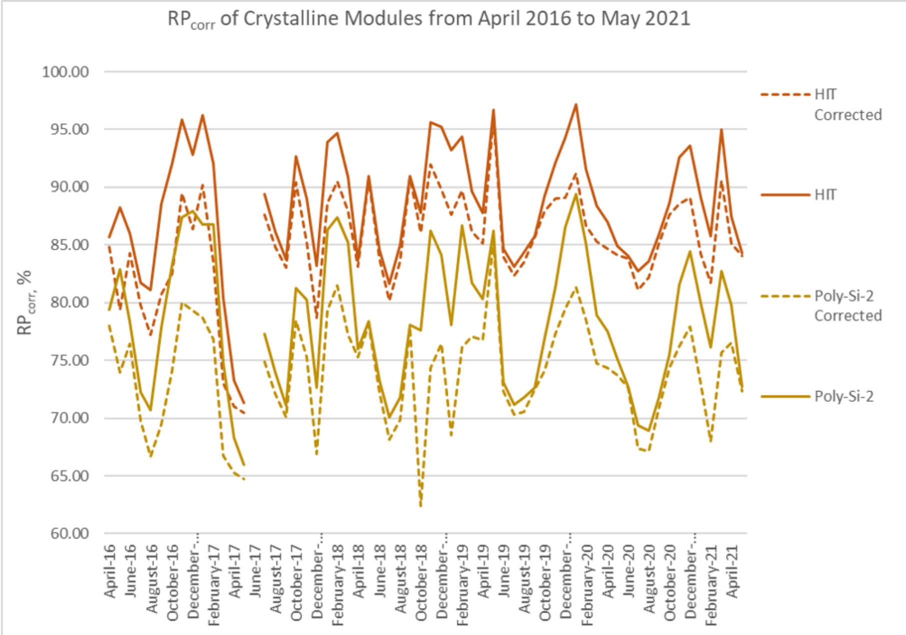


Figure 4.6: R_p and RP_{Corr} of Crystalline Modules from April 2016 to May 2021

In this study, the calculation of R_d is carried out using two different schemes. Firstly, the number of months from beginning to the end the months having no data are not taken into account. Since the modules are exposed to solar irradiation and ambient parameters. It degrades somehow even if it is not measured. The second way is that calculation of R_d for these months is done by using the number of month having data.

In the following table 4.3, there are the equations of the slopes. In this graph, the slope must be negative because the modules must generate less energy in comparison with the and previous times.

In the following table, there are degradation rates (R_d) calculated by both performance rates (R_p) and efficiency(η) and also the average values taken from a NREL publication [36] for the similar modules manufactured as pre and post. Pre and post means that the vales presented before and after the year of 2000 respectively. NREL reached these value by using almost 2000 publicized R_d values. According to these results, R_d are close to each other for both methodof calculations. While R_d for Poly-Si-2 is almost the same for μSi/a-Si ,Mono-Si-1, Mono-Si-2 and Poly-Si-2. In addition, CIS-1, CIS-2, CIGS-1, CIGS-2 and HIT are also close to each other.

If we look at the literature value that is identified by NREL, R_d's for all modules are

Table 4.3: The equation of slope plotted the graph of efficiency of all modules in Figure 4.1

CIS-1	y = -0.0135x + 11.298
CIS-2	y = -0.0097x + 11.536
CIGS-1	y = -0.1022x + 11.636
CIGS-2	y = -0.0439x + 6.3106
μSi/a-Si	y = -0.0056x + 7.7797
Mono-Si-1	y = -0.0023x + 11.755
Mono-Si-2	y = -0.0085x + 11.752
Mono-Si-3	y = -0.0284x + 14.001
Bifi Mono-Si	y = 0.0054x + 16.036
HIT	y = -0.0068x + 15.281
Poly-Si-1	y = -0.0084x + 13.141
Poly-Si-2	y = -0.0127x + 11.092

quite different from measured values. For some of these degradation rates R_d's, there is a large difference between measured and NREL values. For instance, CIGS-1 and CIGS-2 have R_d values are differently as shown in the table 4.4 with 10.66 %/year and 7.18 %/year, respectively. We can conclude that these modules have some problems due to fabrication failures.

NREL values for Mono-Si-3 are again quite different form the measured values with 4.18 %/year while 0.6 %/year in the NERL archive. The difference of R_d is caused climate conditions, which may be the topic of further study. Other modules have close but slightly different values if it is compared with the NREL ones.

If we investigate using the time period for the months that the measurements are carried out as shown in table 4.5, it is observed that R_d increase with small amount in comparison with table 4.4. Of course this result is expected. In this calculation procedure, while the number of months decreasing, the time interval generating electricity of module procedure does not change. It seems that the degradation is increasing.

When all results are compared for all modules and all situations, Mono-Si-1 is the

Table 4.4: The table of R_d calculating from R_p and η with time interval the module generating energy and R_d according to NREL.

	# months real	$R_d(R_p)$	$R_d(\eta)$	NREL (Pre)	NREL (Post)
CIS-1	80	2.21	2.16	–	–
CIS-2	80	1.72	1.70	–	–
CIGS-1	69	10.66	10.54	$\sim$1.9	$\sim$1.2
CIGS-2	75	7.18	7.06	$\sim$1.9	$\sim$1.2
μSi/a-Si	110	0.68	0.67	$\sim$1.8	$\sim$1.1
Mono-Si-1	110	0.49	0.48	$\sim$0.6	$\sim$0.6
Mono-Si-2	106	1.12	1.11	$\sim$0.6	$\sim$0.6
Mono-Si-3	32	4.18	4.06	$\sim$0.6	$\sim$0.6
Bifi-Mono-Si	62	–	–	–	–
HIT	95	1.09	1.08	–	–
Poly-Si-1	110	1.04	1.02	$\sim$0.7	$\sim$0.7
Poly-Si-2	109	1.82	1.79	$\sim$0.7	$\sim$0.7

best module to use long term. Its degradation rate R_d is only 0.49 %/year. Actually, Bifi-Mono-Si looks like smaller R_d but, it couldn't be evaluated. Without considering the modules having If we don't take account into the modules with problematic fabrication, Poly-Si-2 is a less effective module for long term use whose R_d is 1.82 %/year. In addition to these inference, μSi/a-Si module has good R_d with 0.68 %/year. It is acceptable for long term use according to measurement results while the NERL values, which is 1.1 %/year, is higher than our measurement findings

On the other hand, the calculated degradation rates by using corrected performance ratio (RP_{Corr}) in this study only 5 modules, which are CIS-1, CIS-2, HIT, μSi/a-Si, Poly-Si-2 are calculated as mentioned in section 4.2.2. By using the trend line of the graphs in the figure 4.5 and 4.6, the equation of slopes are obtained and presented in table 4.6. The slope of equations (in the eq. 37 is "m") must be negative because of the degradation of modules. Nevertheless, the observations are different as given in the table. All modules have positive slopes and that means that the performance of all modules increase with time although slopes are too small. Hence, the fact that

Table 4.5: The table of R_d calculating from R_p and η with time interval the measured months and R_d according to NREL.

	# months data	$R_d(R_p)$	$R_d(\eta)$	NREL (Pre)	NREL(Post)
CIS-1	74	2.43	2.37	–	–
CIS-2	74	1.88	1.86	–	–
CIGS-1	55	13.62	13.47	$\sim$1.9	$\sim$1.2
CIGS-2	59	9.29	9.13	$\sim$1.9	$\sim$1.2
μSi/a-Si	96	0.79	0.77	$\sim$1.8	$\sim$1.1
Mono-Si-1	96	0.57	0.56	$\sim$0.6	$\sim$0.6
Mono-Si-2	92	1.31	1.29	$\sim$0.6	$\sim$0.6
Mono-Si-3	22	5.95	5.78	$\sim$0.6	$\sim$0.6
Bifi-Mono-Si	61	–	–	–	–
HIT	84	1.24	1.23	–	–
Poly-Si-1	96	1.20	1.19	$\sim$0.7	$\sim$0.7
Poly-Si-2	95	2.12	2.10	$\sim$0.7	$\sim$0.7

the calculation of degradation rates via RP_{Corr} or whether it can be done by using RP_{Corr} seems not reasonable and can be a further topics to study.

Table 4.6: Equations of Slope of Graph for Corrected Performance Rate of 5 Modules

CIS-1	y = 0.0141x + 78.316
CIS-2	y = 0.0405x + 81.69
μSi/a-Si	y = 0.042x + 76.191
HIT	y = 0.0791x + 82.594
Poly-Si-2	y = 0.0101x + 73.539

CHAPTER 5

CONCLUSION

In this thesis, 12 different solar modules of three different groups were analyzed in terms of outdoor performance for Middle Anatolia region. Tests included nine years data from April 2012 to May 2021. In this long term analysis, efficiencies, performance ratios, corrected performance ratios and degradation rates in both methods (efficiency and performance ratio) were calculated and analyzed by plotting graphs. Also degradation rates were compared to each other and with the NREL results.

In the measurements, some data were missed because of system problem. To catch up these missing data, firstly, a code was written in the python. After finding these data, they are inserted to data file properly. Secondly, filtering was done and only meaningful data were taken into account and to calculation. Using monthly data, efficiency, performance ratio and corrected performance ratio were calculated by using excel files.

The efficiencies of modules were as expected in comparison with their fabricated value except CIGS-1 & 2. While the manual value was 11.25 % , the measured ones were 6.73 % and 4.36 %. These values are too low to use these module and as depicted chapter 4 since CIGS-1 & 2. modules had some fabrication problems. The most effective module was Bi-facial Mono-Si as expected with 16.47 % average efficiency and except problematic modules the lowest effective module was a-Si. The closest efficiency of measured one to the laboratory value (14.48 %) was Mono-Si-3 with 13.27 %.

Performance rates were investigated and they were obtained as expected. Mono-Si-1 had the best performance ratios between 2017-2018 and 2020-2021. Its highest value was at January 2021 with 101.85 %. The worst performance ratios were CIGS-1 & 2. As explained before, these modules had fabrication problems. After these modules, Poly-Si-2 had the minimum performance ratio with 48.43 % at April 2017 and generally this module had the worst performance ratio. In addition, corrected performance ratio were calculated. This calculation can be done for only 5 modules because any information about temperature coefficient of other modules couldn't be measured. The most effective PV module was HIT. This factor depended on the module temperature and while increasing or decreasing the module temperature, corrected performance rate decreases. We can say that, HIT modules was not heated to much during its operation.

The most important study of this thesis is degradation rate of testing modules. For calculating this values, two of methods were used and these degradation rates were compared by each other. For Bifi-Mono-Si module, any degradation rate couldn't be found because its slope was positive. We can say that Bifi-Mono-Si module don't have enough information to determine the degradation rate. For other modules, the degradation rates were calculated by using efficiency and performance ratio. For first method as expected and due to problematic fabrication, CIGS-1 & 2 has the worst degradation rates as 10.66%/year and 7.18 %/year, respectively. For degradation rates using second method calculation for these modules are 10.54 %/year and 7.06 %/year respectively. Also Mono-Si-3 had the problematic fabrication and it degraded with 4.18 %/year and 4.06 %/year, respectively. Also the best one is Mono-Si-1 module with 0.49 %/year and 0.48 %/year according to the first and second method respectively. Its NREL value is around 0.6. The closest value of degradation ratio was Poly-Si- 1. While the measured values are 1.04 %/year and 1.02 %/year for first and second method respectively, the NREL value is 0.7 %/year. This thesis, long term efficiencies, performance ratios and degradation rates were analyzed. According to all of these results, Mono-Si technology modules are both more effective and less degrade in comparison to all module for nine years study.

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Appendix A

CALCULATION SCRIPTS

A.1 Finding Missing Data

```
def missingDataFinding(rawData, year, month):

    missingData = 0
    for index in range((int)((len(rawData)))):
        day = math.ceil((index + 1) / 144)
        hour = int((index  144) / 6)
        minute = 10  (index  6)
        date = ( 0  if month  10 else  ) + str(month) + ( /0  if day  10 else  / ) + str(day) +  /  + str(year)
        time = ( 0  if hour  10 else  ) + str(hour) + ( :  if minute  0 else  :0 ) + str(minute) +  :00
        if (rawData[ Date ][index  missingData] != date or rawData[ Time ][index  missingData] != time):
            print("wrong data in " + date +  and  + time)
            missingData += 1
```

A.2 Transforming Daily Data

```
def mouthlyCal(mounthData) :
    invalidData = mounthData[mounthData[ Aux2 ]  10]  filtering for less than 10 for irradietion.

    Powers = [ Power101 ,  Power102 ,  Power103 ,  Power104 ,  Power105 ,  Power106 ,
               Power107 ,  Power108 ,  Power109 ,  Power110 ,  Power111 ,  Power112 ,
               Power113 ,  Power114 ,  Power115 ,  Power116  ]
    Irradiation = [ Aux1 ,  Aux2 ,  Aux3 ,  Aux4 ,  Aux5 ,  Aux6 , Aux7 , Aux8 ]
    Tempratures = [ Temp1 , Temp2 , Temp3 , Temp4 , Temp5 , Temp6 , Temp7 , Temp8 , Temp9 , Temp10 ,
                    Temp11 , Temp12 , Temp13 , Temp14 , Temp15 , Temp16 , Temp17 , Temp18 , Temp19 , Temp20 ,
                    Temp21 , Temp22 , Temp23 , Temp24 ]

    mounthData.loc[invalidData.index, Powers] = 0  if irradietion getting from direct beam smaller than 10, they become 0


    for power in Powers:
        mounthData[power] = mounthData[power] / 6  unit conversion from W to Wh
    for radiation in Irradiation:
        mounthData[radiation] = mounthData[radiation] / 6  unit conversion from W to Wh

    Hourly = pa.DataFrame()
    Daily = pa.DataFrame()
    for power in Powers:
        Hourly[power] = [0.00]  ((int)(len(mounthData) / 6))
        Daily[power] = [0.00]  ((int)(len(Hourly) / 24))
        for day in range((int)(len(mounthData) / (24  6))):
            for hour in range(24):
```

```
            if np.isnan(mounthData[power][day  24  6 + hour  6]):
                Hourly[power][day  24 + hour] = np.NaN
            else:
                for i in range(6):
                    Hourly[power][day  24 + hour] += mounthData[power][day  24  6 + hour  6 + i]
                if (Hourly[power][day  24 + hour]  1):
                    Hourly[power][day  24 + hour] = np.NaN
                else:
                    Daily[power][day] += Hourly[power][day  24 + hour]
        if(Daily[power][day]  1):
            Daily[power][day] = np.NaN

    for radiation in Irradiation:
        Hourly[radiation] = [0.00]  ((int)(len(mounthData) / 6))
        Daily[radiation] = [0.00]  ((int)(len(Hourly) / 24))
        for day in range((int)(len(mounthData) / (24  6))):
            nanRad = 0
            for hour in range(24):
                if np.isnan(mounthData[radiation][day  24  6 + hour  6]):
                    Hourly[radiation][day  24 + hour] = np.NaN
                    nanRad +=1
                else:
                    for i in range(6):
                        Hourly[radiation][day  24 + hour] += mounthData[radiation][day  24  6 + hour  6 + i]
                    if (Hourly[radiation][day  24 + hour]  0):
                        Hourly[radiation][day  24 + hour] = np.NaN
                    else:
                        Daily[radiation][day] += Hourly[radiation][day  24 + hour]
            if (nanRad  8):
                Daily[radiation][day] = np.NaN

    for temp in Tempratures:
        Hourly[temp] = [0.00]  ((int)(len(mounthData) / 6))
        Daily[temp] = [0.00]  ((int)(len(Hourly) / 24))
        for day in range ((int)(len(mounthData) / (24  6))):
            nanTemp=0
            for hour in range(24):
                if np.isnan(mounthData[temp][day  24  6 + hour  6]):
                    Hourly[temp][day  24 + hour] = np.NaN
                    nanTemp +=1
                else:
                    for i in range(6):
                        Hourly[temp][day  24 + hour] += mounthData[temp][day  24  6 + hour  6 + i]
                    Hourly[temp][day  24 + hour] /= 6
                    Daily[temp][day] += Hourly[temp][day  24 + hour]
            if (nanTemp  12):
                Daily[temp][day] = np.NaN
            else:
                Daily[temp][day] /= 24

    return (Daily)
```

A.3 Transforming Monthly Data

```
def yearlyCal(DailyData, MontlyPowers, month):

    Powers = [ Power101 , Power102 , Power103 , Power104 , Power105 , Power106 ,
               Power107 , Power108 , Power109 , Power110 , Power111 , Power112 ,
               Power113 , Power114 , Power115 , Power116 ]
    Irradiation = [ Aux1 , Aux2 , Aux3 , Aux4 , Aux5 , Aux6 , Aux7 , Aux8 ]
    Tempratures = [ Temp1 , Temp2 , Temp3 , Temp4 , Temp5 , Temp6 , Temp7 , Temp8 , Temp9 , Temp10 ,
```

```
                Temp11 ,  Temp12 ,  Temp13 ,  Temp14 ,  Temp15 ,  Temp16 ,  Temp17 ,  Temp18 ,  Temp19 ,  Temp20 ,
                Temp21 ,  Temp22 ,  Temp23 ,  Temp24 ]

isempty=False
if(len(MontlyPowers) == 0):
    isempty=True

for power in Powers:
    if(isempty):
        MontlyPowers[power] = [0.00]   12
    TotalPower = 0.00
    for i in range((int)(len(DailyData))):
        if np.isnan(DailyData[power][i]):
            TotalPower += 0
        else:
            TotalPower += DailyData[power][i]
    MontlyPowers[power][month] = TotalPower
    if (MontlyPowers[power][month] == 0):
            MontlyPowers[power][month] = np.NaN

for radiadition in Irradiation:
    if(isempty):
        MontlyPowers[radiadition] = [0.00]   12
    TotalRadiadition = 0.00
    for i in range ((int)(len(DailyData))):
        if np.isnan(DailyData[radiadition][i]):
            TotalRadiadition += 0
        elif (DailyData[radiadition][i]   10):
            TotalRadiadition += 0
        else:
            TotalRadiadition += DailyData[radiadition][i]
    MontlyPowers[radiadition][month] = TotalRadiadition
    if (MontlyPowers[radiadition][month]   2):
            MontlyPowers[radiadition][month] = np.NaN


for temp in Tempratures:
    if(isempty):
        MontlyPowers[temp] = [0.00]   12
    TotalTemprature = 0.00
    for i in range((int)(len(DailyData))):
        if np.isnan(DailyData[temp][i]):
            TotalTemprature += 0
        else:
            TotalTemprature += DailyData[temp][i]
    MontlyPowers[temp][month] = TotalTemprature/(int)(len(DailyData))
    if (MontlyPowers[temp][month]   50):
            MontlyPowers[temp][month] = np.NaN
return (MontlyPowers)
```

Appendix B

MONTHLY DATA

B.1 Monthly Efficiency

Table B.1: Efficiencies of all modules during testing time

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
	February-12												
	March-12												
	April-12						12.12	13.15			8.42		
	May-12						11.55	12.87			8.18	10.74	
	June-12						11.02	12.29			8.04	10.00	
2012	July-12						10.59	11.81			7.81	9.83	
	August-12			6.66		11.16	11.32	12.62			8.31	10.48	
	September-12			6.04		10.37	10.50	11.72			7.55	9.72	
	October-12			6.06		11.38	11.52	12.88	13.00		7.89	10.76	
	November-12			5.98		12.15	12.31	13.85	13.95		7.92	11.66	
	December-12			6.46		12.46	12.77	14.30	14.35		7.70	12.00	
	January-13			6.80	12.05	13.67	13.40	15.50	15.55		8.07	12.62	
	February-13			5.44	9.57	11.39	11.61	12.92	12.84		7.26	10.92	
	March-13			5.87	9.99	11.88	12.15	13.48	13.19		7.67	11.37	
	April-13												
	May-13												
	June-13												
2013	July-13			5.01	8.16	10.16	10.33	11.42	11.51	11.77	7.32	9.49	
	August-13												
	September-13			5.23	8.76	10.93	11.12	12.31	12.28	13.85	7.68	10.19	
	October-13			5.30	9.21	11.40	11.61	12.88	12.93	15.29	7.56	10.73	
	November-13			5.47	10.06	12.51	12.72	14.15	14.25	16.88	7.88	11.85	
	December-13				11.52	13.18	13.42	14.93	15.17	17.66	7.75	12.62	

Table B.1 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
	January-14			5.43	10.71	13.62	13.97	15.51	15.49	18.15	8.33	13.08	
	February-14			5.10	9.21	11.46	11.68	12.93	13.08	15.21	7.08	10.88	
	March-14			4.55	8.35	10.55	10.81	11.94	11.57	13.54	6.75	9.98	
	April-14			4.81	8.67	11.08	11.32	12.46	12.29	14.36	7.27	10.47	
	May-14			4.74	8.48	11.00	11.24	12.34	12.27	14.32	7.39	10.35	
2014	June-14												
	July-14												
	August-14												
	September-14												
	October-14	10.61	10.99	4.53	8.34	11.32	11.42	12.55		15.01	7.61	10.50	
	November-14	14.15	14.72	5.97	11.73	15.12	15.29	17.00	17.22	20.06	9.49	14.30	
	December-14	12.42	12.70		10.24	12.71	13.09	14.48	14.68	16.77	7.74	12.26	
	January-15	11.46	11.38	4.87	9.69	10.76	11.01	12.51	12.20	15.04	6.52	10.45	
	February-15	11.04	11.17	4.47	8.79	11.91	12.32	13.68	12.86	15.22	7.32	11.13	
	March-15	10.51	10.87	4.19	7.90	11.29	11.55	12.66	12.59	14.52	7.10	10.65	
	April-15												
	May-15	10.04	10.38	4.20	7.11	10.74	10.98	12.01	12.09	14.11	7.24	9.89	
2015	June-15												
	July-15	9.75	10.14	4.21	6.28	10.44	10.58	11.61	11.79	13.88	7.38	9.45	
	August-15	9.44	9.82	4.03	5.79	10.10	10.26	11.25	11.46	13.46	7.28	9.12	
	September-15	10.16	10.55	4.23	5.99	10.82	11.02	12.04	12.25	14.44	7.69	9.74	
	October-15	10.45	10.90	3.97	6.02	11.27	11.50	12.58	14.13	14.85	7.62	10.40	
	November-15	13.56	14.01	5.13	7.70	14.29	14.60	15.98		18.93	8.86	13.34	
	December-15												
	January-16												
	February-16												
	March-16												
	April-16	10.21	10.60	3.92	5.70	10.90	11.17	12.02		14.22	7.26	10.12	16.41
	May-16	10.41	10.85	3.78	5.78	11.37	11.70	12.55		14.65	7.59	10.56	16.91
2016	June-16	10.05	10.50	3.80	5.48	10.92	11.20	12.06		14.27	7.51	9.98	16.24
	July-16	9.51	9.94	3.72	5.06	10.26	10.35	11.30		13.55	7.26	9.21	15.56
	August-16	9.37	9.81	3.66	4.91	10.07	10.27	11.13		13.45	7.28	9.02	15.42
	September-16	10.33	10.81	3.91	5.29	10.89	11.36	12.25		14.69	7.80	9.92	16.52
	October-16	10.79	11.31	3.85	5.44	11.46	11.85	12.90		15.28	7.71	10.61	17.38
	November-16	11.23	11.84	3.92	5.98	11.92	12.28	13.48		15.90	7.43	11.13	18.05
	December-16	11.63	12.11	3.99	6.33	11.69	12.42	13.22		15.40	7.38	11.21	16.95

Table B.1 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono-Si-2	Mono-Si-1	Poly-Si-1	Mono-Si-3	HIT	a-Si	Poly-Si-2	Bi-facial Mono-Si
2017	January-17	11.83	11.99	3.56	5.73	12.19	12.01	13.06		15.97	7.25	11.05	16.78
	February-17	11.03	11.55	3.70	5.40	11.77	12.27	13.19		15.27	7.18	11.05	17.46
	March-17	9.56	10.04	3.23	4.59	10.24	10.63	11.42		13.35	6.51	9.53	15.37
	April-17	8.68	9.09	2.96	4.11	9.31	9.72	10.39		12.16	6.14	8.70	14.20
	May-17	8.33	8.74	2.76	3.92	9.02	9.46	10.15		11.83	6.14	8.41	13.93
	June-17	8.05	8.45	2.79	3.64	8.77	9.17	9.90		11.59	6.15	8.05	13.52
	July-17	9.72	10.18	3.59	4.64	10.14	10.81	11.59		13.96	7.53	9.26	15.96
	August-17	9.94	10.43	3.61	4.73	10.39	11.07	11.89		14.29	7.67	9.42	16.17
	September-17	9.70	10.17	3.46	4.49	10.06	10.73	11.55		13.90	7.27	9.06	15.86
	October-17	10.77	11.31	3.58	4.95	11.26	11.96	12.92		15.38	7.71	10.36	17.31
	November-17	10.22	10.86	3.19	4.67	10.94	11.44	12.55		14.77	6.94	10.23	16.57
	December-17	9.77	10.38	3.03	4.28	10.27	10.79	11.60		13.81	6.39	9.26	13.94
2018	January-18	10.65	11.43	3.10	4.83	11.67	12.23	13.37		15.58	7.20	11.00	17.42
	February-18	10.92	11.56	3.22	4.96	11.86	12.47	13.46		15.71	7.45	11.14	17.77
	March-18	10.67	11.21	3.26	4.87	11.56	11.75	12.99		15.08	7.45	10.86	17.46
	April-18	9.85	10.31	3.32	4.50	10.44	11.01	11.72		13.88	6.97	9.69	16.04
	May-18	10.30	10.88	3.40	4.60	11.07	11.70	12.58		15.09	7.96	9.99	17.33
	June-18	9.67	10.18	3.28	4.43	10.41	10.94	11.77		14.03	7.49	9.34	16.06
	July-18	9.36	9.83	3.19	4.23	9.99	10.58	11.35		13.55	7.33	8.94	15.46
	August-18	9.74	10.23	3.37	4.34	10.38	10.90	11.68		14.10	7.61	9.15	15.91
	September-18	10.49	11.01	3.53	4.58	11.19	11.78	12.64		15.09	8.00	9.95	16.99
	October-18	10.10	10.59			10.77	11.38	12.29		14.56	7.37	9.90	16.33
	November-18	10.89	11.54			11.76	12.40	13.49		15.87	7.57	10.99	17.69
	December-18	9.00	9.87			11.37	11.45	11.76		15.80	6.24	10.72	14.46
2019	January-19	9.02	9.66			11.12	11.29	11.66		15.46	6.24	9.95	14.53
	February-19	10.91	11.53			11.80	12.47	13.49		15.65	7.46	11.05	17.52
	March-19	10.62	11.13			11.28	11.93	12.81		14.87	7.33	10.42	16.83
	April-19	10.24	10.81			11.14	11.74	12.60		14.56	7.29	10.24	16.70
	May-19	11.25	11.82			12.15	12.86	13.77		16.05	8.30	10.99	18.47
	June-19	9.71	10.23			10.53	11.12	11.93		14.05	7.51	9.32	16.12
	July-19	7.92	8.32			8.48	8.96	9.59		11.33	6.09	7.46	13.17
	August-19	9.73	10.23			10.41	10.98	11.78		13.99	7.52	9.15	16.13
	September-19	9.91	10.39			10.57	11.15	12.00		14.23	7.45	9.26	16.22
	October-19	10.28	10.79			11.01	11.60	12.51		14.80	7.49	9.81	16.78
	November-19	10.53	11.13			11.38	11.96	12.98		15.28	7.25	10.37	17.23
	December-19	10.50	11.32			11.81	12.25	13.48		15.64	7.20	11.03	17.56

Table B.1 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
2020	January-20	11.13	11.88			12.25	12.80	14.00		16.12	7.37	11.39	17.98
	February-20	10.60	11.25			11.69	12.30	13.21		15.19	7.25	10.85	17.10
	March-20	10.32	10.80			11.26	11.83	12.57		14.67	7.30	10.06	16.89
	April-20	10.23	10.77			11.08	11.65	12.46		14.44	7.27	9.88	16.57
	May-20	9.91	10.41			10.78	11.38	12.08		14.08	7.34	9.57	16.37
	June-20	9.68	10.21			10.57	11.15	11.87		13.94	7.37	9.27	16.15
	July-20	9.49	9.99			10.23	10.78	11.53		13.72	7.42	8.84	15.67
	August-20	9.62	10.11			10.27	10.70	11.57		13.87	7.50	8.79	15.71
	September-20	9.83	10.35			10.57	11.00	11.92		14.24	7.62	9.14	16.03
	October-20	10.14	10.66			10.95	11.47	12.35		14.70	7.55	9.62	16.51
	November-20	10.58	11.17			11.50	12.03	13.01		15.37	7.23	10.39	17.06
	December-20	10.55	11.20			11.71	12.23	13.26		15.54	7.16	10.76	17.25
2021	January-21	10.38	11.02			11.15	11.69	12.40		14.78	6.90	10.19	16.32
	February-21	8.84	9.60			10.48	11.30	11.83		14.23	6.32	9.70	16.83
	March-21	10.40	11.16			11.90	12.73	13.39		15.76	7.47	10.54	16.66
	April-21	10.01	10.66			11.22	11.83	12.57		14.51	7.30	10.17	16.55
	May-21	9.67	10.23			10.60	11.23	11.91		13.98	7.30	9.27	15.97
	June-21												

B.2 Monthly Performance Rates

Table B.2: Performance rates of all modules during testing time

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
2012	January-12												
	February-12						96.94	89.51			92.13		
	March-12						92.39	87.60			89.46	84.24	
	April-12						88.12	83.65			87.98	78.42	
	May-12			60.65			84.68	80.41			85.44	77.14	
	June-12			59.20		89.30	90.53	85.90			90.87	82.26	
	July-12			53.75		82.98	83.96	79.78			82.55	76.26	
	August-12			53.87		91.02	92.14	87.67	89.77		86.34	84.46	
	September-12			53.14		97.19	98.44	94.26	96.30		86.65	91.50	
	October-12			57.48		99.67	102.13	97.32	99.10		84.25	94.14	

Table B.2 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
	November-12			60.49	107.11	109.32	107.20	105.50	107.36		88.26	98.99	
	December-12			48.37	85.07	91.12	92.90	87.91	88.68		79.46	85.70	
2013	January-13			52.23	88.82	95.04	97.22	91.74	91.09		83.88	89.18	
	February-13												
	March-13												
	April-13												
	May-13			44.58	72.52	81.30	82.59	77.73	79.47	70.94	80.06	74.42	
	June-13												
	July-13			46.48	77.91	87.41	88.96	83.76	84.80	83.50	84.05	79.94	
	August-13			47.15	81.86	91.22	92.85	87.65	89.28	92.14	82.64	84.18	
	September-13			48.65	89.46	100.07	101.78	96.34	98.38	101.74	86.23	92.95	
	October-13				102.43	105.41	107.32	101.63	104.75	106.45	84.78	98.99	
	November-13			48.28	95.25	108.90	111.76	105.59	106.96	109.40	91.08	102.64	
	December-13			45.36	81.89	91.69	93.45	88.00	90.29	91.69	77.41	85.35	
2014	January-14			40.48	74.21	84.41	86.51	81.25	79.85	81.62	73.83	78.31	
	February-14			42.81	77.07	88.63	90.58	84.80	84.85	86.54	79.49	82.18	
	March-14			42.18	75.44	88.01	89.89	83.99	84.71	86.29	80.78	81.21	
	April-14												
	May-14												
	June-14												
	July-14												
	August-14	85.98	89.09	40.25	74.17	90.57	91.35	85.44		90.45	83.20	82.40	
	September-14	114.72	119.34	53.11	104.28	120.90	122.27	115.73	118.88	120.89	103.83	112.21	
	October-14	100.71	102.92		91.01	101.64	104.73	98.55	101.35	101.07	84.63	96.19	
	November-14	92.90	92.24	43.28	86.17	86.06	88.03	85.12	84.25	90.67	71.36	81.99	
	December-14	89.47	90.55	39.77	78.12	95.27	98.51	93.14	88.78	91.74	80.05	87.36	
2015	January-15	85.21	88.12	37.30	70.28	90.31	92.40	86.14	86.92	87.51	77.64	83.53	
	February-15												
	March-15	81.35	84.17	37.33	63.26	85.91	87.82	81.71	83.47	85.03	79.22	77.60	
	April-15												
	May-15	79.06	82.20	37.41	55.80	83.48	84.66	79.04	81.41	83.64	80.70	74.16	
	June-15	76.56	79.64	35.83	51.45	80.80	82.09	76.56	79.12	81.10	79.63	71.55	
	July-15	82.36	85.55	37.62	53.25	86.52	88.11	81.96	84.55	87.01	84.10	76.42	
	August-15	84.67	88.35	35.33	53.50	90.11	91.96	85.60	97.53	89.53	83.29	81.57	
	September-15	109.91	113.57	45.64	68.47	114.31	116.76	108.73		114.10	96.88	104.65	
	October-15												
	November-15												

Table B.2 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
	December-15												
2016	January-16												
	February-16	82.78	85.93	34.81	50.66	87.19	89.38	81.83		85.70	79.43	79.40	89.54
	March-16	84.40	87.96	33.59	51.38	90.92	93.55	85.45		88.28	82.99	82.87	92.29
	April-16	81.45	85.13	33.80	48.76	87.38	89.62	82.08		86.00	82.10	78.29	88.63
	May-16	77.07	80.54	33.12	44.97	82.04	82.78	76.94		81.69	79.36	72.23	84.93
	June-16	75.98	79.49	32.56	43.70	80.53	82.19	75.75		81.08	79.68	70.74	84.14
	July-16	83.74	87.62	34.75	47.05	87.14	90.89	83.38		88.53	85.37	77.87	90.17
	August-16	87.48	91.70	34.24	48.40	91.66	94.82	87.82		92.07	84.29	83.25	94.87
	September-16	90.99	95.99	34.83	53.18	95.35	98.20	91.74		95.84	81.31	87.36	98.50
	October-16	94.24	98.14	35.49	56.31	93.49	99.32	89.95		92.80	80.72	87.94	92.49
	November-16	95.87	97.18	31.70	50.92	97.53	96.03	88.87		96.24	79.35	86.74	91.56
	December-16	89.42	93.62	32.90	48.00	94.15	98.11	89.76		92.05	78.52	86.74	95.27
2017	January-17	77.53	81.42	28.69	40.81	81.87	85.06	77.72		80.43	71.23	74.80	83.86
	February-17	70.39	73.72	26.36	36.55	74.47	77.71	70.75		73.28	67.17	68.28	77.49
	March-17	67.51	70.84	24.59	34.90	72.14	75.71	69.11		71.32	67.20	65.98	76.02
	April-17	50.04	52.51	19.05	24.82	53.80	56.21	51.65		53.58	51.59	48.43	56.58
	May-17	78.79	82.55	31.92	41.29	81.09	86.48	78.91		84.14	82.32	72.63	87.13
	June-17	80.58	84.56	32.07	42.06	83.08	88.58	80.94		86.14	83.87	73.95	88.26
	July-17	78.67	82.42	30.80	39.90	80.44	85.87	78.64		83.78	79.49	71.12	86.57
	August-17	87.32	91.71	31.86	43.99	90.03	95.64	87.95		92.67	84.29	81.27	94.47
	September-17	82.82	88.02	28.40	41.54	87.47	91.50	85.41		89.01	75.95	80.23	90.45
	October-17	79.16	84.16	26.90	38.03	82.15	86.32	78.98		83.22	69.91	72.66	76.10
	November-17	86.31	92.62	27.59	42.91	93.36	97.82	90.97		93.92	78.75	86.34	95.07
	December-17	88.49	93.73	28.62	44.14	94.86	99.77	91.63		94.67	81.43	87.40	96.99
2018	January-18	86.48	90.86	29.03	43.30	92.47	94.01	88.41		90.90	81.51	85.20	95.29
	February-18	79.81	83.57	29.52	40.02	83.50	88.04	79.75		83.68	76.22	76.00	87.54
	March-18	83.52	88.17	30.26	40.86	88.57	93.58	85.61		90.93	87.01	78.40	94.59
	April-18	78.40	82.55	29.15	39.35	83.29	87.47	80.13		84.56	81.91	73.25	87.65
	May-18	75.85	79.69	28.41	37.65	79.93	84.65	77.28		81.66	80.13	70.11	84.39
	June-18	78.94	82.96	30.00	38.58	83.04	87.22	79.50		84.99	83.20	71.81	86.85
	July-18	85.01	89.24	31.36	40.74	89.49	94.26	86.02		90.94	87.45	78.10	92.73
	August-18	81.89	85.81			86.16	91.03	83.66		87.78	80.63	77.64	89.13
	September-18	88.26	93.54			94.03	99.16	91.80		95.66	82.83	86.26	96.56
	October-18	72.96	80.02			90.97	91.55	80.06		95.23	68.21	84.12	78.89
	November-18	73.11	78.28			88.97	90.33	79.39		93.20	68.26	78.07	79.32
	December-18	88.40	93.44			94.39	99.77	91.82		94.34	81.58	86.66	95.59

Table B.2 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
2019	January-19	86.05	90.25			90.20	95.40	87.19		89.63	80.21	81.76	91.83
	February-19	83.04	87.60			89.07	93.87	85.74		87.77	79.69	80.33	91.14
	March-19	91.18	95.84			97.19	102.83	93.75		96.72	90.79	86.25	100.78
	April-19	78.71	82.89			84.19	88.95	81.21		84.66	82.13	73.12	87.97
	May-19												
	June-19	78.88	82.92			83.24	87.79	80.18		84.34	82.23	71.76	88.02
	July-19	80.35	84.24			84.51	89.19	81.70		85.78	81.47	72.66	88.51
	August-19	83.37	87.44			88.07	92.75	85.12		89.23	81.93	76.94	91.59
	September-19	85.33	90.24			91.04	95.68	88.31		92.11	79.29	81.38	94.06
	October-19	85.12	91.76			94.46	97.96	91.72		94.29	78.76	86.55	95.86
	November-19	90.19	96.32			98.01	102.41	95.31		97.15	80.58	89.40	98.14
	December-19	85.95	91.16			93.51	98.42	89.90		91.57	79.26	85.16	93.34
2020	January-20	83.67	87.57			90.07	94.60	85.56		88.43	79.83	78.93	92.19
	February-20	82.94	87.32			88.62	93.21	84.78		87.02	79.57	77.54	90.41
	March-20	80.35	84.41			86.26	91.00	82.23		84.88	80.33	75.12	89.33
	April-20	78.47	82.74			84.56	89.19	80.82		84.04	80.65	72.72	88.17
	May-20	76.92	80.97			81.82	86.20	78.46		82.70	81.14	69.38	85.54
	June-20	77.99	81.97			82.14	85.55	78.75		83.57	82.04	68.94	85.76
	July-20	79.68	83.92			84.53	88.01	81.13		85.82	83.32	71.75	87.48
	August-20	82.23	86.41			87.61	91.78	84.09		88.60	82.56	75.48	90.12
	September-20	85.77	90.56			91.97	96.23	88.55		92.61	79.08	81.55	93.10
	October-20	85.55	90.79			93.63	97.80	90.25		93.64	78.28	84.41	94.15
	November-20	84.12	89.36			89.17	93.54	84.37		89.08	75.45	79.92	89.06
	December-20	71.66	77.82			83.85	90.41	80.50		85.79	69.17	76.12	91.85
2021	January-21	84.32	90.47			95.16	101.85	91.13		95.01	81.75	82.71	90.94
	February-21	81.15	86.44			89.78	94.63	85.56		87.44	79.83	79.79	90.30
	March-21	78.36	82.93			84.79	89.85	81.04		84.25	79.88	72.72	87.18
	April-21	10.01	10.66			11.22	11.83	12.57		14.51	7.30	10.17	16.55
	May-21	9.67	10.23			10.60	11.23	11.91		13.98	7.30	9.27	15.97
	June-21												

Appendix C

MONTHLY CELL TEMPERATURE

C.1 Monthly Cell Temperature

Table C.1: Monthly Cell Temperature of all modules during testing time

	CIS-1	CIS-2	HIT	a-Si	Poly-Si-2
April-16	21.34	22.09	20.25	19.27	20.22
May.16	21.25	21.95	20.52	19.55	20.21
June-16	28.74	29.43	27.70	26.62	27.62
July-16	33.02	33.72	31.59	30.32	31.80
August-16	33.04	33.73	31.61	30.30	31.92
September-16	40.30	41.19	38.18	36.65	38.69
October-16	21.05	21.57	19.60	18.91	19.96
November-16	11.76	12.14	10.50	10.24	10.83
December-16	2.84	3.14	1.93	1.82	02.03
January-17	1.65	02.07	0.97	0.94	01.05
February-17	8.14	8.69	07.07	6.56	7.23
March-17	13.33	13.84	12.30	11.54	12.40
April-17	17.22	17.85	16.17	15.18	16.17
May-17	21.72	22.39	20.93	19.86	20.79
June-17	28.46	29.24	27.74	26.13	27.31
July-17	33.44	34.18	31.94	30.80	32.20
August-17	31.86	32.57	30.27	29.25	30.71
September-17	29.53	30.17	27.83	26.95	28.33
October-17	18.05	18.50	16.67	16.15	17.01
November-17	11.40	11.68	10.24	9.95	10.44
December-17	6.63	6.13	5.89	5.60	5.95
January-18	06.02	4.71	5.20	05.04	5.26

Table C.1 Continued from previous page

	CIS-1	CIS-2	HIT	a-Si	Poly-Si-2
February-18	10.50	8.57	9.48	9.25	8.82
March-18	14.60	12.12	13.72	13.22	1.96
April-18	24.06	23.27	22.74	21.82	22.79
May-18	25.10	26.06	24.13	24.07	24.14
June-18	29.19	30.11	28.02	28.25	28.15
July-18	32.38	33.29	31.09	31.06	31.29
August-18	32.44	33.25	30.65	30.45	31.33
September-18	26.69	27.47	25.18	25.05	25.64
October-18	19.81	19.98	18.53	18.73	-29.27
November-18	12.68	12.80	11.62	11.92	-10.68
December-18	5.21	5.35	5.00	4.89	2.75
January-19	4.13	4.26	3.86	3.95	-5.89
February-19	8.70	8.92	7.84	8.11	-5.66
March-19	12.45	12.99	11.60	11.88	11.36
April-19	15.37	15.88	14.88	15.20	14.60
May-19	23.24	23.82	22.93	23.21	22.49
June-19	28.05	28.77	27.63	27.95	27.47
July-19	28.57	29.25	28.01	28.29	27.90
August-19	29.26	29.86	28.44	28.69	28.72
September-19	25.53	26.15	24.61	24.85	25.50
October-19	21.22	21.75	20.14	20.37	16.59
November-19	14.26	14.68	13.28	13.48	13.29
December-19	6.18	6.43	5.63	5.85	5.20
January-20	04.04	4.41	3.32	3.53	03.03
February-20	7.00	7.41	6.40	6.67	6.39
March-20	13.53	14.06	12.85	13.09	12.59
April-20	16.53	17.11	15.93	16.22	15.38
May-20	22.25	22.93	22.07	22.40	20.81
June-20	26.05	26.70	25.86	26.29	25.14
July-20	31.98	32.60	31.41	31.77	31.55
August-20	31.35	31.98	30.63	30.88	30.85
September-20	28.55	29.13	27.83	28.02	28.04
October-20	22.31	22.71	21.38	21.61	21.64
November-20	10.90	11.24	9.74	9.96	9.52
December-20	8.98	9.17	8.15	8.43	6.43

Table C.1 Continued from previous page

	CIS-1	CIS-2	HIT	a-Si	Poly-Si-2
January-21	6.23	6.49	5.59	5.86	3.76
February-21	8.81	9.29	8.28	8.39	-1.46
March-21	09.01	9.52	8.70	8.86	4.34
April-21	16.11	16.56	15.89	16.19	15.61
May-21	24.34	25.07	24.24	24.57	23.87

Appendix D

MONTHLY POWERS

D.1 Monthly Powers

Table D.1: Monthly Powers of all modules during testing time

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
2012	February-12	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	March-12	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	April-12	NaN	NaN	NaN	NaN	NaN	21.38	23.20	NaN	NaN	14.86	NaN	NaN
	May-12	NaN	NaN	NaN	NaN	NaN	20.73	23.10	NaN	NaN	14.68	19.27	NaN
	June-12	NaN	NaN	NaN	NaN	NaN	24.58	27.43	NaN	NaN	17.95	22.30	NaN
	July-12	NaN	NaN	15.46	NaN	NaN	24.00	26.78	NaN	NaN	17.71	22.28	NaN
	August-12	NaN	NaN	15.00	NaN	25.16	25.50	28.44	NaN	NaN	18.72	23.62	NaN
	September-12	NaN	NaN	13.39	NaN	22.99	23.26	25.97	NaN	NaN	16.72	21.54	NaN
	October-12	NaN	NaN	9.57	NaN	17.97	18.19	20.34	20.53	NaN	12.47	17.00	NaN
	November-12	NaN	NaN	5.33	NaN	10.84	10.98	12.36	12.44	NaN	7.07	10.40	NaN
	December-12	NaN	NaN	4.60	NaN	8.86	9.08	10.17	10.21	NaN	5.48	8.53	NaN
2013	January-13	NaN	NaN	4.47	7.91	8.98	8.80	10.18	10.21	NaN	5.30	8.29	NaN
	February-13	NaN	NaN	5.67	9.97	11.87	12.10	13.46	13.38	NaN	7.57	11.38	NaN
	March-13	NaN	NaN	8.30	14.12	16.79	17.18	19.05	18.65	NaN	10.84	16.06	NaN
	April-13	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	May-13	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	June-13	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	July-13	NaN	NaN	11.38	18.51	23.07	23.43	25.92	26.12	26.72	16.61	21.53	NaN
	August-13	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	September-13	NaN	NaN	10.44	17.50	21.83	22.22	24.58	24.53	27.67	15.35	20.35	NaN
	October-13	NaN	NaN	8.93	15.51	19.21	19.55	21.69	21.78	25.75	12.73	18.07	NaN
	November-13	NaN	NaN	6.28	11.55	14.37	14.61	16.26	16.36	19.39	9.05	13.61	NaN
	December-13	NaN	NaN	NaN	9.35	10.69	10.89	12.12	12.31	14.33	6.29	10.24	NaN

Table D.1 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
	January-14	NaN	NaN	3.39	6.68	8.49	8.71	9.68	9.66	11.32	5.19	8.16	NaN
	February-14	NaN	NaN	6.90	12.45	15.50	15.80	17.48	17.68	20.57	9.57	14.71	NaN
	March-14	NaN	NaN	7.24	13.27	16.78	17.20	18.99	18.40	21.54	10.74	15.87	NaN
	April-14	NaN	NaN	8.78	15.80	20.20	20.64	22.71	22.40	26.17	13.25	19.09	NaN
	May-14	NaN	NaN	8.98	16.07	20.83	21.28	23.37	23.23	27.11	13.99	19.60	NaN
2014	June-14	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	July-14	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	August-14	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	September-14	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	October-14	15.08	15.62	6.44	11.86	16.10	16.23	17.84	NaN	21.33	10.81	14.93	NaN
	November-14	10.51	10.93	4.43	8.71	11.22	11.35	12.62	12.78	14.89	7.05	10.62	NaN
	December-14	7.15	7.31	NaN	5.89	7.32	7.54	8.34	8.45	9.66	4.46	7.06	NaN
	January-15	8.66	8.60	3.68	7.32	8.13	8.31	9.45	9.22	11.36	4.93	7.89	NaN
	February-15	10.00	10.12	4.05	7.96	10.79	11.16	12.40	11.65	13.80	6.63	10.09	NaN
	March-15	14.80	15.31	5.91	11.13	15.90	16.27	17.82	17.73	20.45	10.00	14.99	NaN
	April-15	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	May-15	20.10	20.80	8.41	14.25	21.51	21.99	24.05	24.22	28.26	14.51	19.81	NaN
2015	June-15	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	July-15	23.24	24.16	10.02	14.95	24.87	25.22	27.67	28.09	33.06	17.58	22.52	NaN
	August-15	21.08	21.92	8.99	12.91	22.54	22.90	25.10	25.57	30.03	16.25	20.35	NaN
	September-15	20.48	21.27	8.53	12.07	21.80	22.20	24.27	24.68	29.10	15.50	19.63	NaN
	October-15	14.48	15.11	5.51	8.34	15.62	15.94	17.44	19.59	20.60	10.56	14.41	NaN
	November-15	15.94	16.47	6.03	9.05	16.80	17.16	18.78	NaN	22.26	10.41	15.68	NaN
	December-15	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	January-16	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	February-16	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	March-16	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	April-16	20.54	21.32	7.87	11.46	21.92	22.47	24.18	NaN	28.60	14.61	20.35	32.99
	May-16	17.71	18.46	6.42	9.83	19.33	19.89	21.35	NaN	24.91	12.90	17.96	28.76
2016	June-16	21.24	22.20	8.03	11.59	23.09	23.68	25.49	NaN	30.16	15.86	21.09	34.32
	July-16	22.43	23.44	8.79	11.93	24.20	24.41	26.67	NaN	31.98	17.12	21.72	36.71
	August-16	20.24	21.17	7.90	10.61	21.74	22.18	24.03	NaN	29.04	15.73	19.47	33.28
	September-16	19.80	20.72	7.49	10.14	20.88	21.78	23.48	NaN	28.16	14.96	19.02	31.67
	October-16	16.54	17.34	5.90	8.34	17.57	18.17	19.78	NaN	23.42	11.81	16.26	26.65
	November-16	12.75	13.45	4.45	6.79	13.54	13.95	15.31	NaN	18.07	8.45	12.65	20.50
	December-16	9.69	10.09	3.33	5.28	9.74	10.35	11.02	NaN	12.84	6.15	9.34	14.13

Table D.1 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
2017	January-17	8.33	8.44	2.51	4.03	8.59	8.46	9.20	NaN	11.25	5.11	7.79	11.82
	February-17	13.00	13.61	4.36	6.36	13.87	14.46	15.54	NaN	18.00	8.46	13.03	20.57
	March-17	14.06	14.77	4.75	6.75	15.05	15.64	16.79	NaN	19.62	9.58	14.02	22.59
	April-17	14.71	15.40	5.02	6.96	15.77	16.45	17.60	NaN	20.59	10.40	14.74	24.04
	May-17	14.47	15.18	4.80	6.82	15.66	16.44	17.64	NaN	20.55	10.67	14.61	24.19
	June-17	13.76	14.40	3.19	3.89	17.92	18.80	25.87		25.86	13.96	12.99	34.94
	July-17	21.36	22.38	7.89	10.20	22.28	23.76	25.48	NaN	30.68	16.54	20.34	35.09
	August-17	21.47	22.53	7.79	10.22	22.43	23.92	25.69	NaN	30.87	16.56	20.36	34.93
	September-17	19.22	20.14	6.86	8.89	19.92	21.26	22.88	NaN	27.53	14.39	17.95	31.42
	October-17	16.00	16.81	5.32	7.35	16.72	17.76	19.19	NaN	22.84	11.45	15.38	25.71
	November-17	10.37	11.02	3.24	4.74	11.10	11.61	12.74	NaN	14.99	7.05	10.38	16.82
	December-17	11.56	12.29	3.58	5.06	12.16	12.78	13.74	NaN	16.35	7.57	10.96	16.51
2018	January-18	8.62	9.25	2.51	3.91	9.45	9.90	10.82	NaN	12.62	5.83	8.91	14.10
	February-18	10.02	10.62	2.96	4.56	10.89	11.45	12.36	NaN	14.42	6.84	10.23	16.32
	March-18	14.07	14.78	4.31	6.42	15.25	15.50	17.13	NaN	19.89	9.83	14.32	23.03
	April-18	20.30	21.26	6.85	9.28	21.53	22.70	24.16	NaN	28.63	14.37	19.98	33.08
	May-18	18.26	19.27	6.03	8.14	19.62	20.73	22.29	NaN	26.74	14.10	17.71	30.71
	June-18	20.12	21.19	6.82	9.21	21.66	22.75	24.50	NaN	29.19	15.58	19.42	33.41
	July-18	21.11	22.18	7.21	9.55	22.54	23.87	25.61	NaN	30.57	16.53	20.16	34.88
	August-18	21.69	22.79	7.51	9.66	23.12	24.29	26.01	NaN	31.41	16.94	20.38	35.45
	September-18	19.91	20.90	6.70	8.70	21.24	22.38	24.00	NaN	28.65	15.18	18.90	32.26
	October-18	15.80	16.56	0.53	0.70	16.85	17.80	19.22	NaN	22.78	11.53	15.48	25.54
	November-18	11.75	12.45	NaN	NaN	12.69	13.38	14.56	NaN	17.13	8.17	11.86	19.09
	December-18	7.50	8.23	NaN	NaN	9.48	9.54	9.81	NaN	13.17	5.20	8.94	12.05
2019	January-19	8.51	9.11	NaN	NaN	10.49	10.65	11.00	NaN	14.58	5.88	9.38	13.70
	February-19	11.30	11.94	NaN	NaN	12.22	12.92	13.97	NaN	16.21	7.73	11.44	18.14
	March-19	19.35	20.30	NaN	NaN	20.56	21.74	23.36	NaN	27.11	13.37	19.00	30.68
	April-19	16.14	17.02	NaN	NaN	17.54	18.48	19.84	NaN	22.93	11.47	16.12	26.30
	May-19	19.10	20.07	NaN	NaN	20.63	21.82	23.38	NaN	27.24	14.09	18.66	31.35
	June-19	18.81	19.81	NaN	NaN	20.39	21.55	23.12	NaN	27.21	14.55	18.05	31.23
	July-19	21.59	22.67	NaN	NaN	23.11	24.42	26.13	NaN	30.88	16.60	20.33	35.89
	August-19	21.11	22.19	NaN	NaN	22.57	23.80	25.55	NaN	30.35	16.31	19.84	34.98
	September-19	19.63	20.59	NaN	NaN	20.93	22.09	23.78	NaN	28.19	14.76	18.34	32.12
	October-19	17.45	18.30	Nan	NaN	18.68	19.67	21.22	NaN	25.12	12.71	16.64	28.48
	November-19	12.84	13.58	NaN	NaN	13.88	14.59	15.82	NaN	18.64	8.84	12.65	21.02
	December-19	6.54	7.05	NaN	NaN	7.35	7.62	8.39	NaN	9.74	4.48	6.87	10.93

Table D.1 Continued from previous page

Year	month	CIS-1	CIS-2	CIGS-2	CIGS-1	Mono -Si-2	Mono -Si-1	Poly -Si-1	Mono -Si-3	HIT	a-Si	Poly -Si-2	Bi-facial Mono-Si
2020	January-20	10.82	11.56	0.25	NaN	11.92	12.45	13.62	NaN	15.68	7.17	11.08	17.49
	February-20	9.98	10.59	Nan	0.67	11.01	11.59	12.44	NaN	14.31	6.82	10.22	16.10
	March-20	16.34	17.10	NaN	NaN	17.82	18.72	19.90	NaN	23.22	11.55	15.92	26.74
	April-20	19.08	20.09	NaN	NaN	20.66	21.74	23.23	NaN	26.93	13.57	18.43	30.90
	May-20	19.95	20.96	NaN	NaN	21.71	22.90	24.32	NaN	28.34	14.78	19.27	32.94
	June-20	19.11	20.15	NaN	NaN	20.87	22.01	23.44	NaN	27.52	14.56	18.29	31.89
	July-20	22.37	23.55	NaN	NaN	24.11	25.40	27.17	NaN	32.34	17.49	20.84	36.95
	August-20	22.61	23.76	NaN	NaN	24.13	25.14	27.19	NaN	32.59	17.63	20.65	36.93
	September-20	19.73	20.78	NaN	NaN	21.21	22.08	23.92	NaN	28.57	15.29	18.35	32.16
	October-20	16.70	17.55	NaN	NaN	18.03	18.89	20.33	NaN	24.20	12.42	15.83	27.18
	November-20	14.08	14.86	NaN	NaN	15.30	16.00	17.31	NaN	20.44	9.62	13.83	22.69
	December-20	9.10	9.65	NaN	NaN	10.09	10.54	11.43	NaN	13.39	6.17	9.27	14.87
2021	January-21	8.45	8.97	NaN	NaN	9.08	9.52	10.09	NaN	12.03	5.62	8.29	13.28
	February-21	13.13	14.25	NaN	NaN	15.56	16.78	17.56	NaN	21.13	9.39	14.41	24.99
	March-21	14.66	15.72	NaN	NaN	16.76	17.94	18.86	NaN	22.21	10.53	14.85	23.48
	April-21	14.78	15.74	NaN	NaN	16.57	17.46	18.56	NaN	21.42	10.77	15.01	24.43
	May-21	20.85	22.06	NaN	NaN	22.86	24.23	25.68	NaN	30.15	15.75	19.99	34.45
	June-21												