ΠΑΝΕΠΙΣΤΗΜΙΟ ΔΥΤΙΚΗΣ ΑΤΤΙΚΗΣ
ΣΧΟΛΗ ΜΗΧΑΝΙΚΩΝ
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UNIVERSITY of WEST ATTICA
FACULTY OF ENGINEERING
Department of Electrical & Electronics Engineering

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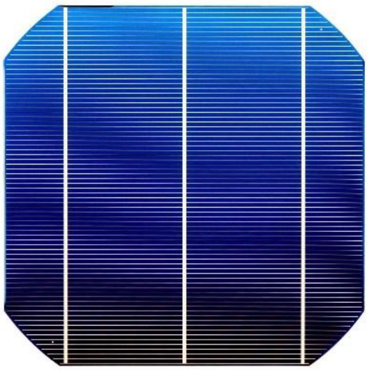
Master of Science in
Internetworked Electronic Systems

MSc Thesis

PHOTOVOLTAIC PANELS - RESEARCH AND EXPERIMENTAL MEASUREMENTS ON SOLAR PANEL TYPES, CHARACTERISTICS AND PERFORMANCE



Student: Dimitrokallis, Georgios- Angelos, IES-0012
MSc Thesis Supervisor: Vokas, Georgios, Dr. Professor

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ABSTRACT

This study shows how real life performance differs from manufacturers' datasheets. The results of measurements experimentally taken from different types of photovoltaic panels prove that the performance is highly impacted by various conditions, but also potential internal problems.

The research covers main types of photovoltaic panels and their characteristics along with analysis on the crucial internal and external factors which may reduce their efficiency. The attributes of HT-IV400 are described, as this instrument was used for the experimental measurements. Following are the readings taken from five different photovoltaic panels, under various weather conditions. Examined models are four Suntech 190S24 and one Sunearth 12572. The measurements are converted to values based on STC conditions and compared with nominal values gives by the manufacturers. All the readings show distinct underperformance. Based on the theoretical part of the research and since the panels were in used for a significant period of time before the experiment, the study presents the high impact of aging and degradation processes on the real life performance levels of photovoltaics.

KEYWORDS:

Degradation, eco-friendly, electricity, monocrystalline, organic, panels, photovoltaic, polycrystalline, solar, thin-film

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I wish to show my appreciation to my primary supervisor, Georgios Vokas, who guided me and helped me to finalize this project. I would also like to extend my special thanks to my friends and family who supported me and offered deep insight into the study.

TABLE OF SYMBOLS – ACRONYMS – ABBREVIATIONS

°C	Celcius degree
°F	Farenheit degree
A	Amperage
AI	Current temperature coefficience
Al	Aluminum
AM	Air Mass
AP	Power temperature coefficience
a-Si	amorphus-Silicon
AU	Voltage temperature coefficience
Ca	Calcium
CdTe	Cadmium telluride
CIGS	copper indium gallium selenide
CIS	copper indium selenide
CuInSe2	Copper indium selenide
DLID	Direct Light Induced Degradation
ECT	Equivalent Cell Temperature
EVA	Ethylene-Vinyl Acetate
FF	Fill Factor
GaAs	Gallium Arsenide
Ge	Germanium
HOMO	Highest occupied Molecular Orbital
I	Current
IEC	International Electrotechnical Commission
IMPP	Maximum Power Point Current
IP	International Protection
IR	Infrared
ISC	Short Circuit Current
ISO	International Organization for Standardization
ITO	Indium Tin Oxide
LCD	Liquid Crystal Display
LID	Light Induced Degradation
LUMO	Lowest Unoccupied Molecular Orbital
LVD	Low Voltage Directive

m2	square meter
Mg	Magnesium
MPH	Miles Per Hour
MPPT	Maximum Power Point Tracking
N	Negative
NOCT	Normal Operating Cell Temperature
OPV	Organic PhotoVoltaic
OSC	organic solar cell
P	Power
P	Positive
PAS	Publicly Available Specifications
PET	Poliethilene glycol Terephthalate
PID	Potential Induced Degradation
PMAX	Maximum Power Point
POE	POlyolefin Elastomer
PTC	PVUSA Test Contitions
PV	PhotoVoltaic
PVUSA	PhotoVoltaics for Utility Scale Applications
Rs	Series Resistance
RSH	SHunt Resistance
Si	Silicon
STC	Standard Testing Conditions
T	Temperature
UV	Ultra Violet
UVID	Ultra Violet Induced Degratation
V	Voltage
VMPP	Maximum Power Point Voltage
VOC	Open Circuit Voltage
W	Watt
η	Efficiency
σρ	purity factor

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INTRODUCTION:
Aims, objectives and research questions – Thesis outline

The purpose of this research is to list through measurements experimentally taken from different types of photovoltaic panels, in order to examine the results of their performance in different conditions, but also to check the panels for any internal problems such as broken cells which may affect the panel's performance.

Firstly, the different types of photovoltaic panels along with their peculiarities will be analyzed and further the factors that reduce the efficiency of panels will be investigated, divided into categories of internal and external aspects. Following, the process of degradation will reviewed in order to show the impact of aging, PID and LID phenomenon on panels' capability. The measurements for various types of panels will be held with the HT-IV400 instrument, which attributes are thoroughly presented. Based on the measurements given in a datasheet, the manufacturer's values will be compared with the experimental ones. The experimental readings will be presented in relevant table for each examined photovoltaic – four Suntech 190S24 models and one Sunearth 12572. The obtained values will be converted to STC conditions levels and evaluated in contrast with the manufacturer's expectations. Finally, the comparison of the measurements and the expected power output will show the potential difference in data given by the manufacturers versus the performance in real conditions. The contradiction will be demonstrated in diagram form, in order to visually stress the observed contrast. Since the examined panels are used already for significant period of time, it is expected that their performance may not only not reach the desired values, but also to show considerable gap between the predicted calculations and real values. In such case, possible reasons for lower performance will be pointed out, bases on the theoretical analysis of the factors and phenomenon impacting the levels of photovoltaics efficiency.

CHAPTER 1:
Types of photovoltaic panels

Photovoltaic panels are constructed from solar elements, each of which is a properly processed thin semiconductor with a thick surface. The impact of solar radiation creates an electrical voltage and with the proper connection to a load, electricity is generated. Solar photovoltaic cells are grouped in order to form photovoltaic panels of standard power from 10W to 300W. Photovoltaic panels can be electrically connected to each other in order to form photovoltaic arrays.

There are three main photovoltaic panels' types: monocrystalline, polycrystalline and Thin-Film (all presented in the below figure no.1). In this research five photovoltaics will be examined, four of which are monocrystalline Suntech panels and one is a polycrystalline Sunearth panel.

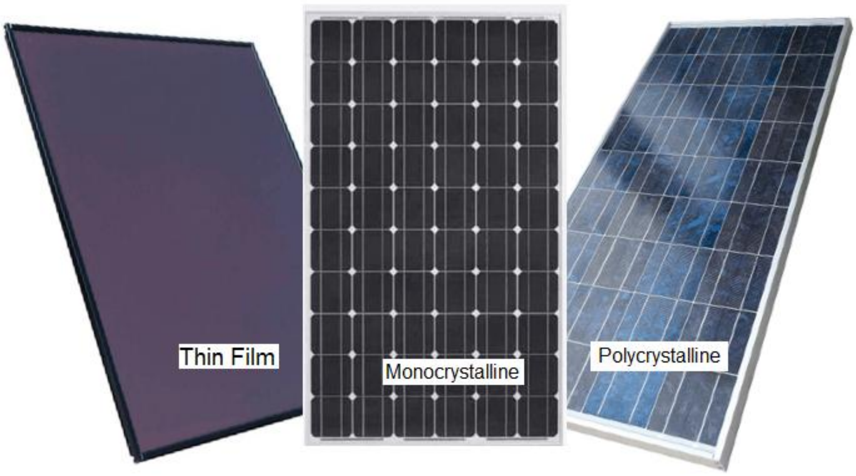

Figure no.1

1. 1 Monocrystalline photovoltaics

1. 1. 1 Analysis

Approximately 90% of the manufactured photovoltaic panels are based on silicon (Si). This is mainly due to the huge global scientific and technical infrastructure for this material since the 1960s. Numerous studies by large governments and industries have provided with the necessary results in order to create the equipment to obtain the desired purity and crystalline structure of the required that led to finding the silicon. Its characteristics and abundance on earth made it a capable mean of exploiting the solar energy. Depending on the producer's processing steps, different types of silicon such as monocrystalline, polycrystalline or amorphous materials were invented, from which the photovoltaic elements were further on produced.

Monocrystalline photovoltaics have been the most common photovoltaic panels for many years and are among the oldest and most efficient ways to generate solar electricity. Originally they were developed for aerospace and satellite television purposes and were later used in photovoltaic panels to produce solar energy. Monocrystalline solar cells, which are dark blue or black square elements with rounded corners, are interconnected to form solar panels. Bibliography: [No 1, 27, 28] In the figure below (no.2), a single monocrystalline cell along with a solar panel are presented:

Figure no.2

The process of monocrystalline silicon cells manufacturing is quite complex, which results in their high production cost. Monocrystalline cells are cut from a cylindrical silicate crystal, created as per the Czochralski process. During this process in molten silicon a rotating silicon rod is immersed, on which slowly melted silicon adheres, creating the crystal which consists of as pure silicon as possible. Depending on the speed of the rotation and rise of the rod, the desired diameter is obtained.

If the crystal was simply cut across to create the cells, then these cells would obtain a round shape, creating problems in panels assembling. For this reason, before cross-cutting, the cylinder is cut lengthwise on 4 sides in order its cross section to become as square as possible. The remaining piece of silicon is then cut into thin slices, which are glued together to form the final structure. Bibliography: [No 1, 27]

In the figure below (no.3) a single crystal silicon cylinder is presented:

Figure no.3

1. 1. 2 Advantages and disadvantages of Monocrystalline Photovoltaics

1. 1. 2. 1 Advantages

Longevity

The monocrystalline silicon photovoltaic panels are classified as the first generation of solar technology and have been present on the market for many years. Some models which have been installed in the early 70's are still functional and able to generate electricity to this day, which shows their long life and durability. According to many photovoltaic industries, single-crystal panels can last up to 50 years and their maximum productivity is around 25 years. Many engineers claim that every year there is a decrease of 0. 5% in panel’s efficiency, although by keeping their surface clean, they can continue to produce electricity. Bibliography: [No 1, 2, 27]

High efficiency

Another feature that makes monocrystalline photovoltaics widespread is their high efficiency. These panels are suitable to convert a very large amount of solar energy into electricity. Additionally, the space required for their installation is small compared to other types of photovoltaics, which in combination with their high efficiency makes them ideal in many cases. Single crystal panels' efficiency exceeds 20%. Moreover, monocrytalline solar cells contain high levels of silicon, which make them more effective in direct sun light. Therefore, if we want to produce the largest possible amount of electricity from a specific surface, the most appropriate choice of photovoltaic panel is single crystal one. Bibliography: [No 2]

Power generation and resistance to high temperatures

Large electricity generation is another important advantage of monocrystallic silicon photovoltaic panels. In addition to generating more electricity per square meter than other types of photovoltaics, they also provide great financial benefits and reductions in electricity bills. Monocrystalline solar cell panels reduce the amount of electricity they need to operate while at the same time they are highly resistant to high temperatures. Like other types of photovoltaics, these panels show a small drop in performance when the ambient temperature is around 50°C. However, in monocrystalline photovoltaics, this drop is less significant than in other photovoltaic panels. Bibliography: [No 2]

Eco-friendly characteristics

It is also worth mentioning that monocrystalline photovoltaics are more environmentally friendly than other types of panels. Unlike many photovoltaic panels, they do not contain cadmium, a material that is highly toxic and carcinogenic to humans and animals. Although there are no risks during the panels' operation, due to cadmium when the panel needs to be replaced it has to be included into special recycling programs. Another environmental benefit

of monocrystalline photovoltaic is the reduced usage of limited sources of fuel and greenhouse gases released into the atmosphere. On the top this type of panels uses less electricity than local power plants.
Bibliography: [No 2]

1. 1. 2. 2 Disadvantages

High cost

Regardless of many important advantages of single crystal photovoltaic panels, there are some features that make them unsuitable in some cases. Their production costs are very high and the process by which they are manufactured is very complicated. About a third of all photovoltaic systems operating currently are based on single-crystal solar cells. The units are actually more expensive both in manufacturing and final price, but that is balanced by their high performance. In addition, during the Czochralski process a large amount of silicon remains unused. Since the silicon cylinder is cut on its 4 sides and only the excess crystal is suitable for the construction of the panels. Bibliography: [No 3]

Panel surface sensitivity

The need of frequent surface cleaning is another disadvantage of this type of panels. If a single crystal panel is covered by shade, dust or snow, it can cause the circuit to collapse. In the situation when a panel, which is a part of the array, gets covered, it is preferred to check for micro-reversals in order to prevent the whole panel array from collapsing. Therefore, in areas where there is limited sunlight and frequent risk of snowfall, another types of photovoltaic would be more convenient. Bibliography: [No 3]

Fragility

The fragility of the monocrystallic panels is another very important feature that should be taken into consideration. Although there is protective glass surface over the solar cells, the risk of damage is high as the overall structure of this type of panel is quite sensitive (detailed structure of the panel is presented in the figure no.4 below). Therefore, for example the photovoltaic panels should not be placed on a roof under tree branches, as there is a high risk that the solar panels will break in case of branch fall. Bibliography: [No 3, 27]

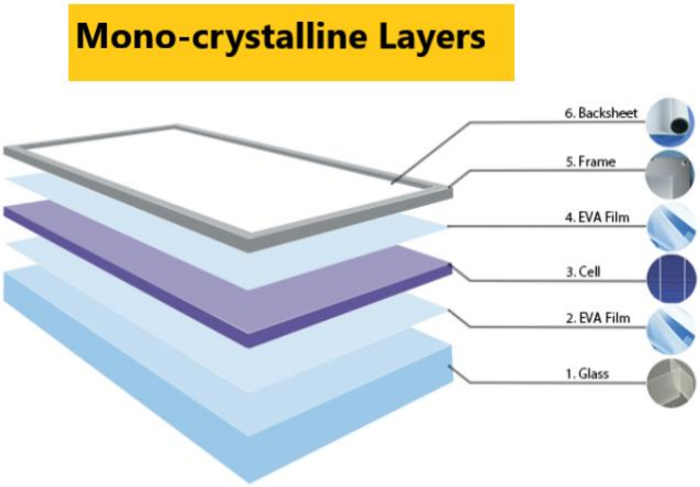

Figure no.4

1. 1. 3 Pros and cons conclusions

In conclusion, the photovoltaic monocrystalline silicon is expensive due to its complex and time-consuming production and at the same time it has a sensitive and fragile structure. Nevertheless, this type of panel continues to be very common. Its popularity arises from the fact that in comparison to other types of photovoltaics, it can exploit to a large extent the space where it is placed, since it has remarkable performance in proportion to the covered square meters. As a result, monocrystalline panels are preferred on restricted spaces and small ceilings. At the same time, they can produce a large amount of electricity, while very small amount of electricity is needed from the local power supply units for the production purposes. Bibliography: [No 2, 3, 4]

The below figure (no.5) presents an example of monocrystalline photovoltaic placed on the restricted space of a vehicle.

Figure no.5

1. 2 Polycrystalline photovoltaics

1. 2. 1 Analysis

Polycrystalline silicon, known also as polysilicon, is a high-purity polycrystalline type of silicon, used as a raw material by many photovoltaic panels and solar cell manufacturers. Polysilicon is produced in a chemical cleaning process, called the Siemens process. During this process, the volatile silicon compounds are distilled and afterwards, at high temperatures, decomposed into silicon. The molten silicon is then poured into a ceramic hopper and cooled to obtain the desired structure. The most characteristic features of polycrystalline cells are square shape, blue color and mosaic appearance, which is created thanks to many different crystals included in the cells texture.

Along with the Siemens process, there is another alternative method of silicon cleaning. It is based on fluidized bed reactor, which is used to perform a variety of multiphase chemical reactions. In this type of reactor, a fluid passes through a solid granular material at fairly high speeds, in order to suspend the solid and make it behave as though it were liquid. Due to its many advantages, the liquidation process is now frequently used in many industrial applications.

Although recently silicon deficiencies have been observed in the photovoltaic industry, innovative ways of faster polycrystalline solar cells production continue to be chased. Bibliography: [No 4, 27]

In the below figure (no.6) polycrystalline silicon and solar cells are presented.

Figure no.6

Regardless of the fact that the monocrystalline silicon is a more efficient conductor, polycrystalline silicon is the basic raw material used in crystalline silicon photovoltaic industries. It is used to produce conventional solar cells and was first introduced to this field in 1981. Until 2008 there were only 12 solar cell companies producing polycrystalline silicon, but by 2013, due to increased demand, the number of related manufacturers increased to 100. Polycrystalline solar panels are commonly used due to their lower production cost. They are the second most preferred choice in the photovoltaic market, almost as good as a single crystal photovoltaic and overall more efficient than Thin-Film panels.

1. 2. 2 Advantages and disadvantages of polycrystalline photovoltaics

1. 2. 2. 1 Advantages

Production cost

The use of polycrystalline silicon in the production of the solar cell requires relatively small amounts of raw material. This results in higher profits and increased efficiency in production. In order to form a solar cell, polycrystalline silicon can be placed in alternative cheaper material instead of a pure silicon wafer. Thus the production costs are reduced. The fact that a silicon wafer is not necessary for the production of a polycrystalline solar cell balances the silicon deficiencies that are occasionally raised by the polycrystalline photovoltaic production industries. A simpler construction is another feature which determinates the lower productions cost of polycrystalline panels. They not only require less processing than monocrystalline solar cells, but their production process is much faster and less financially harmful to industries as there is no waste of silicon. Thanks to their lower production cost, polycrystalline panels are available to wider range of customers. Furthermore, the high number of polycrystalline photovoltaics’ manufacturers leads to strong competition in terms of panel prices. This tends to keep purchasing prices low, although many manufacturers may not be able to withstand the pressure of competitiveness.

Longevity

Similarly, to monocrystalline photovoltaics, the polycrystalline ones also have a long lifespan and can function for up to 25 years. Frequent cleaning of their surface and general maintenance can increase the performance and efficiency of photovoltaic panels. It is crucial to avoid any scratches and cracks, as they may increase the risk of rain entering the inside of the panel and such situation easily can lead to a short circuit. Bibliography: [No 1, 2, 27]

Eco-friendly characteristics

In addition to being able to produce energy from sunlight and to help in greenhouse gases reduction, many manufacturers of polycrystalline photovoltaics have developed more advanced technologies in the panels' disposal in order to remove lead-containing welds. This type of panels is manufactured from substances much less harmful to both environment and humans. Moreover, the recycling of the materials included in polycrystalline panels is now easier. Bibliography: [No 2, 4]

Decreased cost of electricity

Like any type of photovoltaic, polycrystalline panels actively contribute to lower electricity costs. Even if polycrystalline panels produce significantly less electricity than monocrystalline ones, they still provide great saving solution in terms of electricity bills.

1. 2. 2. 2 Disadvantages

Power generation and resistance to high temperatures

The efficiency of the solar cells is a powerful factor determining the correct choice of a photovoltaic panel. The efficiency of polycrystalline panels varies between 15% and 17%, which is much lower than monocrystalline photovoltaics. The polycrystalline solar cells are very sensitive to high temperatures. There is a considerable reduction in their efficiency when the temperature arises, which results in producing less and less energy under high temperature conditions. This can be easily observed when comparing a monocrystalline and a polycrystalline photovoltaic of the same manufacturer, as for every degree Celsius above 20 °C the polycrystalline panel shows a drop in energy production by 0.02%.
Bibliography: [No 4, 27]

Installation Area

In comparison with other panels, polycrystalline photovoltaics require more space to be installed. In order to be able to achieve the efficiency comparable to other photovoltaics, the polycrystalline panel will need more square meters. Therefore, they are preferred for larger spaces, rather than for small ceilings and roofs. Bibliography: [No 4] The figure (no.7) below presents a solar park of polycrystalline photovoltaics.

Figure no.7

1. 2. 3 Pros and cons conclusions

To sum up the overall characteristics of polycrystalline panels, although the cost of their solar cells manufacturing is significantly lower in comparison to other types of panels, their performance and efficiency in energy production reaches less satisfactory levels. Furthermore, their tolerance to high temperatures is lower than monocrystalline photovoltaics and much larger space is required to reach the desired efficiency. However, this does not mean that purchasing a polycrystalline panel will not bring important benefits; it will still significantly lower the cost of electricity and at the same time will contribute to the protection of the surrounding environment.
Bibliography: [No 1, 4, 27]

1. 3 Thin-Film

1. 3. 1 Analysis

Thin-Film photovoltaic is another type of panels, also known as "third generation" panels due to many different production and processing methods (example: amorphous silicon (a-Si), copper-disulfide copper (CuInSe2 and CIS, etc.). The amorphous silicon panels, the most common in this category, consist of thin coated films which are produced by the deposition of semiconductor material on a low-cost support substrate such as glass or aluminum. The definition of "amorphous photovoltaic" comes from the random way in which silicon atoms are arranged. Bibliography: [No 21, 27, 28] The structure of a thin photovoltaic film is presented in the figure no.8. A single photovoltaic Thin-Film panel (no. 9) along with a park of photovoltaic Thin-Film (no.10) is also presented in the figures below:

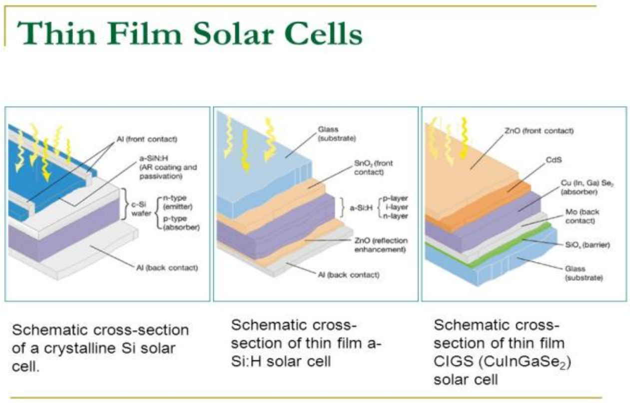

Figure no.8

Figure no.9

Figure no.10

1. 3. 2 Advantages and disadvantages of Thin-Film

1. 3. 2. 1 Advantages

Resistance to weather conditions

Compared to crystalline panels, Thin-Film photovoltaics are not affected by high temperatures. They have a low temperature coefficient which means that the energy production is increased when the temperatures are higher. Opposite to mono- and polycrystalline panels which perform lower in high temperature conditions, Thin-Film's efficiency not only stays resistant, but increases. This factor is impressive, since areas where sunlight is readily available are also usually hot in terms of temperature. Because of this, Thin-Film solar panels often have an actual output that's very close to the one they're rated for. This can make planning a solar power system much easier using this kind of panel.

Moreover, under diffuse radiation and indirect sunlight (in cloudy conditions) Thin-Film performs much more satisfactory than crystalline panels.
Bibliography: [No 22, 27, 28]

Production cost

Another important advantage of Thin-Film is a low production cost. Less semiconductor elements are used in comparison to other photovoltaics. For example, CdTe-based solar cells need far less raw material (up to 100 times less), and lesser manufacturing cost than silicon cells. Thin-Film cells also absorb sunlight at nearly the ideal wavelength. Therefore, the power generated by thin-film solar cells is the least expensive currently available today. Bibliography: [No 9, 22, 27]

Wide range of usage

Thin-Film panels are produced in various shapes (round, square, hexagonal, etc.). This factor broadens the fields where the panels can be potentially used. Depending on the requirements of the installation surface, they can be adjusted to meet the needs. Thin-Film can be applied to almost all types of surfaces - such as metal, plastic and even paper (in the laboratory). Bibliography: [No 9, 22] As shown in the below figures, Thin-Film photovoltaics are frequently used in uncommon fields, like electric mobility (no.11), space shuttles or satellites (no.12), vehicles like ambulances and buses (no.13 and no.14), but also in vehicle charging stations (no.15).

Due to their high flexibility and low weight they are ideal for innovative solar structures, which can solve electricity deficits even in most difficult conditions.

Figure no.11

Figure no.12

Figure no.13

Figure no. 14

Figure no.15

Flexibility

High durability is another significant factor in favor of Thin-Film panels. They are less sensitive to breakage than mono- and polycrystalline cells. Therefore, they are easier to install and transport as due to the lower risk of damage, they can be handled without highly professional equipment. On the top Thin-Film photovoltaics are much lighter in weight, which also is a beneficial feature in terms of transport and installation. Bibliography: [No 22, 27]

Efficiency

Lower performance used to be a disadvantage of Thin-Film panels, as it was observed approximately between 6% and 12%. Although thanks to latest technologies using CdTe and CIGS materials, the efficiency of Thin-Film panels has rapidly risen and now can reach beyond 21%. Such productivity is outperforming even the polycrystalline silicon cells. Therefore, we may assume that Thin-Film has high perspectives to further benefit from technology developments. Bibliography: [No 9, 22, 27]

1. 3. 2. 2 Disadvantages

Durability

Thin-Film panels' lifespan can be considered a weak factor, as it is expected to last approximately 20 years. Additional negative feature is the considerable drop in the efficiency. The aging is faster than in mono- and polycrystallic photovoltaics. This results also in shorter warranty given by the manufacturers. Some Thin-Film materials have shown significant degradation of performance over time and stabilized efficiencies can be 15-35% lower than initially advised values. Bibliography: [No 22, 27]

Higher Total Costs

Thin-Film panels are characterized by approximately a 7 to 10 percent conversion rate for energy drawn from the sun. Therefore, they can only draw about half the wattage from sunlight in comparison to mono- and polycrystalline panels. This means that Thin-Film photovoltaics require twice as much installation space for the same amount of power.

Although panel costs (which account for around 50% of the total installed price) have been declining as a result of more efficient and competitive manufacturing– installation costs have remained on the similar levels. Consequently since twice as many panels need to be installed in order to get the same results in energy outcome – the overall cost advantages of lower panel prices are covered by the final cost. Bibliography: [No 22, 27]

Longevity

Since the Thin-Film technology is new and still hasn't been well tested, it is not possible to judge whether the lifespan of these photovoltaics can reach the other types characteristics. There are concerns that in Thin-Film panels there may be a more rapid decrease in electrical production than other types of photovoltaics. Bibliography: [No 22, 27]

Toxicity Concerns

Both CdTe (larger amounts) and CIGS (smaller amounts) materials use Cadmium, which is classified as one of the 6th most toxic substances. While use of CdTe on a residential roof doesn't pose a significant risk, there is some concern about utility, as well as the long term effects. Since authorities in Europe are currently looking at the possible more demanding regulations regarding products containing Cadmium, this could have an impact on the sale of thin-film solar panels in Europe. Bibliography: [No 9, 22]

1. 3. 3 Pros and cons conclusions

Thin-Film panels' performance is on much higher levels than crystalline photovoltaic in demanding weather conditions such as cloudy sky or high temperatures. Their price is much affordable due to the lower amount of silicon used in their production. These photovoltaics have high flexibility and are easy to handle, as they are less fragile. On the other hand though, Thin-Film efficiency does not reach the other photovoltaics, as they need double space in order to produce the same amount of energy. Considering that, the benefit of lower panel cost of the does not end up as Thin-Film being finally a more economic solution. The aging is most probably quicker than in mono- and polycrystalline cells and since the drop of efficiency is more significant, Thin-Film panels' lifespan is expected to be shorter as well. Bibliography: [No 21, 22]

1. 4 Organic Photovoltaics – OPVs

1. 4. 1 Analysis

A new photovoltaic technology, the organic photovoltaics, has started to enter the field in the last years. Organic photovoltaics consist of a photovoltaic cell made of conductive organic polymers or molecules (usually carbon), suitable for creating an electric charge from the light absorption. Overall, their performance is less remarkable than the silicone technology, with only few exceptions. In the below figure (no.16) the manufacturing of organic photovoltaic cells is presented along with the final product example (no.17). Bibliography [No 27, 28]

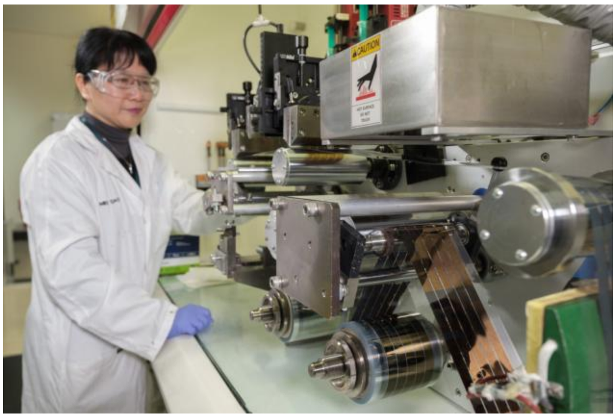

Figure no.16

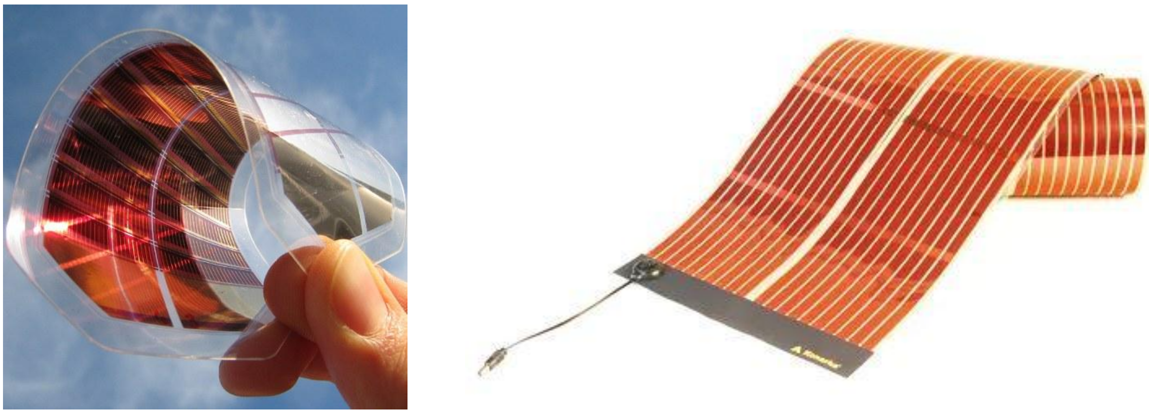

Figure no.17

Organic photovoltaics are divided into four categories, based on their material and the order of placement of the individual layers. The categories are as follows:

Single Layer OPVs:

Single Layer OPVs are consisted of the simplest organic structure. The structure is based on a polymer created by excitons (an electron-hole combination in a dielectric or a semiconductor), which are compressed by two conductive electrodes. The positive electrode (anode) is usually made of Indium Tin Oxide (ITO) with high work function. In contradiction, the negative electrode (cathode) of a low work function is usually made from substances such as aluminum (Al), magnesium (Mg) or calcium (Ca). The difference of work function between the two conductors sets up an electric field in the organic layer. When the organic layer absorbs light, electrons will be excited to the LUMO (lowest unoccupied molecular orbital) and leave holes in the HOMO (highest occupied molecular orbital) thereby forming excitons. The potential created by the different work functions helps to split the exciton pairs, pulling electrons to the positive electrode and holes to the negative electrode. Bibliography: [No 15, 16, 27, 28] A structure of a single layer OPV is presented in the below figure (no.18)

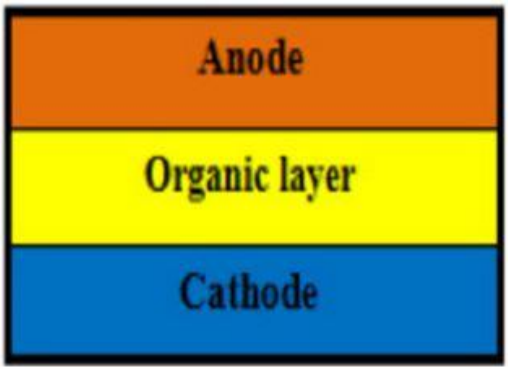

Figure no.18

Bilayer OPVs:

Bilayer OPVs include two layers between the anode and the cathode. The materials of which these two layers are created, intentionally differ in terms of electron affinity and ionization energy. This enables the development of electrostatic forces at the layer’s interface. The layer with the highest electron concentration and ionization energy acts as an electron acceptor, while the one with the lowest as a donor. This structure splits excitons much more efficiently than the one in the single layer photovoltaic cell. Bibliography: [No 15, 16, 27] The structure of Bilayer OPVs is presented in the figure below (no.19)

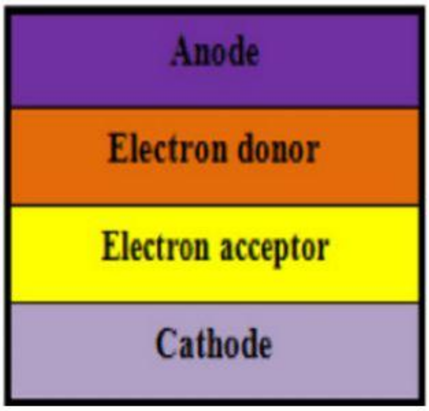

Figure no.19

Bulk Heterojunction OSC:

Bulk Heterojunction OSC is a more improved type of organic photovoltaics than the single and the bilayer OPVs. Between the anode and the cathode there is a layer, which is a blend of donor and acceptor materials with the greatest possible difference in electron concentration and ionization energy. It improves the bilayer shape because the thickness of the layer is comparable to the diffusion distance of the exciton. Thus, the created excitons can more easily approach the donor-acceptor interface and break down into electrons and holes in larger quantities. Afterwards, the electrons and holes are collected by the corresponding acceptor (the electron donor also acts as an acceptor of holes and vice versa) and are led to the anode and cathode respectively. Bibliography: [No 16, 27, 28] The structure of bulk heterojunction cell is presented in the figure below (no.20)

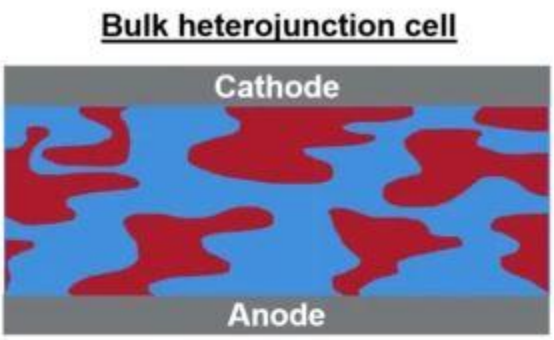

Figure no.20

Graded Heterojunction OSC

Graded Heterojunction OSC is a combination of the two previous structures (bilayer and bulk heterojunction), where instead of a flat interface between the active organic layers, one type of polymer penetrates into the other. This structure combines the short electron travel distance present in bulk heterojunction with the advantage of the charge gradient of the bilayer technology. Bibliography: [No 16, 27]

1. 4. 2 Advantages and disadvantages

1. 4. 2. 1 Advantages

Production cost

The low production cost is the main and more distinct advantage of organic photovoltaics, as the used production materials for these panels are more economical than substances common in inorganic photovoltaic, such as crystals made from Si, Ge, GaAs, etc. Therefore, mass manufacturing is an easy available option. Bibliography: [No 6, 15, 16]

Resistance to weather conditions

Organic solar panels are more efficient in diffused light conditions and in a cloudy environment. More specifically, when there is sunshine, their efficiency is 8-9%, while in cloudy conditions it is around 13%. This means that for less sunny countries such as the north, this type of photovoltaic is ideal. Bibliography: [No 6, 15, 16]

Flexibility

Organic photovoltaics are flexible and easy to handle. Thanks to the high flexibility they can be effortlessly and economically printed in many shapes and colors. Thus, they are often used in small appliances, door frames and even in smart clothes technologies. This is an important advantage as it allows the manufacturers to create renewable energy sources in all possible fields and not only for stationary systems. Bibliography: [No 6, 15, 16] Installation of organic photovoltaic on a car is presented in the below figure (no.21)

Figure no.21

1. 4. 2. 2 Disadvantages

Performance

Organic solar energy panels present much lower performance than inorganic photovoltaics. In real conditions they reach usually only less than 10%. It is related to their small exciton diffusion lengths and low carrier mobility. Bibliography: [No 6, 15, 16]

Lifespan

Organic photovoltaics show much lower lifespan than other solar panels. The pick of their performance lasts approximately 10 years, as they are highly sensitive to external factors, such as mechanical stress, moisture and continuous light and air conditions. Bibliography: [No 6, 15, 16]

1. 4. 3 Pros and cons conclusions

Organic photovoltaic is a new technology with promising perspectives. It can be adapted to wide variety of applications thanks to their flexibility and ability to be formed in numerous shapes. Another important factor allowing a mass production of organic photovoltaic is their low manufacturing cost, which is actually incomparable to other types of solar panels. On the other hand, though, the performance is their great disadvantage. Not only are they less efficient than other photovoltaic types, but also have a shorter lifespan and higher sensitivity to weather conditions and lower resistance to mechanical stress.

Bibliography: [No 6, 15, 16, 27]

CHAPTER 2:
Lifespan and recycling opportunities

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2. 1 Lifespan of photovoltaic panels

The expected solar panels lifespan is about 30 years until it should be decommissioned. It is crucial to point out that this average lifespan is highly dependent on various internal and external factors along with risks and determinant processes, which will be analyzed in the following sections. Of course the approximate panel's lifespan is related to its type, as mentioned previously. Nevertheless, generally speaking, by investing in high-quality solar elements, ensuring that the panels are installed correctly and carrying out systematic monitoring/maintenance, the degradation processes can be remarkably reduced and the optimal efficiency of the panel can be kept throughout their expected lifespan.

And when the panels reach the end of their power-generating lifespan and need to be replaced, they are still of value. Rather than sending waste solar panels to landfill, recycling can extract most of the valuable components and raw materials for the production of new panels or use in other industries.

2. 2 Recycling opportunities

Except of the numerous environmental advantages which solar energy offers during the operational time of each photovoltaic panel, the solar cells remain eco-friendly also at their disposal. Regardless the fact that all photovoltaic cells contain certain amount toxic substances, some of them reach an astonishing 96% recycling efficiency, which is still aimed to increase. Numerous materials used in photovoltaics manufacturing can be repurposed on high levels, both in case of silicon and Thin-Film based panels.

Mono- and polycrystalline photovoltaics reach around 95% in terms of the glass recycling. Glass from these solar panels can be repurposed for coatings or packaging. All of the metal frame, which contains aluminum, can be reused for manufacturing of new solar panels. Another recyclable substance is silicon, which can be extracted on levels around 85% for use in solar panels, electronics, or batteries. Even broken wafers can be melted and used gain for manufacturing of new silicone elements.

Thin-Film photovoltaics during their recycling process are divided into solid and liquid materials. Liquid undergo dewatering process in order to ensure purity. The remaining substance goes through metal processing to finally separate the various semiconductor materials. On average, up to 95% of the semiconductor materials can be reused. As for the solid elements, they get purified into glass, saving 90% of the glass elements for easy re-manufacturing.

Moreover, also laminating and encapsulating materials - Polyethylene glycol terephthalate (PET) and ethylene-vinyl acetate (EVA) – can be respectively recovered up to for 5% and 10% of the waste from a solar cell.

Latest developed process aim to extract the PET and EVA substances without using solvents that cause pollution, in order to make the recycling process more environmentally friendly.

CHAPTER 3:
Factors affecting the levels of efficiency

Factors affecting the levels of photovoltaics efficiency can be divided into internal and external conditions. The internal conditions include the structural characteristics of the photovoltaic cell, such as Rs resistance, aging, micro-cracks (fracture at the surface of the cells), visual loss, spatial placement of photovoltaic cells in the photovoltaic frame and reversing diode. The external conditions are related to environmental factors, such as radiation, shading, temperature, pollution or wind.

3. 1 Internal conditions

Rs Resistance

Rs resistance is an important factor that plays a key role in the efficiency of a photovoltaic cell. The increase in the distance between the face of the element and the p-n junction is proportionally related to the resistance and therefore to the power loss. Thus, in order to have a better level of efficiency the Rs must be minimized as much as possible. Bibliography: [No 1, 2, 28, 29, 35, 37]

Aging

For each photovoltaic panel, its age and its active usage period are a crucial factor of their efficiency. Due to the wear of the photovoltaic panels as well as the data that make up the photovoltaic system, it is expected that over time each solar cell will present a small drop in the amount of the produced electricity produced. The drop in the efficiency is usually estimated at 1% to 2% for each passing year. Bibliography: [No 5, 11, 29]

Micro-cracks

In many cases a decrease in the efficiency of a panel is not caused by a standard wear and tear condition, such as aging, but by a mechanical damage that the elements of the panel have suffered from. These damages are called micro-cracks, which stands for fractures in the photovoltaics' hives. The reason why damages may occur can arise from human errors usually related to improper handling such as unprofessional or careless transportation or installation, or even to incorrect maintenance or cleaning habits. However, this phenomenon can also be caused by rough weather conditions, such as for example an intense hail. The damage is not necessarily visible to the naked eye, as the panel may have been micro-cracked but the outer protective glass may not be broken. For this reason, in order to detect any micro-cracks, a check with the method of electroluminescence is required. Bibliography: [No 20, 23, 25] On below figure (no.22, no.23 and no.24) several examples of micro-cracked photovoltaics panels are presented

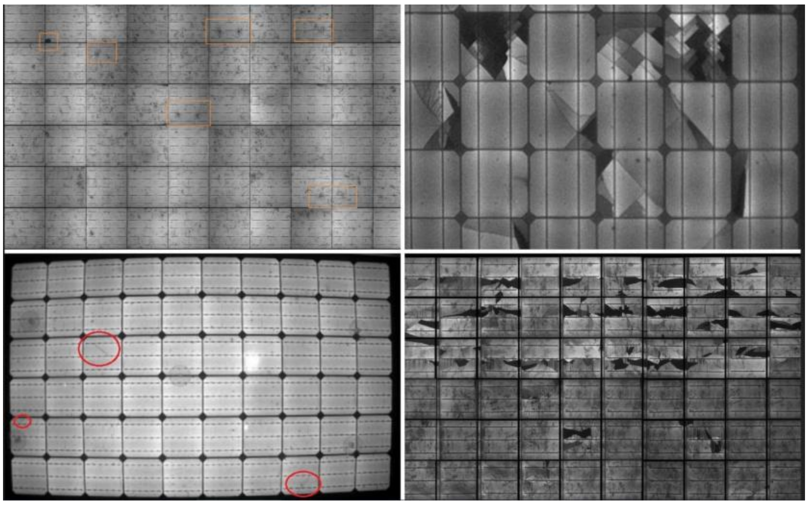


Figure no.22

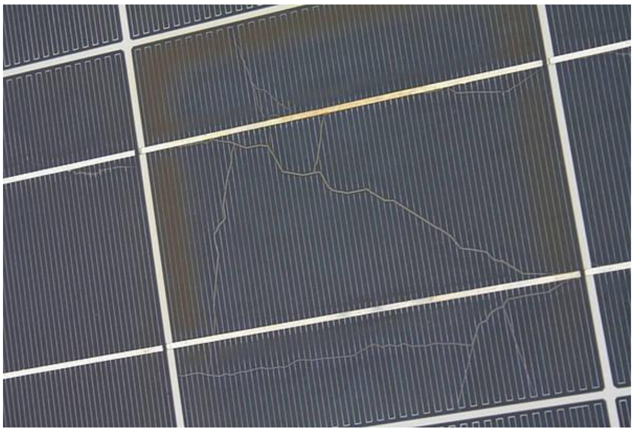


Figure no.23

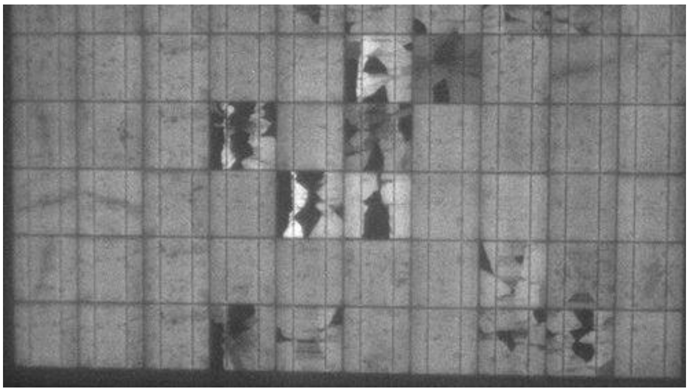


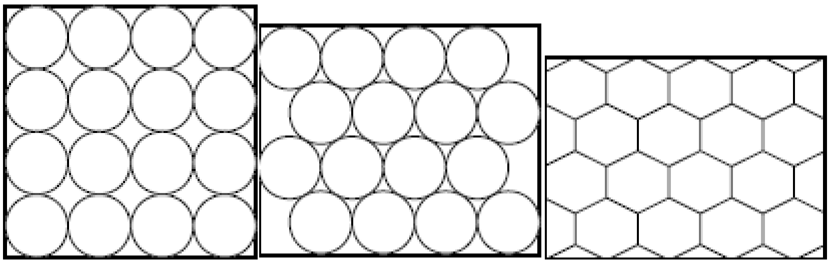
Figure no.24

Visual losses

The visual losses are the differences in the reflectivity of the photovoltaic panel (glass, reflective coating, photovoltaic material) in relation to the corresponding STC (Standard Testing Conditions). Visual reflectivity of the photovoltaic panel, in relation to the corresponding value in STC conditions, increases as the angle of incidence of the sun's rays on its surface increases, especially at angles of incidence greater than 50 °C. On the top, there are losses due to differentiation of the polarization of the incident solar radiation during the day. The average effect of this factor is determined to be around 3%. Finally, visual losses are also observed due to low values of solar power density. The efficiency of the solar cell is reduced due to the low values of solar radiation, by about the value of 200 W / m^2. Visual losses are not so remarkable for good quality commercial panels. However, in the case of moderate-quality panels, these energy losses prove to be relatively significant and are generally estimated at 3%. Bibliography: [No 11, 25, 29, 36]

Spatial placement

The spatial positioning of photovoltaic cells in the panel is important since the density of the elements is proportional to the coverage factor of the panel. This is defined as the ratio of the total active surface of the solar panels. The surface of the semiconductor absorbs and converts the solar radiation. On below figure (no.25) the three most popular ways to place photovoltaic cells on a panel are presented.



1 2 3

Figure no.25

The value of the coverage rate ranges from:

0. 75 to 0. 79 for circular elements in parallel rows (fig. no.25 1)

0. 88 to 0. 91 for circular elements merged with each other (fig. no.25 2)

0. 96 to 0. 99 for hexagons elements that cost even more (fig. no.25 3)

Bibliography: [No 11, 18, 20, 29]

The reversing diode

The reversing diode prevents the electric accumulator from discharging through the photovoltaic panel, when it is not illuminated and causes energy losses of approximately 1%. The rate of return loss is equal to 0.99

3. 2 External conditions

Radiation

The energy produced by a photovoltaic panel on an annual basis is directly related to the available solar radiation. Of course, the solar radiation strength depends on the geographical location of the system. The solar energy that falls on the surface of a panel is directly dependent on the orientation of the panel towards the sun. In order to receive the larger amounts of solar energy, the panel should be properly oriented and positioned at the optimal angle of inclination. The bases, at additional cost, can be set as rotating, in order to follow the direct sunlight. Such an installation increases the solar radiation results for greater electricity generation and as a result a greater power generation. Bibliography: [No 20, 24, 26, 29, 33]

Temperature

As the temperature rises, a corresponding increase in the internal concentration of the semiconductor carriers occurs, resulting in more reconnections of carriers. Thus, a strong leakage current is created through the diode, which causes a reduction of the Voc and a considerable decrease in the efficiency of the photovoltaic cell. As the temperature of the photovoltaic panel rises, its efficiency drops. Bibliography: [No 5, 18, 20, 29, 33] In the figure (no.26) below the proportion between the temperature and the efficiency of the solar cell is presented.

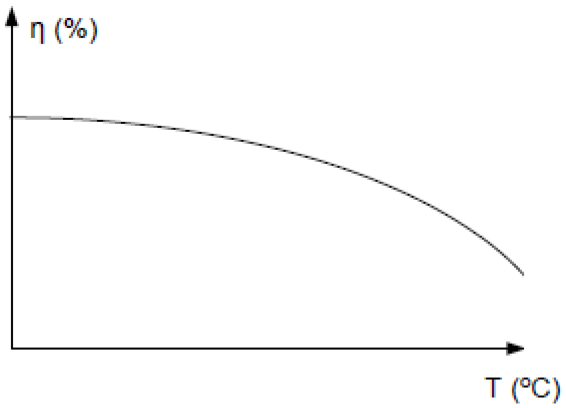


Figure no.26

The wind

The wind speed is highly important in determining the temperature of the panel. The higher wind speeds result in lower operating temperatures of the photovoltaic panel as they cool the cells down. For example, in the conditions where the cold north winds blow, the photovoltaics operate better at lower temperatures than in apnea conditions, regardless the level of the solar radiation. However, when considering the summer winds, this phenomenon is opposite. Hot winds results in higher temperature of the panel's surface and therefore affect negatively its productivity. Bibliography: [No 5, 18, 20, 33]

Pollution

Another important issue reducing the efficiency of photovoltaic panels is dirt on the surface of the panel. Factors such as dust, leaves or birds' impurities, but on the other hand snow in winter or salt if installation is settled in coastal areas, can easily decrease the performance of photovoltaics. This risk factor is even more considerable in urban and industrial areas, due to the soot present in the atmosphere, which adheres firmly to the glass surface of panels. The solution to overcome this factor is proper maintenance of the panels' surface. In order to protect their efficiency, it is necessary to thoroughly clean the photovoltaic panels with proper detergent. The cleaning process need to be precise but also careful, in order to avoid causing any micro-cracks mentioned in the previous sections. The correct adjustment of the panels' placement can also appear useful in keeping the needed care of the surface. In areas with frequent snowfalls or windstorms, solar panels are usually placed at a 90 or at least 45 degrees slope in order to avoid snow and dust accumulation. When a photovoltaic panel is located in an area with high levels of pollution, the estimated performance calculations should include the corresponding reduction in electricity generation. Such calculations can be obtained by using the purity factor σρ. This factor is defined as the ratio of the electric power produced by the polluted photovoltaic panel divided by the electric power it produces when its surface is completely clean. The more the value of σρ drops under 1, the more intense is the pollution of the specific environment, the smaller is the slope of the photovoltaic panel or the more infrequent are the rainfalls in this area. Bibliography: [No 1, 33, 36]

Shading

The shading is another crucial factor influencing the efficiency energy production by photovoltaic panels. There two basic scenarios where the phenomenon of shading may occur. The first are the obstacles encountered on the horizon of panels. These can be buildings, vegetation, surrounding terrain height etc. The other scenario is related to limited installation area, for example on the roofs of buildings where shading of the one panel row is caused by the adjacent installation. Especially in the second case, the effects of shading can be very significant. A typical photovoltaic panel consists of photovoltaic cells of the same electrical characteristics connected in series. Therefore, the shading of a single photovoltaic cell could influence the energy production levels of the whole row. A shaded element simply behaves like a p-n diode in a closed circuit, which receives from the rest of the functional photovoltaic elements a high reverse voltage. If the illuminated cells of the panel are numerous, this voltage can reach the breakdown voltage of the shaded part and cause its destruction. The shaded element acts like a large resistor, which renders the energy offered by the rest of panel’s cells. Prolonged shading of one element in combination with intense lighting of the rest of the section, can easily lead to the damage of this element and as a result to the destruction of the entire panel, as it is not possible to replace a defective element. This phenomenon is referred to as Hot Spot Effect (refer to next section for more details). In order to prevent such a risk, photovoltaic panels are equipped with bypass diodes, which are connected in parallel to the cells. Such a structure allows the use of a photovoltaic panel, even if it includes a damaged cell. Bibliography: [No 1, 5, 18, 25, 28, 29, 33, 35, 36, 37]

Hot spot effect

The phenomenon of hot spots can occur due to material failure on one of the elements of a photovoltaic panel. This can happen due to manufacturing fault, incorrect connection of the polarity between cells or partial shading of an element. Regardless of the reason, the results of hot spots are exactly the same in all scenarios – the defective photovoltaic element get overheated and in consequence totally destructed.

Hot - spot effect occurs when there is a photovoltaic cell that gives lower current in comparison to the rest elements of the same series. Bibliography: [No 18, 29, 33]
The figure below (no.27) presents a shaded photovoltaic cell connected in series. This shaded element is in high risk of getting burned.

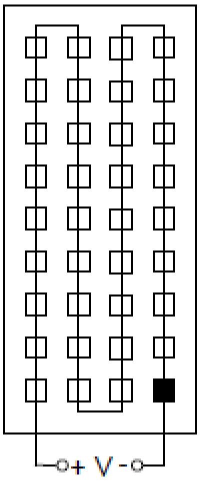


Figure no.27

Following figures show the impact of hot spot phenomenon on the photovoltaic panels, perceived by the method of thermography (no.28) or as visible to a naked eye of the observer (no.29). It is crucial to point out that in early stages of the hot spot effect, its destructive result may not be visible if not examined with technology tools (see figure no.30).

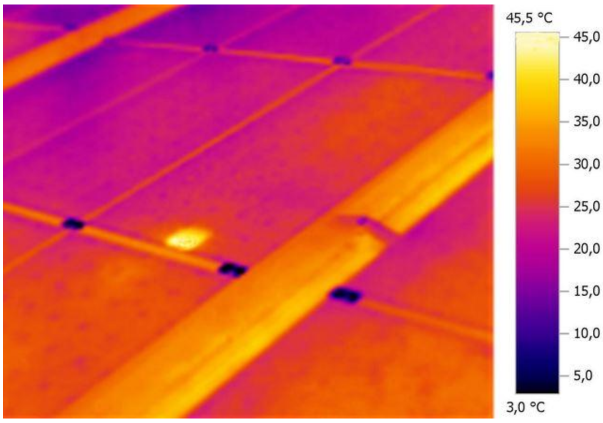


Figure no.28

Figure no.29

Figure no.30

3. 2. 1 The effect if shading on different connections

Photovoltaic cells can be connected in series or in parallel. Following is the characteristic output in voltage and current for both types of connections:

The effect of shading in series connection

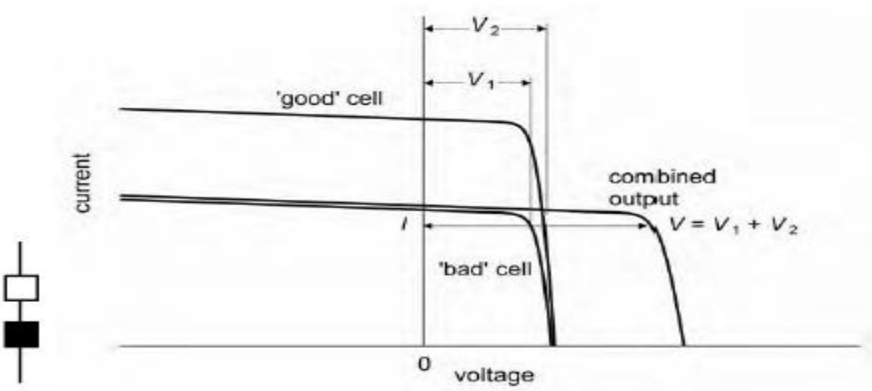


Figure no.31

In the above characteristics (figure no.31) the combined output of the open circuit voltage (V_{OC}) is the sum of the two separate voltages. One of the shaded 'bad' cell marked as V_1 and the other of the fully functional 'good' element described as V_2. Therefore, $V_{OC} = V_1 + V_2$.

The combined short circuit current I_{SC} of the circuit, when elements are connected in series, can be calculated by reversing the 'good' element's characteristic towards the axis of the current. The total current I_{SC} will be the point of intersection of the two individual characteristics. Such a calculation is presented in the figure below (no.32)

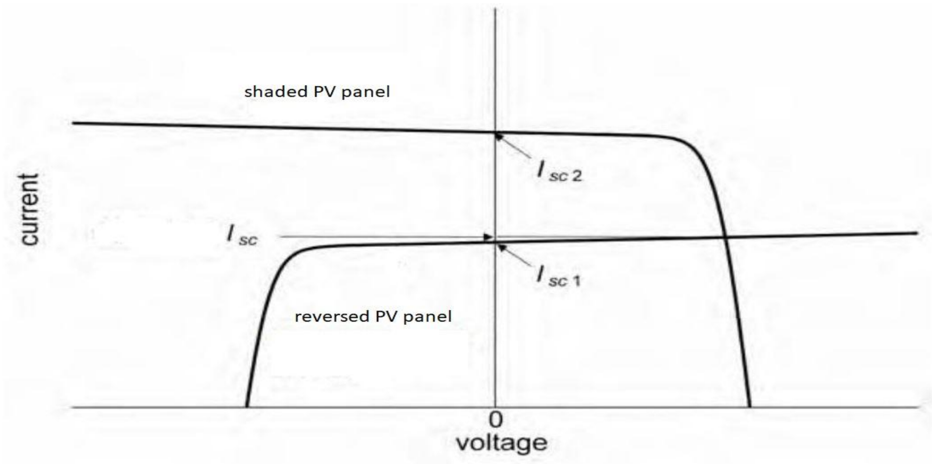


Figure no.32

A shading element in series reduces the current of non-shaded elements causing them to produce higher voltage which may result in reverse polarization of the shaded photovoltaic element. This energy loss in the shaded element is converted into heat that can cause fracture or total destruction. The temperature of the shaded element can reach 150°C what can be destructive to photovoltaics.

This risk can be avoided by using a bypass diode mentioned above. The diode is connected in parallel with the photovoltaic cells in order to protect them from opposite polarization. In standard operating conditions where none of the elements is shaded, each cell is correctly polarized and the bypass-diode is not conductive. When the shaded cell gets reversibly polarized and produces short circuit current, the diode protects it by getting conductive. Bibliography: [No 24, 25, 29, 30]

The below figure (no.33) shows the characteristic of the mentioned protective mechanism.

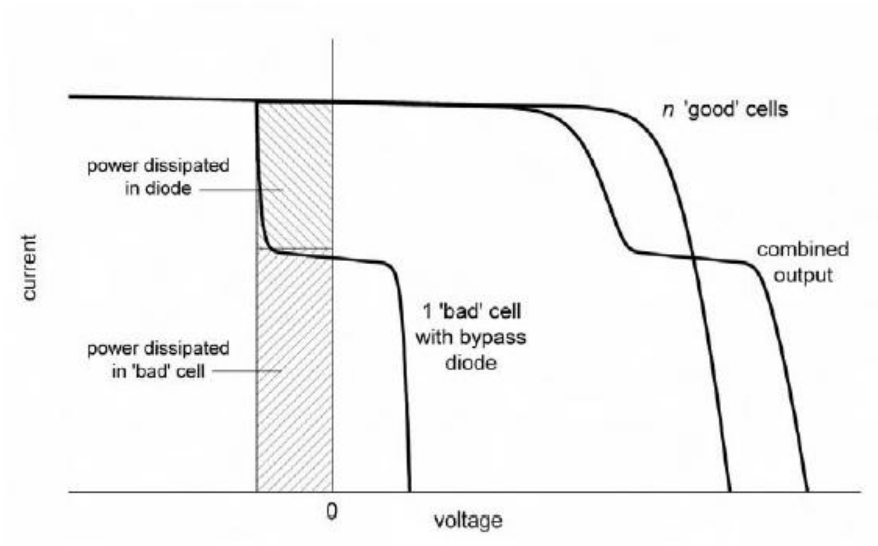


Figure no.33

When the circuit is protected by bypass-diode, the combined characteristic of the circuit is almost equal to the output of the ‘good’ cell. In conclusion, the above characteristic proves that with the installation of a bypass-diode, the total output is improved.

The effect of shading in parallel connection

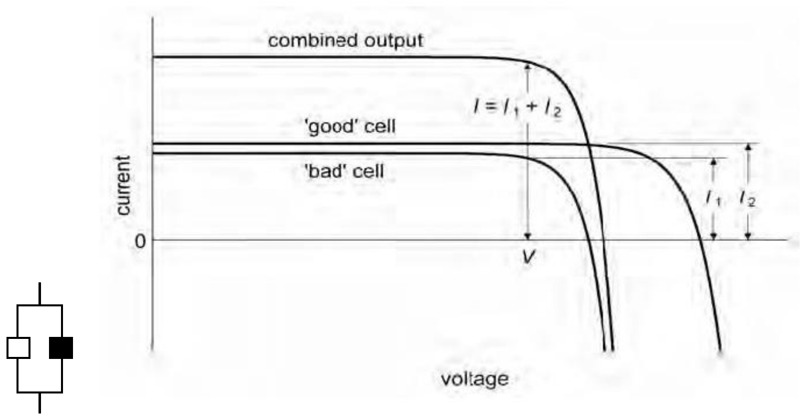


Figure no.34

The above characteristics (figure no.34) present two cells in parallel connection, where the total characteristic of short circuit current (I_{SC}) is the sum of the two individual currents I_{SC1} and I_{SC2}. Therefore, $I_{SC} = I_{SC1} + I_{SC2}$.

The alternative way to calculate the total voltage of the elements connected in parallel is to reverse the characteristic of the "good" photovoltaic cell towards the voltage axis. The total open circuit voltage V_{OC} will be the voltage at the point of intersection of two individual characteristics. This process if presented in the figure below (no.35)

Bibliography: [No 1, 2, 5, 18, 20, 29, 30]

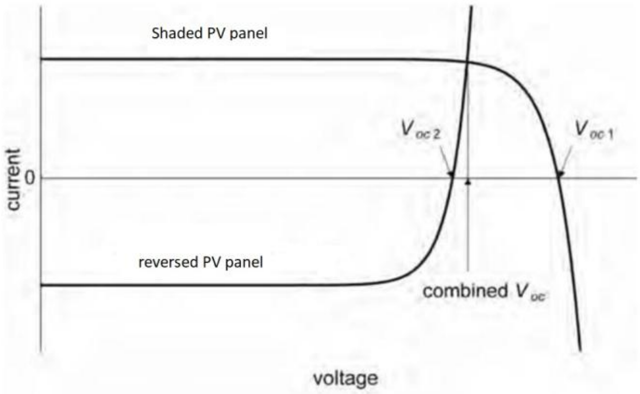


Figure no.35

3. 3 Key factors causing solar panels' degradation

There are different forms of mechanical and chemical degradation caused by the panel's exposure to light, these include:

- Light-induced degradation
- Potential induced degradation
- Age-related degradation

Light-induced degradation (LID)

Light-induced degradation is an interaction between the crystalline silicon cells on the panel and the outside environment. LID can last days or over a week.

LID can have a form of direct light-induced degradation (DLID). Direct exposure to sunlight during the period of initial setup can cause the electronics within the photovoltaic cells to warp or buckle from the heat. DLID can last a few hours.

Another type of LID is UV light-induced degradation (UVID). As a result of initial exposure to sunlight, the crystalline silicon oxides on the surface of the panel and forms a layer of boron dioxide that reduces the photovoltaic's efficiency.

During the first period (approximately 1,000 hours), there's an adjustment time frame when the photoconductivity is minimized, what reduces the panel's performance by 1-3%. After the adjustment period, both the photoconductivity and the efficiency get stabilized on the normal levels. Bibliography [No 11, 39]

Potential induced degradation (PID)

Potential induced degradation (PID) is caused by a high potential difference between the semiconductor material (cell) and other parts of the module (glass, mount or aluminum frame). This potential difference can lead to current leakage and as a result to the migration of negative and positive ions. This phenomenon is presented in the figure below (no.36). Negative ions flow out via the aluminum frame, while positive ions (sodium ions) emerge to the cell surface. These migrations affect the cell by reducing its photovoltaic process and lead to power losses.

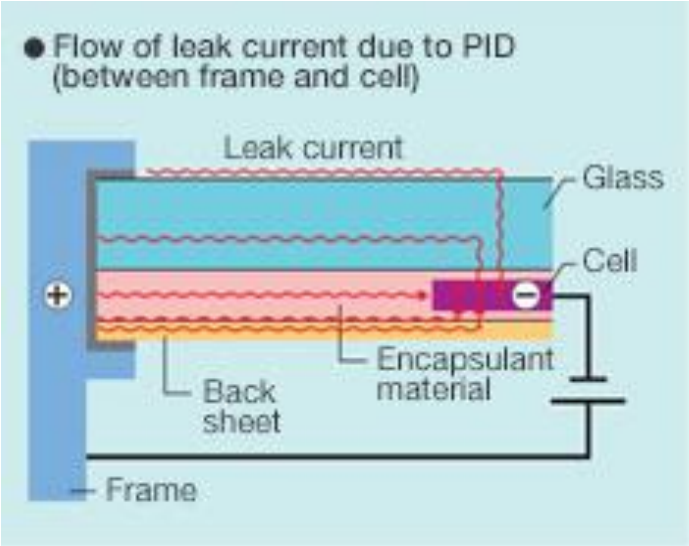


Figure no.36

PID consequences can be held responsible for power losses of up to 55%. Moreover, the effects are not immediately visible – it can take several months or even years to notice the impact of the PID. The PID is closely linked to environmental factors, such as humidity or temperature, and the configuration of the photovoltaic system, such as grounding, module and cell type. The mobility of ions accelerates in high humidity and temperature conditions, which increases the PID effect. However, these are parameters that cannot be controlled. On the other hand, the voltage potential and sign of the module have also an important impact on the PID phenomenon. It depends on the position of the panel in the array and the system grounding (refer to figure below no.37). Usually, PID is related to a negative voltage potential to earth and the highest risk falls on the most negative panel. It has been proved that the chemical composition of glass, encapsulating material or anti-reflective coating, has a significant impact on the occurrence of PID. As an example, the sodium contained in the glass can be a cause of PID. Bibliography [No 11, 34, 37, 39]

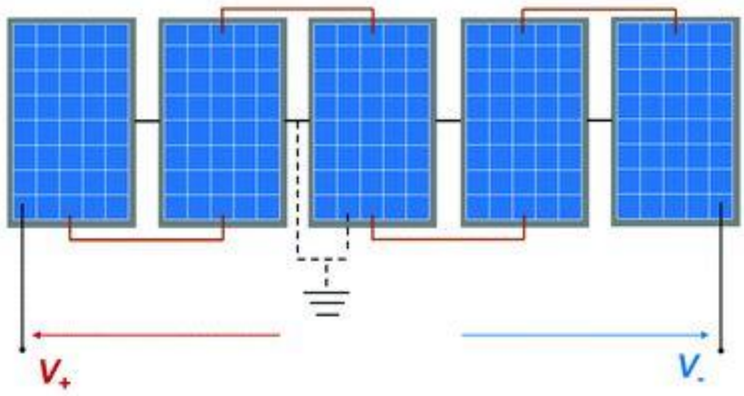


Figure no.37

Another determining factor is the resistance to moisture of the used material, as the humidity increases conductivity and therefore, ion migration. The Potential induced degradation (PID) can be reversible or irreversible, depending on its roots. The PID caused by electrochemical reactions is irreversible, as it induces film delamination in the photovoltaic panel or electro-corrosion.

The PID phenomenon consists of three stages. During the first stage, the fall of performance can be observed on levels 4-7%. At this stage it is yet impossible to notice the PID, even by using a thermocamera or any other means of high level technological equipment.

The second stage of the phenomenon caused a drop in the efficiency measured as approximately 10-20%. The PID still cannot be observed through thermocamera, due to low temperature differences between the PID affected cells and the rest of functional elements. The offset of V_{OC} and I_{SC} are low and therefore might be misread as normally estimated error frame for the measurement instruments. However, at this stage the PID might be noticed if the panel is measured under load. This method though can lead to mistaken conclusions, as it can’t determine if the panel is for sure affected by PID, since the measurement under load should be performed with a connected inverter. The inverter set the power output to the correct values, in order for the panel to achieve its full power output in proportion to the existing weather conditions (irradiance, temperature, etc). Therefore, even if the comparison is made between the healthy and the PID affected panels, it’s difficult to find out which of the panels is defected.

During the third stage, a decrease of more than 25% can be detected in the performance levels of PID affected panel. This degradation can be found after 2-3 years counting from the start of the PID negative process. At this stage the power loss may be pass even the 55%. At such high levels of degradation, the PID is visible when using a thermocamera, as the phenomenon is already very distinctive. As at the previous stage, the measurements should be held with the panel under load, in order to achieve greater accuracy.

In order to prevent the panels from PID impact, anti PID devices can be used to reduce or even eliminate its effects. These systems reboost the elements during the night by imposing them to a high positive potential when the array voltage falls below a defined threshold. This procedure is able to reverses the ion migration which occurs during functioning hours in the daytime. The standard levels of performance can be reached again in about one month after the installation of the anti PID system. However, it is important to mention that the time needed for the efficiency levels to be recovered depends on how long the PID was affecting the panel. If the panels have been subject to PID impact for a long time, the regeneration will last approximately half of the total degradation period. The power consumption of the anti PID is low, which is another important benefit of these systems.

For photovoltaics projects at the development stage resistant modules can be used in order to avoid or at least to limit PID phenomenon. These modules are obtained by using alternative materials, which show much lower degradation rate when exposed to rough conditions. The disadvantage of this prevention method may be the increased initial project cost. However, PID effects will be significantly decreased or even fully eliminated in the long-term if changes are made to the design of the photovoltaic systems, modules or cells. Bibliography: [No 1, 2, 5, 18, 20, 21, 23, 39]

Age-related degradation

Due to constant exposure to environmental factors, it is natural that solar panels degrade over time. The age-related degradation is caused by external factors impacting the efficiency of the photovoltaics. Weather conditions such as heavy rainfall, snowfall or ice, as well as high temperatures and warm winds can cause hardening of the crystalline silicon, frame corrosion and cell contamination. Furthermore, factors such as hail, ice, dust and sand can also cause micro-cracks on the surface of the panel. Another factor accelerating the age-related degradation are cracks on glass, as any damage to the seal of the panel can result in water getting inside and further destructive results such as corrosion, PID or short circuit.

Moreover, the electrochemical reactions made on the surface of the semiconductor materials may create shadows that reduce the amount of light absorbed by the panel and in consequence the produced power. Bibliography: [No 5, 37, 39]

3. 3. 1 The factors affecting solar panel degradation

There are several factors which determine the speed of solar panels degradation over time. Some of these factors depend on manufacturer while others are affected by the installer and/or owner.

Quality

The low quality materials and components used in the panel constructions (such as the solar glass, aluminum frame, and solar cells) can more easily break or alter. Some manufacturers reduce the amount of aluminum used in the frame in order to provide more competitive prices of their product, but obviously thinner frames are more vulnerable to damage.

It is important to underline that even if the panel has a low initial cost, it can appear less economical in the long run. If the failure rate is higher, this can lead to higher maintenance cost or even a replacement.

Short-Circuited Cells

Short circuit can be observed at cell interconnections, as visible on below figure (no.38). This phenomenon frequently occurs in Thin-Film cells, as in this type of the photovoltaics the top and rear contacts are placed much closer to each other. A closer distance makes it easier for the contacts to be shorted together either by pin-holes or by regions of corroded or damaged cell material.

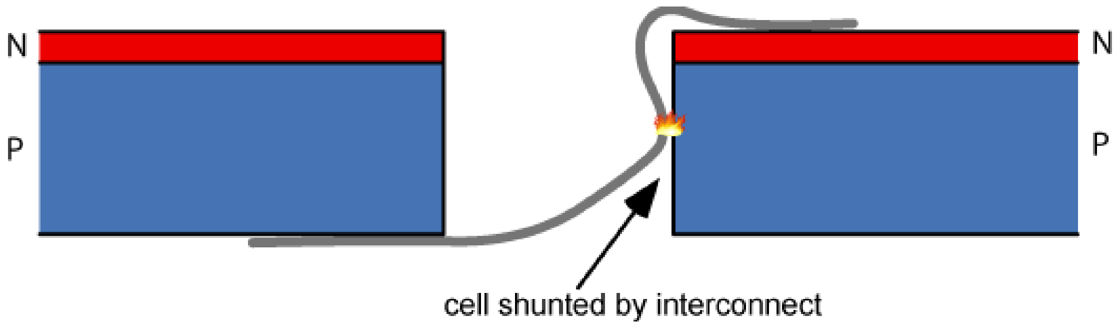


Figure no.38

Also the module structure can be affected by short circuit. Regardless the fact that each module is tested before its release, the module short circuits is frequently the result of defected manufacturing. They can be caused by insulation degradation due to weather conditions, resulting in delamination, cracking or electrochemical corrosion.

Bibliography [32]

Open-Circuited Cells

The open circuit is a common failure mode usually caused by cell cracking. Nevertheless, thanks to redundant contact points and interconnect-busbars (as presented in the below figure no.39) it is still possible for the cell affected by this failure to remain functional. Factors such as thermal stress, hail or damage during manufacturing and installation can lead to cell cracking and latent crack. The latent cracks can remain undetectable during manufacturing inspection and appear at later stages of photovoltaic life. Bibliography [32]

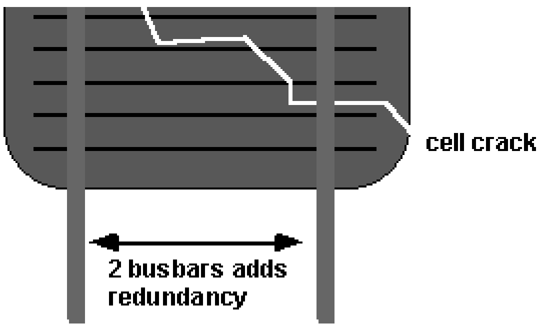


Figure no.39

Interconnect Open-Circuits

Interconnect open circuit failures may occur due to expansion and contraction of cells' materials. Exposure to cyclic thermal stress and wind loading can significantly increase the risk of this phenomenon. Bibliography [32]

Also the module structure can be affected by open circuit failures, usually in the bus wiring or junction box.

Module Glass Breakage

The damage of the protective glass surface of the panel is a considerable factor increasing the degradation process. There are numerous reasons which can lead to the glass surface shattering, such as incorrect transportation and handling, but also thermal stress and weather conditions (wind or hail).

Module Delamination

Module delamination used to be a much more common failure mode in early photovoltaics technologies. Currently it is not considered a frequent factor. The main cause for this phenomenon is the reduction in bond strength. These reductions can be either triggered by moisture or photothermal aging and thermal stress created by temperature differences and humidity expansion.

Hot-Spot Failures

Hot-spot effect described in previous sections also has a high impact on photovoltaics degradation. Manufacturing fault, incorrect polarity connection between cells or partial shading can lead to overheating and in consequence to hot-spot failure.

Bypass Diode Failure

As analyzed previously, bypass diodes are used to protect the panel form false polarized current. Nevertheless, these protective systems can themselves be subjects to failure. Bypass diode malfunction is usually caused by overheating, occurring often due to usage of undersized diodes. In order to minimize the impact of the overheating, the junction temperatures should be kept below 128°C.

Encapsulant Failure

Most common photovoltaic encapsulant materials are EVA (Ethyelne Vinyl Acetate), silicons and POE (Polyolefin elastomer), which protect the fragile silicon cells and their electrical insulation in order to avoid short circuits. With the influence of UV exposure the encapsulate materials can be impacted by degradation. Even if UV absorbers and other encapsulant stabilizers are used to ensure a long life for the panel, encapsulant materials slowly deplete finally leading to panel degradation. An important example of encapsulant failure is browning of the EVA layer, because of acetic acid build-up. This can lead to gradual reductions and power losses, where the initially constant loss rate significantly increases in time and can reach approximately 10% per a decade period.

Panel assembly

Regardless the quality of the used materials, panel’s lifespan is highly affected by the way its elements are assembled. Incompatible materials and components can affect the amount of oxidation or voltage leak and therefore can lead to increase of LID or PID risk.

Installation

Following the correct assembly, professional storage and handling of the panels during their transportation and installation are crucial to avoid unwanted damage. Factor such as micro-cracks or scratches caused by incorrect handling or improper electrical connections created during installation can remarkably affect the performance of a panel.

It’s also essential for the panel to be placed with the optimal angle and clamping, in order to take the best advantage of the self-cleaning ability and mechanical resistance.

Maintenance

Generally speaking, photovoltaic panels don’t require intensive maintenance. Nevertheless, in order to keep the desired performance levels, it is mandatory to keep their surface free of dust or debris, as a noticeable amount of build-up impurities may affect the electricity output.

It is crucial to regularly monitor also the connections, cabling, and inverters to ensure all are properly fixed and functional.

Weather conditions

Extreme weather conditions, such as heatwaves, hurricanes, thunderstorms and snowstorms, increase the rate of age-related degradation. Sudden differences in temperature levels affect the panel components, which contract and expand, causing cracks and other damage. The impact on the photovoltaic can be related to any extreme weather phenomenon (hot or cold). Extremely high temperatures negatively impact the performance of the solar cells, as they can lead to hot spot or bypass diode failure. On the other hand, the heavy snowfall and snow freezing on the surface of the panel by impose pressure and lead to cracks. Cracks can also be caused by hail. Hurricanes or thunderstorms may not affect the panel themselves, but they can throw debris on its surface and break it. Bibliography [No 14]

The expected efficiency of each photovoltaic model can be analyzed based on below characteristics:

Maximum Power Point (P_{MAX})

The P_{MAX} is the main characteristic of the solar panel power output. It calculates which combination of the volts and amps results in the highest wattage (Volts x Amps = Watts).

When using a Maximum Power Point Tracking (MPPT) charge controller or inverter, this is the point that the MPPT tries to keep the volts and amps at a level to maximize the power output. The wattage that a solar panel is listed as is the P_{MAX} where $P_{MAX} = V_{MPP} * I_{MPP}$.

Bibliography [No 30, 38]

Maximum Power Point Current (I_{MPP})

The I_{MPP} is the current (amps) when the power output is the greatest. It is the actual amperage, which is aimed to be observed when it is connected to the MPPT solar equipment under standard test conditions. Bibliography [No 30, 38]

Maximum Power Point Voltage (V_{MPP})

The V_{MPP} is the voltage when the power output is the greatest. It is the actual voltage, which is aimed to be observed when it is connected to the MPPT solar equipment under standard test conditions. Bibliography [No 30, 38]

Open Circuit Voltage (V_{OC})

Open circuit voltage shows how many volts the solar panel outputs under circumstances with no load on it. V_{OC} is shown when the measurement is performed only with a voltmeter across the plus and minus leads. Since the solar panel isn't connected to anything, there is no load on it, and it is producing no current.

This is a very important characteristic, as it presents the maximum voltage that the solar panel can produce under standard test conditions. This is a value determining how many solar panels can be connected in series with an inverter or charge controller.

V_{OC} reaches its maximum levels usually in the morning hours, when the panels are at their coolest temperature and encounter high radiance from the sun. Bibliography [No 30, 38]

Short Circuit Current (I_{SC})

Short Circuit Current shows how many amps of current the solar panels are producing when not connected to a load but when the plus and minus of the panels wires are directly connected to each other. I_{SC} is shown when the measurement is performed only with an ammeter across the plus and minus leads. This is the value of the highest current the solar panels will produce under standard test conditions. Bibliography [No 30, 38]

Tolerance +/- (%)

Power tolerance is a measure of how much electrical power a solar panel can produce above or below its rated capacity at any time.

During solar panel manufacturing, it is standard practice to carry out a flash test, exposing each panel to a flash of light (1-30 ms of 1,000 W/m^2), a substitute for sunlight, and measuring power output. The panels are then sorted according to the measured power values which vary in range up to 5% of the rated output. Bibliography [No 4, 30]

Temperature coefficient Alpha (%/C) of I_{SC}

Temperature coefficient of short-circuit current (I_{SC}) measures the changing short-circuit current values of the photovoltaic module, when the solar cell temperature increases or decreases. Bibliography [No 4, 30, 31]

Temperature coefficient Beta (%/C) of V_{SC}

Temperature coefficient of open circuit voltage (V_{OC}) measures the changing open circuit voltage values of the photovoltaic module when the temperature increases or decreases. Bibliography [No 4, 30, 31]

Temperature coefficient Gamma (%/C) of P_{MPP}

The photovoltaic temperature coefficient of power indicates how strongly the photovoltaic array power output depends on the cell temperature, meaning the surface temperature of the photovoltaic array. It is a negative number because power output decreases when cell temperature increases. Manufacturers of photovoltaics usually provide this coefficient in their product datasheets, often named either as temperature coefficient of power, power temperature coefficient, or max power temperature coefficient. Bibliography [No 4, 30, 31]

Parasitic Resistances R_S and R_{SH} (Ω)

Solar cell is mainly represented as a current source with a diode connected in parallel. The circuit also consists of two resistances named as Series Resistance (R_S) and Shunt Resistance (R_{SH}).

The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current.

Series resistance in a solar cell has three causes: firstly, the movement of current through the emitter and base of the solar cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. Series resistance does not affect the solar cell at open-circuit voltage since the overall current flow through the solar cell, and therefore through the series resistance is zero. However, near the open-circuit voltage, the IV curve is strongly affected by the series resistance. A straight-forward method of estimating the series resistance from a solar cell is to find the slope of the IV curve at the open-circuit voltage point.

Significant power losses caused by the presence of a shunt resistance, R_{SH}, occur usually due to manufacturing defects, rather than poor solar cell design. Low shunt resistance results in power losses in solar cells by providing an alternate current path for the produced current. The amount of current passing through the cell junction is reduced by such diversion, which in consequence reduces the voltage from the solar cell. The phenomenon of a shunt resistance is particularly severe Especially at low light levels, when lower amount of less light-generated current is produced, the phenomenon of a shunt resistance is particularly severe and the loss of the current to the shunt has a larger impact.

For more accurate simulation of all photovoltaic cells, and in particular for amorphous, the R_{SH} should be corrected according to the irradiance.

In the below figure (no.40) the phenomenon of Series Resistance (R_S) and Shunt Resistance (R_{SH}) are presented in equivalent circuit of a photovoltaic cell.

Bibliography [30, 31, 40]

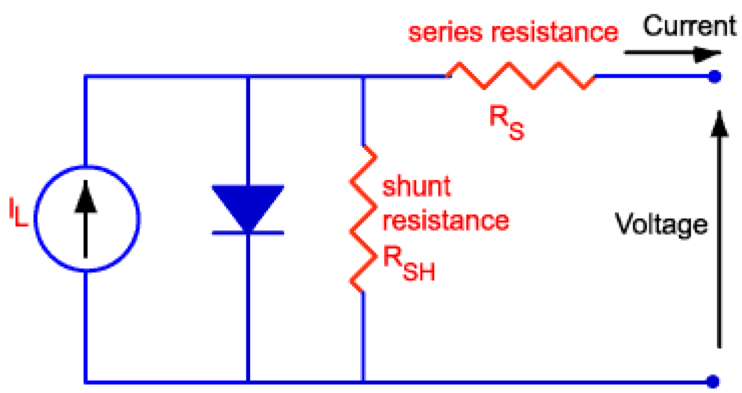


Figure no.40

Degradation (%/yr)

The productivity and the electricity production of a photovoltaic panel may decrease over time depending on factors such as weather conditions, module type and frame structure etc. The reduction of panel performance over time is called degradation. An estimated degradation rate is usually approximately 0.5% - 1%. A degradation rate implies that production from a solar panel will decrease at this particular rate per year. This means that if the rate is stated as 0.5%, in 20 years the panel is expected to be producing approximately 90% of the electricity it produced in during the first year.

Standard Test Conditions (STC)

The electric output performance of a photovoltaic panel is typically tested under standard test conditions (STC). Such practice guarantees that the comparison and the output evaluation of different photovoltaic modules are investigated in relatively most independent conditions. STC is standard set of conditions used along industry. It indicates the performance of photovoltaic panels at a cell temperature of 25°C (77°F) and an irradiance of 1000 W/m^2 with an air mass 1.5 (AM1.5). However, these conditions are rarely encountered in the real-world. Many manufactures apply STC-based performance measurements in the flash tests of their products.

Normal Operating Cell Temperature (NOCT)

NOCT takes a more realist view, more similar to actual real world conditions. Therefore it can give power estimation, which can actually be observed in the functioning solar panel. Instead of 1000 W/m^2 specified for STC, it uses 800 W/m^2, which is closer to a mostly sunny day with scattered clouds. It is based an air temperature of 20°C (68°F), not a solar cell temperature, and includes a 2.24MPH (~1 m/s) wind cooling the back of a ground mounted solar panel. These ratings will be relatively lower than STC, but much more realistic. Bibliography [12, 26]

PVUSA Test Conditions (PTC)

In the mid-1990s the National Renewable Energy Laboratory (NREL) developed a set of test conditions to measure solar panel performance under real world conditions. The conditions were called Photovoltaics for Utility Scale Applications Test Conditions or PVUSA Test Conditions, know more commonly as PTC.

The temperature is the main difference between STC and PTC. Under PTC, everything is heated up as if it were placed in the sun. The solar cells are warmed up to their estimated normal operating cell temperature which is typically around 45°C (113°F). The ambient temperature is set to 20°C (68°F), and a 2.2 MPH (~1 m/s) wind blows cooling the panel.

Bibliography [8]

Fill Factor (FF)

The Fill Factor (FF) is basically a measure of quality of the solar cell. The value is calculated by comparing the maximum power to the theoretical power that would be output at both the open circuit voltage and short circuit current together. Bibliography [41]

The Fill Factor, more commonly known by its abbreviation FF, is a parameter which, in conjunction with V_{OC} and I_{SC}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{OC} and I_{SC}, as presented in below figure:

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}} = \frac{P_{MPP}}{V_{OC} \cdot I_{SC}}$$

4.1 Performance calculations in STC vs. random conditions.

In this section, performance calculations are presented in random testing conditions for Conergy PowerPlus 215P polycrystalline photovoltaic. In figure below, expected performance characteristic observed in Standard Test Conditions are visible as presented by the manufacturer (figure no. 41).

Nominal output (P_{non})	215W
Voltage at maximum performance (U_{mpp}) [7]	28.55V
Current at maximum performance (I_{mpp}) [7]	7.63A
Off-load voltage (U_{oc}) [7]	35.54V
Short-circuit current (I_{sc}) [7]	8.11 A
Temperature coefficient (P_{mpp})	−0.44%/°C
Temperature coefficient (U_{oc}), absolute	−0.117V/°C
Temperature coefficient (U_{oc}), in percent	−0.33%/°C
Temperature coefficient (I_{sc}) absolute	4.73mA/°C
Temperature coefficient (I_{sc}) as a percentage	0.059%/°C

Standard test conditions defined as follows: 1,000 W/m² radiant power at a spectral density of AM 1.5 and a cell temperature of 25°C

Figure no.41

In opposite, four calculations in real life environment are shown in the following chapters of this section. All calculations show the effect of increased temperature and different irradiation on STC tested performance values. First two calculations refer to temperature level of 55°C, with irradiation level of 1000 W/m^2 and 600 W/m^2 respectively. The following two calculations refer to even more increased temperature of 60°C and the same irradiation levels of 1000 W/m^2 and 600 W/m^2.

Below calculations prove that the increment in temperature level leads to drop in voltage, but raise in current. In consequence, total drop of productive power is observed. It is important to mention that calculations undertaken with same temperature values and different levels of irradiation do not show difference in voltage. Therefore, the higher the increase in temperature in comparison to STC values, the lower is the overall efficiency of the photovoltaic panel.

4.1.1 Temperature 55°C and irradiation 1000 W/m^2 vs. 600 W/m^2

Sought performance characteristics: U_{OC}, I_{SC} and P_{MPP}

Conditions: Temperature 55 °C and for irradiation 1000W/m^2

Calculation:

$U_{OC,55}=U_{OC,25}*(1+\Delta T*A_U)=35.54*(1+(55-25)*(-0.0033))=32.02V$

$I_{SC,55}=I_{SC,25}*(1+\Delta T*A_I)=8.11*(1+(55-25)*(0.00059))=8.25A$

$P_{MPP,55}=P_{MPP,25}*(1+\Delta T*A_P)=215*(1+(55-25)*(-0.0044))=186.6W$

Sought performance characteristics: U_{OC}, I_{SC} and P_{MPP}

Conditions: Temperature 55 °C and for irradiation 600W/m^2

Calculation:

$U_{OC,600,55}=U_{OC,25}*(1+\Delta T*A_U)= 35.54*(1+(55-25)*(-0.0033))=32.02V$

$I_{SC,600,55}=0.6*I_{SC,25}*(1+\Delta T*A_I) =0.6*8.11*(1+(55-25)*(0.00059))=4.95A$

$P_{MPP,600,55}=0.6*P_{MPP,25}*(1+\Delta T*A_P) =0.6*215*(1+(55-25)*(-0.0044))=112.0W$

4.1.2 Temperature 60°C and irradiation 1000 W/m^2 vs. 600 W/m^2

Sought performance characteristics: U_{OC}, I_{SC} and P_{MPP}

Conditions: Temperature 60 °C and for irradiation 1000W/m^2

Calculation:

$U_{OC,60}=U_{OC,25}*(1+\Delta T*A_U)=35.54*(1+(60-25)*(-0.0033))=$ 31,45V

$I_{SC,60}=I_{SC,25}*(1+\Delta T*A_I)=8.11*(1+(60-25)*(0.00059))=8.28A$

$P_{MPP,60}=P_{MPP,25}*(1+\Delta T*A_P)=215*(1+(60-25)*(-0.0044))=181.89W$

Sought performance characteristics: U_{OC}, I_{SC} and P_{MPP}

Conditions: Temperature 60 °C and for irradiation 600W/m^2

Calculation:

$U_{OC,600,60}=U_{OC,25}*(1+\Delta T*A_U)= 35.54*(1+(60-25)*(-0.0033))=31.44V$

$I_{SC,600,60}=0.6*I_{SC,25}*(1+\Delta T*A_I) =0.6*8.11*(1+(60-25)*(0.00059))=4.97A$

$P_{MPP,600,60}=0.6*P_{MPP,25}*(1+\Delta T*A_P) =0.6*215*(1+(60-25)*(-0.0044))=109.13W$

CHAPTER 5:
Instruments used in photovoltaic measurements

In order to observe and measure the photovoltaic performance, several instruments can be used. Curve tracers assist in maintenance and troubleshooting of photovoltaics. Following, their characteristics are analyzed based on the example of HT I-V 400 instrument. This particular device is supported by additional accessories, such as HT304N Reference Cell and HT M304 Mechanical Inclinometer. Another type of instruments used for measurement of photovoltaic characteristics is infrared thermometer. It performs the measurements of the temperature levels and is described in the following parts of this section based on model HT3305. Bibliography [No 11]

5.1 Presentation of HT I-V400 multifunction instrument

In the below section a general description of HT I-V 400 instrument's characteristics and handling is described, along with its main functions, examples of the interface and standard accessories.

5.1.1 General description of the HT I-V 400 device

HT I-V 400 is the perfect choice for the standard maintenance of photovoltaic panels. When using I-V 400, possible failures and issues in the photovoltaic can be detected extremely rapidly and efficiently. The field measurement of the I-V characteristic and of the main characteristic parameters is held both for a single panel and for panel array. Along with the I-V characteristic of the tested photovoltaic, I-V 400 measures also the values of panel's temperature and incident irradiation. The instrument processes the acquired data and displays the I-V characteristic at standard test conditions (STC), in order to compare the values with the expected levels stated by the manufacturer, immediately providing the OK / NO result of the test. Thus, the I-V 400 is able to determine on the spot whether the tested panel or array respects the characteristics declared by the manufacturer. The operator doesn't have to do any calculations. The instrument carries out the comparison quickly, efficiently and automatically. A direct measurement of panels in series is presented on the below figure (no.42). Bibliography [No 11]

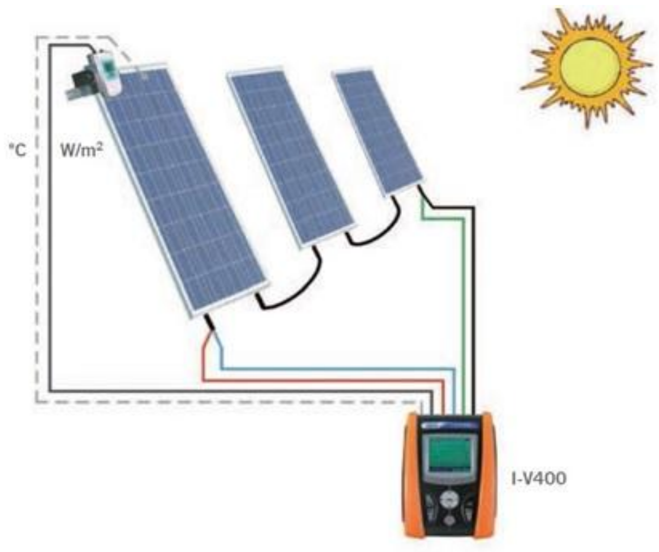


Figure no.42

In some photovoltaic installations, for example roof-top installations, it may be difficult to access the panel's output cables, which may need to be accessed at the combiner box or at the inverter's inputs. In such difficult conditions, the measurement of I-V characteristics can be performed by estimating the environmental parameters, such as irradiation and temperature, through a remote optional unit SOLAR-02. The remote unit is positioned next to the photovoltaic panels and it is connected to the relevant probes of I-V 400 in order to measure environmental parameters. The synchronization between the two units guarantees the measurements are up-to-date. Thanks to SOLAR-02 the processing of the I-V characteristics at STC is possible without using long extension cords cable. In the figure below, a measurement with remote irradiance/temperature unit SOLAR-02 is shown (figure no.43).

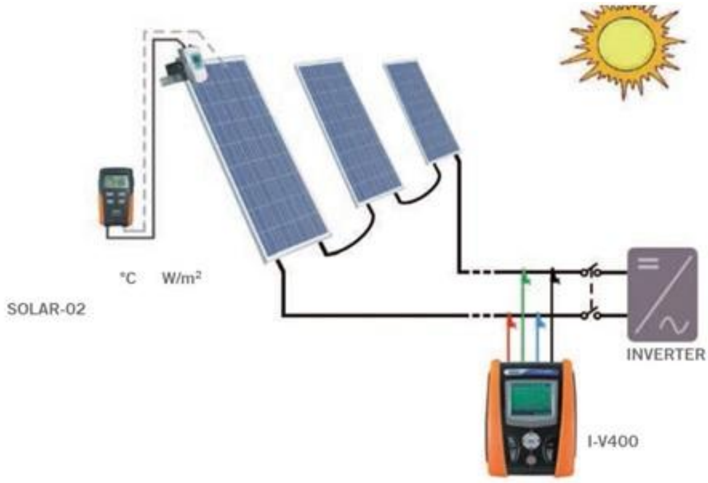


Figure no.43

Output current or voltage from the panel or array is measured with the 4-terminal method. This method always provides precise and accurate measurements, as it allows extending the measurement cables without requiring any compensation for their resistance. The I-V 400 stores a database of photovoltaic panels in its internal memory. This database can be updated at any time both via the management software and directly on the device. Bibliography [11, 13]

5.1.2 Functions of the HT I-V 400 device

The I-V 400 has several measurement functions, as stated below:

- Measurement of output voltage from panel/array up to 1000V DC
- Measurement of output current from panel/array up to 10A DC
- Measurement of solar irradiation [W/m^2] with reference cell
- Measurement of module temperature, automatic or by means of external probe
- Measurement of output DC and nominal power of panel/array
- Measurement of the resistance of photovoltaic panel in series

Furthermore, below features are worth mentioning, as they improve the test handling:

- Synchronization with remote unit SOLAR-02
- Numerical and graphical display of I-V characteristic
- Quick test mode
- Mechanical inclinometer for the detection of the incidence angle of solar irradiation
- 4-terminal measuring method
- Extrapolation to standard test conditions (STC)
- Evaluation of testing result: OK / NO
- Management of up to 30 types of photovoltaic panels in the internal database
- Internal memory for data saving
- Recalling results on the display
- Optical/USB port for PC connection
- Help on line on the display

5.1.3 Interface examples of the HT I-V 400 device

In the below figures examples of user interface are presented. Figure no.44 shows the main menu with available features (Test, Settings, Modules, Data Recall, PC Connection), which can easily be browse by cross buttons and chosen by pressing ENTER.

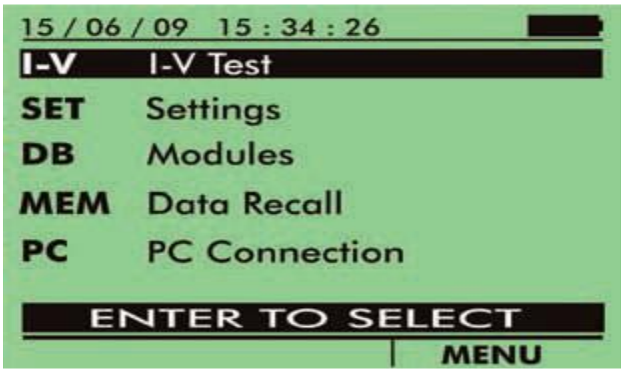


Figure no.44

The next figure (no.45) presents numerical measurement which gives positive result, marked as OK. The screen display provides with the breakdown of the measured characteristics and direct, crystal clear message informing about the result of the undertaken test.

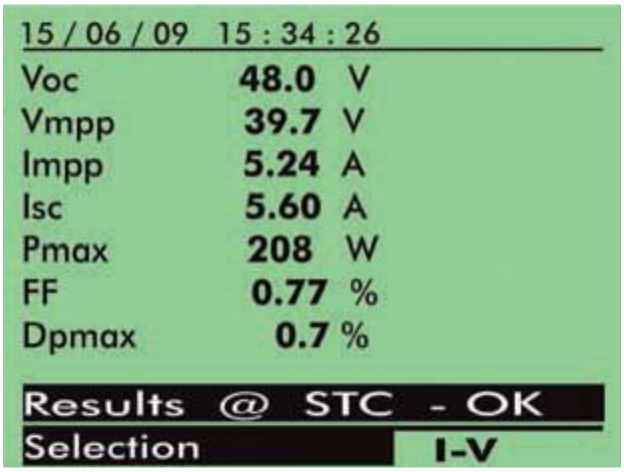


Figure no.45

The instrument has also the ability to present the taken measurements in a form of a graph. The figure below (no.46) shows a graph of a positive measurement result (marked as OK), while the following figure (no.47) presents the opposite negative measurement (marked as NO), again in a graph form.

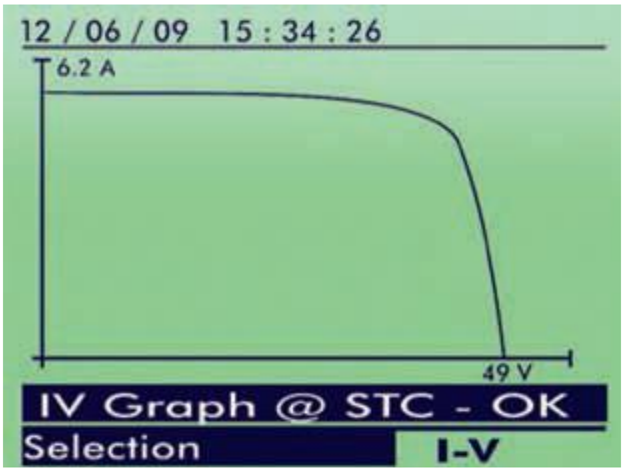


Figure no.46

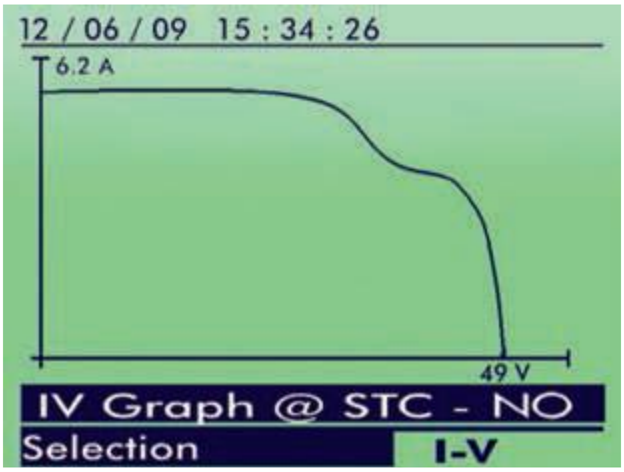


Figure no.47

The last figure (no.48) shows the interface when adding of a photovoltaic panel to the internal memory database of the I-V 400 device.

Figure no.48

5.1.4 Examples of standard accessories of HT I-V 400

One of the standard HT I-V 400 accessories is a HT 304N Reference Cell with Tilt Stand and Connection Cable, presented on the figure below (no.49). Bibliography [No 11]

Figure no.49

The aim of HT 304N is to sense the solar radiation and to pass the data through to HT I-V 400. As a passive sensor HT 304N doesn’t require any power supply, therefore it is forbidden to apply any voltage to its outputs. This instrument has an aluminum frame, which protects its fragile glass surface from any possible mechanical shock. Nevertheless, when using the device, it is crucial to avoid any risk of glass damage, which can be cause by contact with abrasive surfaces.

Another very important point ensuring the correct handling of the instrument is its positioning. The sensor needs to be installed in a clear position, with no obstructions, which could introduce shading or reflections affecting the readings. The instrument always shall be placed in parallel with the photovoltaic panel. The maximum allowed error is up to ± 2° of angle. An imperfect parallelism between the sensor and the photovoltaic may considerably affect the outcome of the measure.

In order to minimize the error in positioning angle and to assure that the instrument will be steady, the usage of the tilt stand is highly recommended. The tilt stand shall be placed in a central position of the photovoltaic panel edge. The stand is provided with a fixing screw, which is compatible with holes placed on the back side of the panel frame. When positioning the sensor on the tilt stand, in order to avoid shadowing effects, the device’s connectors should be oriented downside, as much as possible.

Before performing the readings, the sensor should be prepared to a steady state. In order to achieve that, the instrument should be exposed to the test conditions (radiation, temperature, and inclination) at least 1 minute before the start of the measurements. Bibliography [No 11]

Below technical and general specifications of HT 304N are presented.

Technical specifications:

Irradiation	
Range [W/m^2]	Accuracy (*)
50 ÷ 1400	±3.0% of readings

(*) Accuracy is grant under the following conditions:

• Temperature: -20 ÷ 50°C ; Incidence angle: 90° ± 25° ; Air mass (AM): 1.5

General specifications:

Available reference cells:	MONO-Crystalline and MULTI-Crystalline Silicon
Guidelines	
Safety:	IEC/EN 61010-1
Technical literature:	IEC/EN 61187
Calibration:	IEC/EN 60904-2
Mechanical protection:	IP65 in compliance with IEC/EN 60529
Pollution degree:	2
Mechanical characteristics	
Dimensions (LxWxH):	120x85x40 mm
Weight:	260g
Environmental conditions	
Working temperature:	-20°C ÷ 50°C
Storage temperature:	-20°C ÷ 60°C

This instrument complies with the requirements of the European Low Voltage Directive 2006/95/CE (LVD) and EMC Directive 2004/108/CE

Another standard accessory of HT I-V 400 instrument is M304 Mechanical Inclinometer, shown in the figure below (no.44)

Figure no.44

HT M304 mechanical inclinometer is used to detect solar incidence angle. In order to verify the correct angle, the inclinometer should be placed and held on the plane of the panel. Correct result is obtained when the sun shadow falls on the disc within the ‘limit internal circle’ marked on the disc of HT M304. If the shadow falls elsewhere, the incidence angle between sun rays and the surface of the panel is too high and therefore not compatible with the test conditions declared by the panel manufacturer. As a result, any measurement which is undertaken in these conditions will perform incorrect result. Bibliography [No 11]

Below general specifications of HT M304 are presented:

Characteristics	
Manufacturer	HT Instruments
Model	M304
Length [mm (in)]	224 mm
Width [mm (in)]	99 mm
Depth [mm (in)]	96 mm
Weight [kg (lb)]	0.5 kg (1.1 lbs)

5.2 Presentation of HT3305 Infrared thermometer

Since the temperature has a major impact on the photovoltaics efficiency and performance, it is crucial to observe the temperature levels of the panels. The easiest way to perform the relevant measurements is the usage of an infrared digital thermometer, such as for example a HT3305 presented on the figure below (no.45). Bibliography [No 11]

Figure no.45

5.2.1 General description of HT 3305 device

HT 3305 is a very comfortable and practical instrument to obtain the readings on infrared temperature of photovoltaic panels. It is featured with laser system providing visual and sound indications, which get activated for every change in values level. It is designed to perform quick measurements and to timely detect any temperature variation. On the top it is compatible with type K probe thermocouple for measurements inside liquid substances and chamber.

Below descriptions of the instrument's parts are shown in the following figure (no.46) as per manufacturers manual.

1. IR sensor and laser pointer
2. LCD display
3. + key
4. - key
5. MODE key
6. Trigger key T
7. Battery cover
8. Input for type K probe
9. Battery cover cap
10. Battery pack

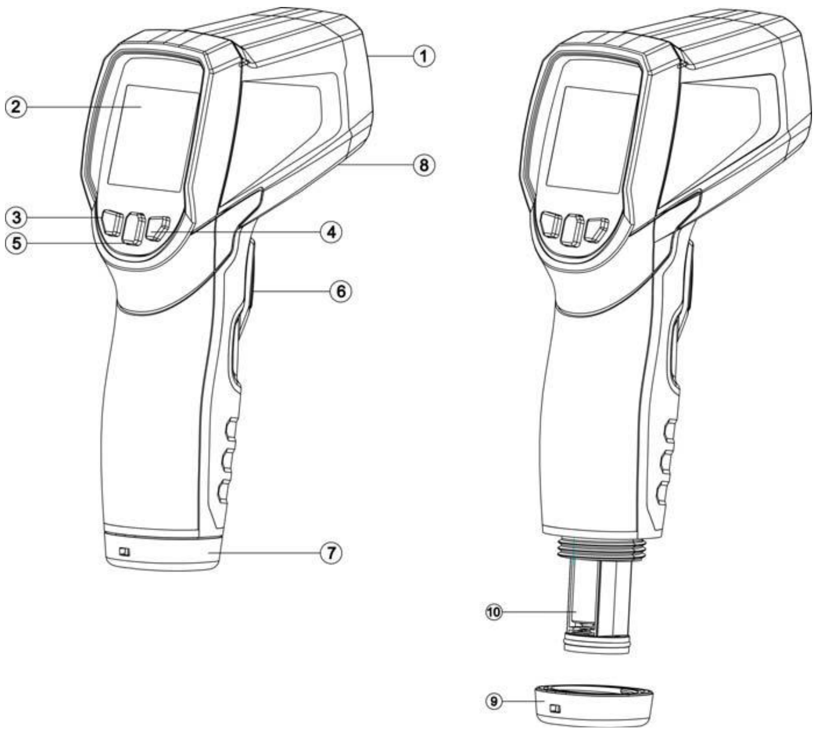


Figure no.46

In order to perform correct temperature measurement by using HT 3305, distance/spot ratio of the instrument has to be taken into consideration. It is crucial to ensure that the measured target's dimensions are at least as large as the unit's spot. The smaller the object is, the closer to it the device should be positioned. For example: if the distance from the object is 240mm (9.4inch), the spotted section of the object should be at least of 12mm (0.5inch) in order to achieve a correct temperature reading. When high accuracy is required, it is crucial for the tested object to be at least twice as large as the spot size. The ratio between the distance and the spot area is analyzed in the below figure (no.47). Bibliography [No 11]

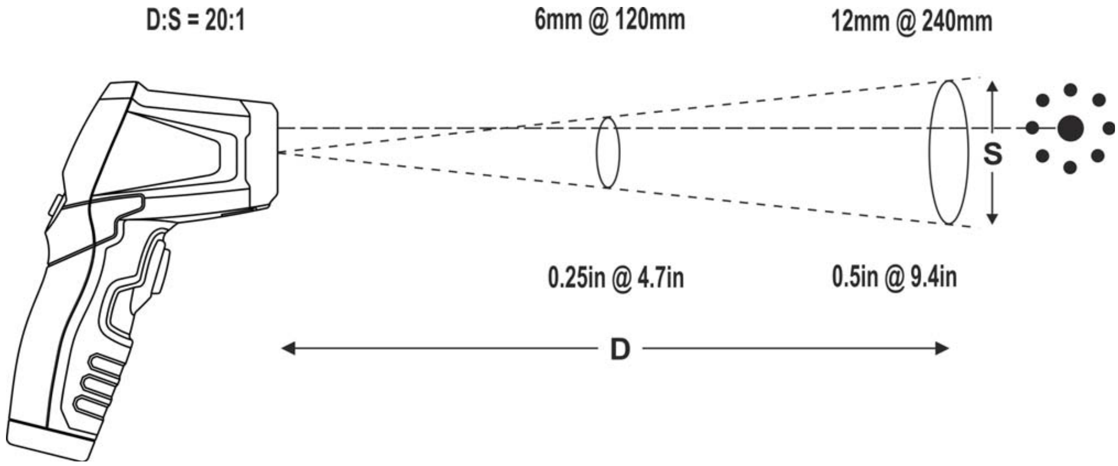


Figure no.47

5.2.2 Features of HT3305 device

The HT 3305 instrument has the following features ensuring an effective and precise temperature reading:

- Infrared temperature measurement up to 1000°C (1832°F)
- Measurement’ scale both in °C/°F
- Temperature measurement with type-K probe
- Laser pointer area for an immediate localization of distance/spot
- Distance / Spot ratio D:S = 20:1

Furthermore, below features are worth mentioning, as they improve the test handling:

- Automatic reading lock (HOLD)
- Auto Power OFF
- LCD with backlight
- Detection of MAX, MIN, AVG and DIF values
- High and Low alarm threshold setting
- IP54 mechanical protection

Below technical and general specifications of HT 3305 are presented.

Technical specifications:

Infrared temperature measurement

Function	**Range**	**Resolution**	**Accuracy**	**Response time**
°C	-50°C ÷ 20°C	0.1°C	±3.5°C	<150ms
	20°C ÷ 300°C		±(1%rdg + 1°C)	
	300°C ÷ 1000°C		±(1.5%rdg)	

Reading repeatability:

-50°C ÷ 20°C (-31°F ÷ 68°F) -> ±1.8°C (±3.2°F)

20°C ÷ 1000°C (68°F ÷ 1832°F) -> ±0.5%rdg or ±0.5°C (±0.9°F)

Spectrum response: 8 ÷14µm

D/S ratio: 20:1

IR sensor: thermopile

Allows emissivity: selectable in the range: 0.01 ÷ 1.00

Laser: pointer (<1mW, Class 2 compliance with IEC/EN60825-1)

Over range indication: "----" symbol at display

Reference guidelines:

EMC: IEC/EN61326-1

Laser source: IEC/EN60825-1, Class 2

Max operating altitude: 2000m (6592ft)

General specifications:

Size (L x W x H):	180 × 105 × 55mm (7 x 4 x 2in)
Weight (batteries included):	240g (8ounces)
Mechanical protection:	IP54
Drop test:	2m

CHAPTER 6:
Experimental tests of photovoltaic panels

For the purposes of this research, the following photovoltaic panels were tested, in location Egaleo, Athens, Greece:

- Four different panels of Suntech 190S24 190w model
- One panel of Sunearth 12572 165w model

6.1 Manufacturer's specification for tested models.

Each of the tested models has the following specifications, as declared by the manufacturer and analyzed below.

SUNTECH 190S24 190w

Pmax (W)	**190.00**
Voc (V)	**45.20**
Vmpp (V)	**36.6**
Impp (A)	**5.20**
Isc (A)	**5.62**
FF (%)	**75**
Alpha (%/C)	**0.050**
Beta (%/C)	**-0.34**

Suntech 190S24 190w is claimed to have high module conversion efficiency, reaching up to 14.9%. The manufacturer positive tolerance on levels 0/+5%, which ensures power output reliability. The model is also certified to withstand extreme wind (3800 Pascal) and snow loads (5400 Pascal). Another feature is the self clean ability, obtained by anti-reflective, hydrophobic layer, which improves light absorption and reduces surface dust. The manufacturer states the excellent performance of the model in weak light conditions, which can be observed during mornings, evenings and/or cloudy days. All Suntech panels are currently sorted and packaged by amperage, which maximizes the system output by reducing mismatch losses by up to 2%.

SUNEARTH 12572 165w

Pmax (W)	**165.00**
Voc (V)	**43.90**
Vmpp (V)	**35.70**
Impp (A)	**4.63**
Isc (A)	**5.10**
FF (%)	**72**
Alpha (%/C)	**0.06**
Beta (%/C)	**-0.34**

Sunearth 12572 165w uses highly anti-reflective solar glass. Sun-Earth solar panels are produced with a textured cell surface and tempered glass to reduce reflection of sunlight. This anti-reflective coating in blue color increases the absorption of light in all weather conditions. Long lifespan is another advantage of this model, as the manufacturer claims that the panel can last for at least 25 years. A 5-year warranty is given on material and workmanship, while output of panel is guaranteed at levels of 90% after 10 years and at 80% after 25 years of usage. The producer underlines the excellent construction of the panel, as it is able to resist corrosion caused by rain, water and gas. Thanks to anti-shocking performance, Sunearth panels are also resistant to hail and work under atrocious weather conditions, where temperature changes rapidly. Since these panels are popular in many areas, such as building roofs, photovoltaic power plants and telecommunication stations, the manufacturer takes benefit also from already existing high reputation of the product. Bibliography [No 17]

6.2 Experimental results

The experimental tests were performed in order to compare the real life efficiency of the photovoltaics with their nominal performance declared by their manufacturer's. The first measurement of Suntech panel took place in February. The results of this measurement are presented below as A) Suntech. Further three Suntech models were tested in August and their readings are described below respectively as B), C), D) Suntech. The last measurement shows Sunearth model readings, held also in August and marked as E) Sunearth.

In regards to the environmental conditions, the irradiance was very satisfying on both days, when the measurements took place. It could be defined as approximately $800W/m^2$. The temperature during the first set of testing was exactly 25°C, which is a perfect match with STC standard temperature. During the second set levels from ~40°C to 50°C were reached on the surface of the panels. The B), C) and D) readings on Suntech models were taken early morning, while the last measurement of the Sunearth panel took place at noon, with highest temperature all over the area.

A) **SUNTECH 190S24 190w**

Table of results

	Pmax [W]	Voc [V]	Vmpp [V]	Impp [A]	Isc [A]	Irrad. [W/m^2]	Module Temp. [°C]	FF [%]
Result	Not Ok (-8.60%)							
Measured	140,33	39,94	29,28	4,79	5,47	800,00	25,00	64,00
STC	173,65	40,48	30,08	5,77	6,84	1000,00	25,00	63,00
Nominal	190,00	45,20	36,60	5,20	5,62	1000,00	25,00	75,00

The weather conditions present on the day of the above reading were nearly ideal if compared to STC values. Based on the perfect temperature (25°C) and sufficient irradiance levels ($800W/m^2$), it could be assumed that the measured values should have obtained o positive test result and would have reached the nominal levels as declared by the manufacturer.

Although, the result of the testing was negative (-8.60%) and the maximum produced power calculated as STC was of approximately 16W lower than the value expected as per the datasheet.

The contrast between the STC calculated values and the performance levels expected by the manufacturer is presented in the below diagrams, based on maximum produced power (diagram no.1) and voltage/amperage (diagram no.2) respectively. Both diagrams prove that neither the voltage and the amperage nor is consequence the maximum produced power managed to reach the levels of the nominal stated efficiency.

Diagram no.1 - Comparative diagram of power (STC vs. Nominal)

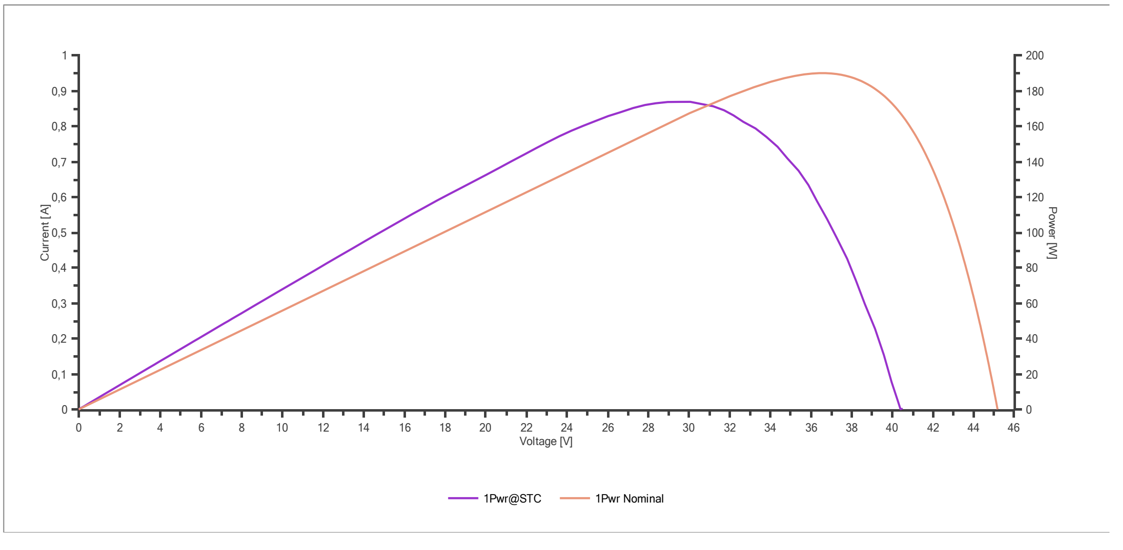
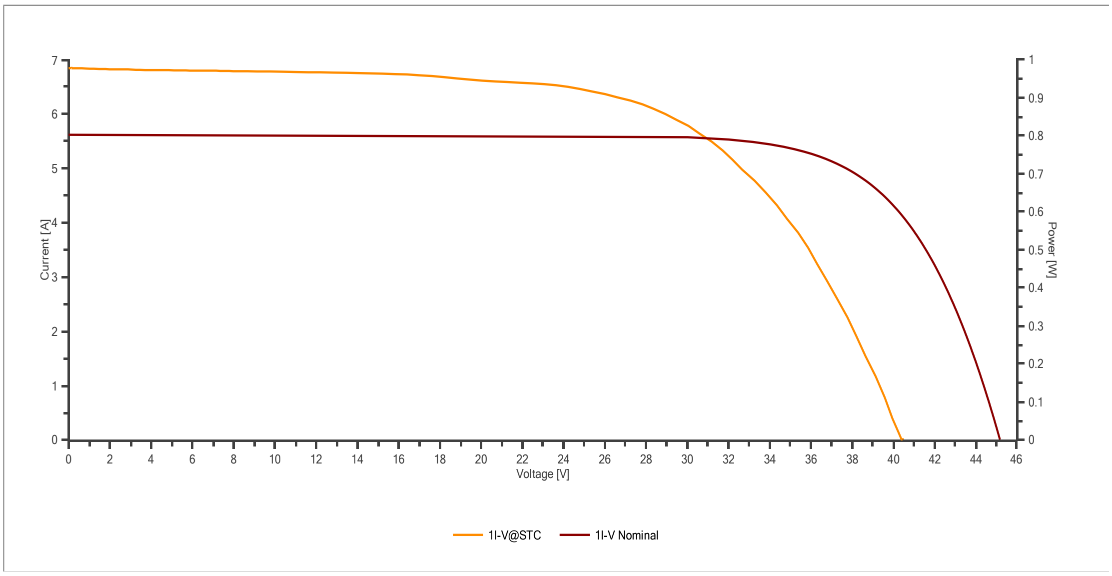


Diagram no.2 - Comparative diagram of voltage and amperage (STC vs. Nominal)



B) SUNTECH 190S24 190w

Table of results

	Pmax [W]	Voc [V]	Vmpp [V]	Impp [A]	Isc [A]	Irrad. [W/m2]	Module Temp. [°C]	FF [%]
	Not Ok (-34.78%)							
Measured	93,88	36,93	25,56	3,67	4,44	810,00	41,00	57,00
STC	123,91	39,43	27,56	4,50	5,44	1000,00	25,00	58,00
Nominal	190,00	45,20	36,60	5,20	5,62	1000,00	25,00	75,00

As analyzed in previous sections of this research on the example of Conergy PowerPlus 215P readings, the increased temperature has a dramatic impact on the efficiency of the photovoltaic. This relevance is distinctively visible also in the values obtained in the Suntech 190S24 190w reading held in August.

This test was as well marked as negative, with even higher difference of -34.78%. Even if calculated based on STC, this panel's performance is far below the expectation of the manufacturer, with maximum produced power falling under approximately 66W below the nominal value.

In these reading a contrast between the STC calculated values and the performance levels expected by the manufacturer is present even on a higher scale. Below diagrams show the value differences based on maximum produced power (diagram no.3) and voltage/amperage (diagram no.4) respectively.

Both diagrams prove that for this panel both the voltage and the amperage, and of course as a result also the maximum produced power, are on even less satisfying levels than in the previous test.

Diagram no.3 - Comparative diagram of power (STC vs. Nominal)

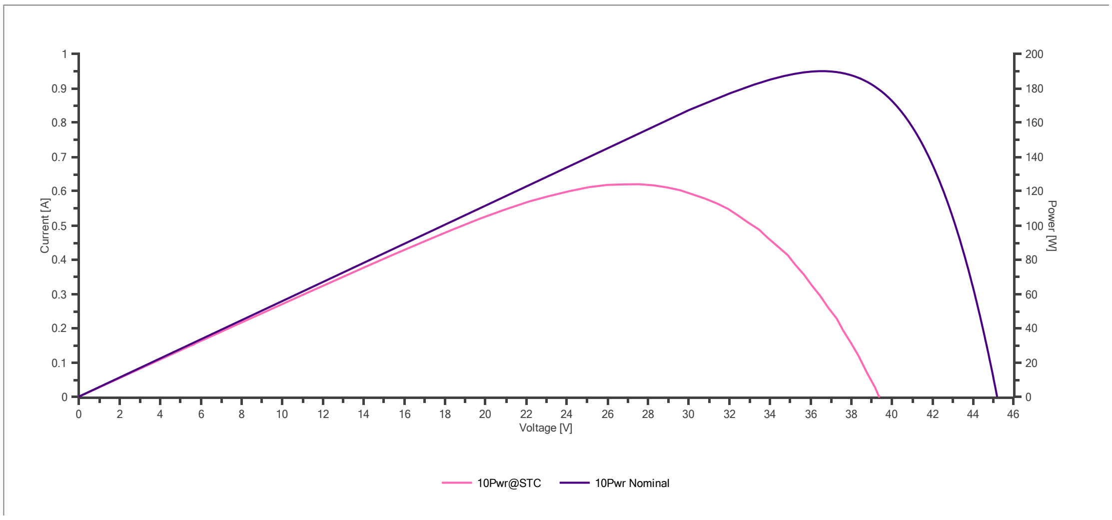
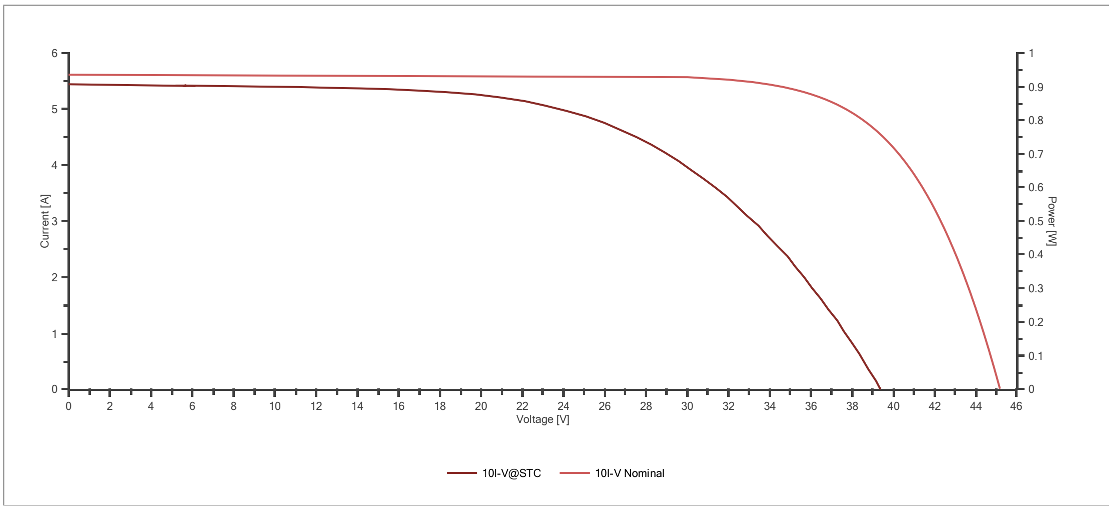


Diagram no.4 - Comparative diagram of voltage and amperage (STC vs. Nominal)



C) SUNTECH 190S24 190w

Table of results

	Pmax [W]	Voc [V]	Vmpp [V]	Impp [A]	Isc [A]	Irrad. [W/m2]	Module Temp. [°C]	FF [%]
	Not Ok (-18,32%)							
Measured	140,33	39,94	29,28	4,79	5,47	972,00	42,90	64,00
STC	155,19	42,41	31,78	4,88	5,57	1000,00	25,00	66,00
Nominal	190,00	45,20	36,60	5,20	5,62	1000,00	25,00	75,00

Next Suntech 190S24 190w testing held in August was also stated as negative, although with a lower difference of -18.32%. The external conditions were again not ideal due to increased temperature levels. The irradiance though was closer to STC values. The performance of the panel was relatively better than the previous test.

Nevertheless, even if calculated based on STC, also this panel's performance didn't reach the expectation of the manufacturer, as the maximum produced power was observed under approximately 35W below the nominal value.

In the below diagrams, the value differences based on maximum produced power (diagram no.5) and voltage/amperage (diagram no.6) are presented. Both diagrams also for this panel show that the levels of the voltage/amperage and the maximum produced power didn't meet the expectations of the nominal values.

Diagram no.5 - Comparative diagram of power (STC vs. Nominal)

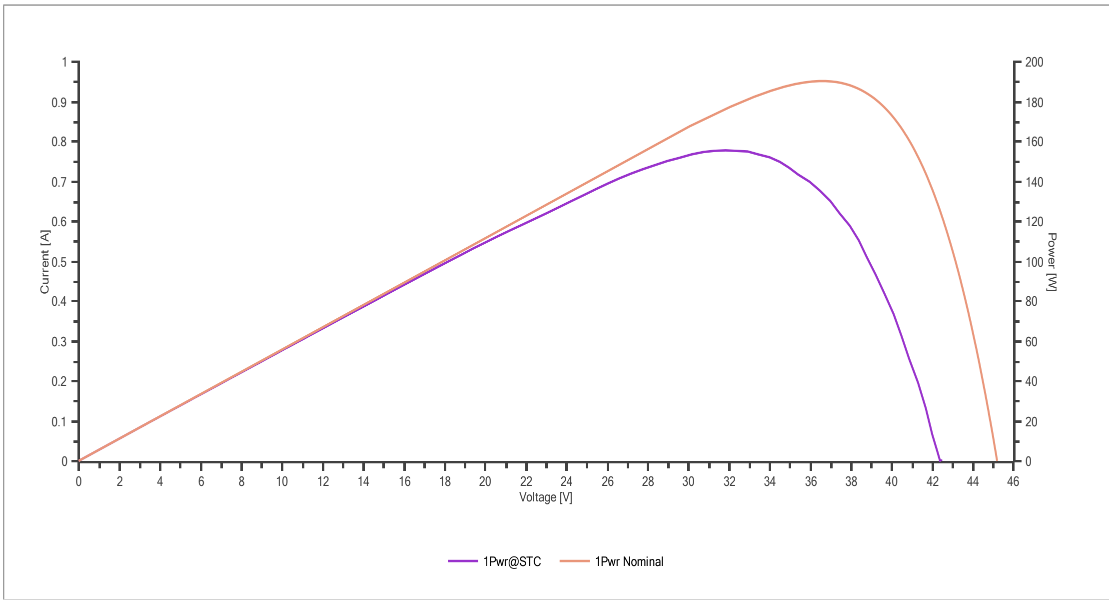
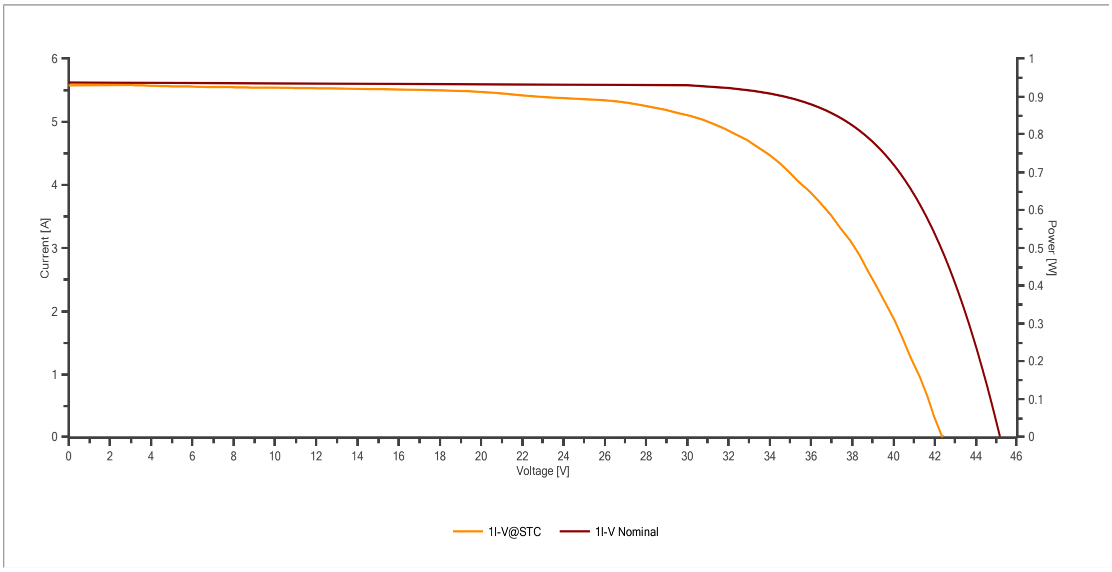


Diagram no.6 - Comparative diagram of voltage and amperage (STC vs. Nominal)



D) SUNTECH 190S24 190w

Table of results

	Pmax [W]	Voc [V]	Vmpp [V]	Impp [A]	Isc [A]	Irrad. [W/m2]	Module Temp. [°C]	FF [%]
	Not Ok (-17.21%)							
Measured	128,29	40,14	30,63	4,19	4,92	864,00	40,20	65,00
STC	157,30	42,57	32,69	4,81	5,63	1000,00	25,00	66,00
Nominal	190,00	45,20	36,60	5,20	5,62	1000,00	25,00	75,00

The fourth Suntech 190S24 190w measurement also undertaken in August had similar results with the previous panel testing. Similarly, the external conditions were characterized by increased temperature and slightly lower irradiance. Due to the fact that the temperature was on a little bit lower level, the overall performance of the panel reached better result than the previous reading.

Nevertheless, this was not enough to obtain a positive test outcome, the reading was again marked as negative, with a difference of -17.21%. When calculated based on STC, also for this panel the maximum produced power was on unsatisfactory level, approximately 33W below the nominal value. Thus again values declared by the producer were not able to be obtained.

Accordingly, the below diagrams demonstrate the results' imbalance based on maximum produced power (diagram no.7) and voltage/amperage (diagram no.8).

Both diagrams also show inadequate values of the voltage and amperage, as well as the maximum produced power. One more time the nominal values are not reached.

Diagram no.7 - Comparative diagram of power (STC vs. Nominal)

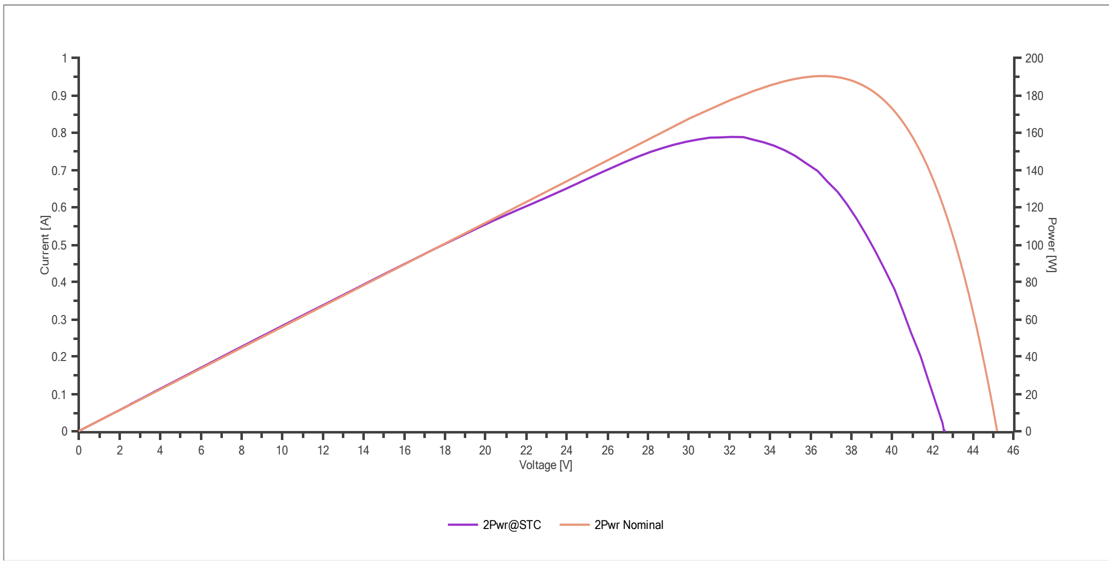
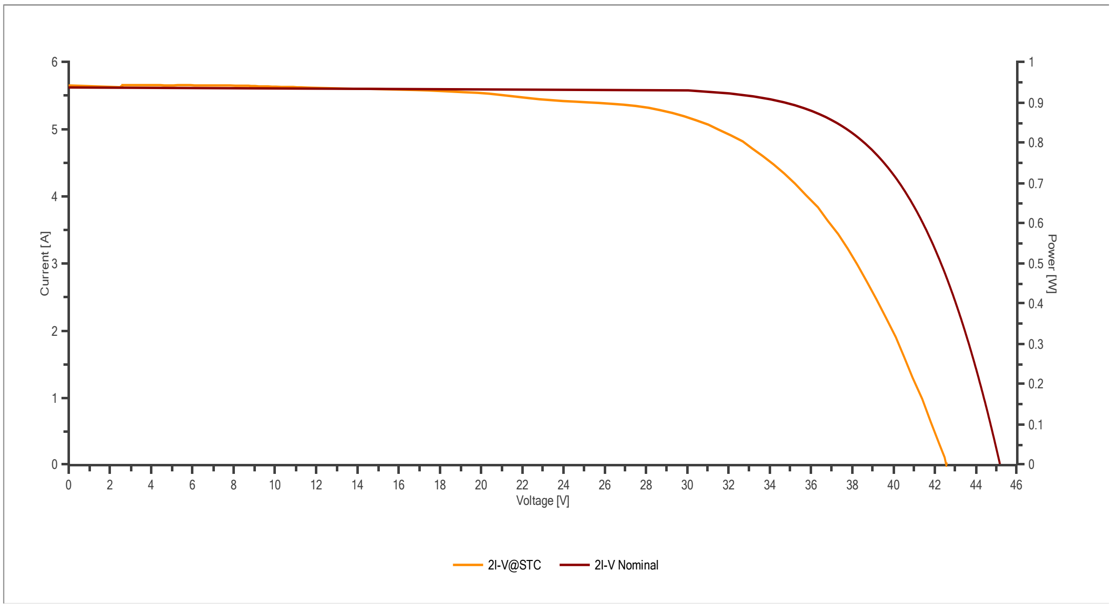


Diagram no.8 - Comparative diagram of voltage and amperage (STC vs. Nominal)



E) Sunearth 12572 165w

Table of results

	Pmax [W]	Voc [V]	Vmpp [V]	Impp [A]	Isc [A]	Irrad. [W/m2]	Module Temp. [°C]	FF [%]
	Not Ok (-93,72%)							
Measured	7,08	2,36	2,04	3,47	3,92	765,00	50,00	77,00
STC	10,36	2,60	2,31	4,48	5,01	1000,00	25,00	80,00
Nominal	165,00	43.90	35.70	4.63	5.10	1000,00	25,00	72,00

The model Sunearth 12572 165w was tested in August too and unfortunately provided the worst results. It is important to mention that during the measurement, the environmental conditions were far from beneficial. The observed temperature was double than the STC. Moreover the irradiance was on the lowest level from all performed measurements.

Nevertheless, even if those features are taken into consideration, the overall performance was extremely disappointing. The panel not only received a negative test result, but the efficiency calculated in STC was 93.72% lower than expected. This reading is far the most unsatisfactory, as the maximum produced power was observed approximately 155W below the declared nominal value. Here not only the expectations were not met as per testing instrument datasheet, but the performance managed to obtain less than 10% of the maximum power assured by the producer. Since the external conditions were not extremely various from previously analyzed tests, it may strongly be assumed that the unacceptable results were caused by internal failures.

The below diagrams illustrate the extreme contradiction between obtained values and expected performance level. The diagrams are based on maximum produced power (diagram no.7) and voltage/amperage (diagram no.8) approach. Both diagrams show clearly substandard values of all measured parameters.

Diagram no.7 - Comparative diagram of power (STC vs. Nominal)

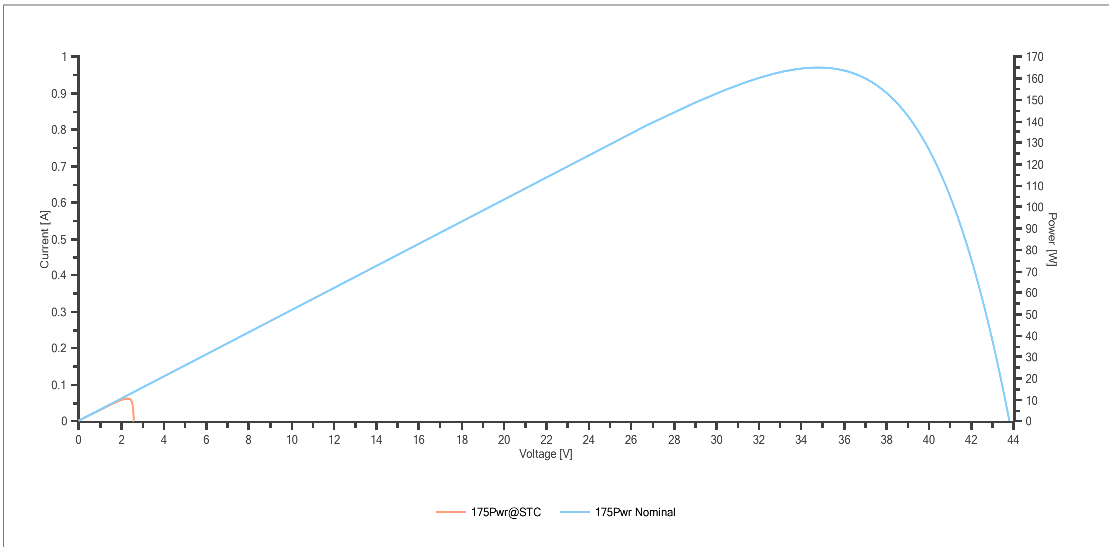
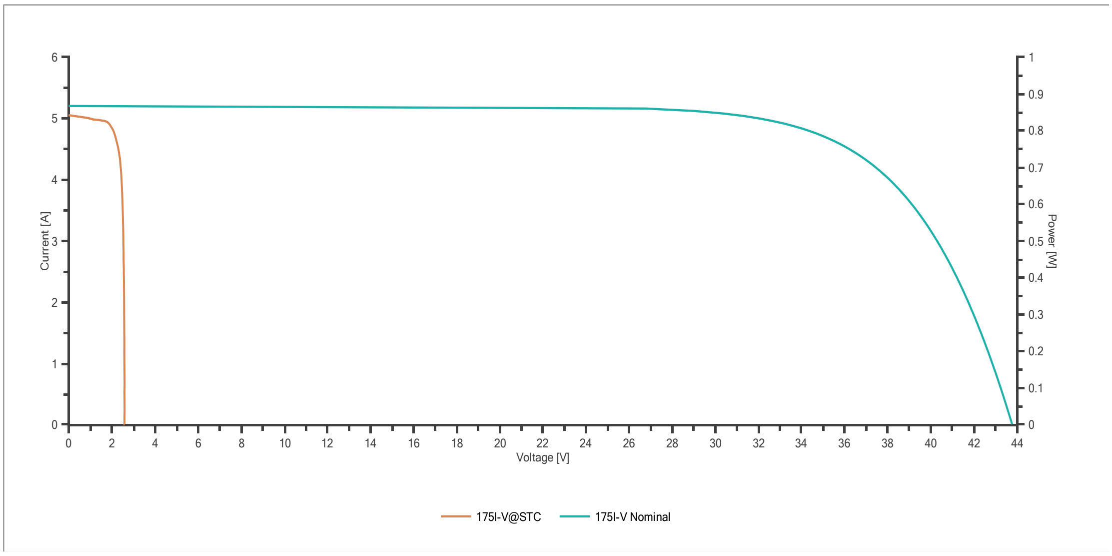


Diagram no.7 - Comparative diagram of voltage and amperage (STC vs. Nominal)



CHAPTER 7:
Conclusions – Further Research

In the theoretical sections of this research advantages of the photovoltaics along with desired and expected nominal values of manufacturers' datasheets were presented. Unfortunately, the measurements taken in real life as analyzed on the calculations for Conergy PowerPlus 215P, but also as clearly visible in the experimental readings undertaken for the purposes of this research prove that the expectations of the manufacturer's can be highly unrealistic. If we consider that the STC measurements are artificially stimulated, it is possible to claim that manufacturers may easily fall in the trap by taking the first imperative of a good quality for granted, while they focus exclusively on simulated in-production performance, production costs and competitive prices. Nevertheless, real conditions data show that the most significant decision is to keep the highest quality of elements and structure. Only in this way the rough impact of the internal and external factors which the photovoltaic will be facing throughout their lifespan can be balanced. The negative factors in any case will lead to degradation, although better quality products will stay less affected for longer.

It is crucial to understand that the datasheets give indicative and static information, whilst the real life conditions are dynamic and can't be fully predicted in theoretical expectations. Even if key risk factors affecting the desired efficiency are being taken into consideration by the manufacturers, it is still impossible to predict how intense and how frequent will negative circumstances be and how highly they will impact each photovoltaic.

In regards to the undertaken experimental measurements, as shown in the results' tables and diagrams presented in the previous section (no. 6.2), all tested photovoltaics have performed below the nominal performance stated in manufacturers' datasheets. Regardless the season of testing, the irradiance was very good (approximately 800). The temperature was the main difference between the two sets of measurements. During the first set exactly 25°C were measured, as STC standard temperature. During the second set from ~40°C to 50°C were observed on the surface of the photovoltaics. The second set started early morning and the last measurement (The Sunearth panel) took place at noon with high temperature all over the area. That high temperature difference on panels' surface proved that temperature is the key factor in the photovoltaic panel performance. As the temperature rises, a corresponding increase in the internal concentration of the semiconductor carriers occurs, which results in more re-connections of carriers. Thus, a strong leakage current is manifested through the diode, which causes a reduction of the V_{OC} and essentially a decrease in the efficiency of the photovoltaic panel. These conclusions of the performed readings prove the impact of the external factors on the efficiency of the photovolatics (section 3.2). Moreover, performed measurements, as well as calculations based on random conditions testing of Conergy PowerPlus 215P (section 4.1), demonstrate that it is the temperature that plays the key role in the photovoltaic efficiency. It is crucial to point out that slight decrease in irradiance level has lower impact on the panel's performance in comparison to the increase in temperature.

Furthermore, this is clearly seen in February's test (A Suntech 190S24 190w), which was performed on a windy day. Therefore, the weather condition cooled the surface of the photovoltaic panel and since the desired temperature was achieved, despite the slightly lower level of the irradiance, this photovoltaic reached the best performance values of all the readings. In comparison, the day of August's tests wasn't windy at all, what caused extremely high temperature on the panels' surface to be even more devastating for the readings.

The high impact of the increased temperature on the overall efficiency of the photovoltaics has been proven by numerous related study researches along the globe. The destructive effect of high temperature regardless the photovoltaics' type was observed for example by fellow researchers in several Universities such as in Massachusetts (USA), Zarqa (Jordan), Thessaloniki (Greece), Ho Chi Minh (Vietnam), Nilai (Malaysia). Therefore, the increased temperature levels are experimentally proved to be the key factor in efficiency loss of photovoltaics. Bibliography [42, 43, 44, 45]

The aging was another common issue, which clearly has affected the degradation of the panels. As analyzed in section 3.3 related to key factors of panels' degradation, the aging has significant influence on the photovoltaics efficiency. The tested panels were all about 10 years in service from its manufacturing date. The loss of the efficiency, according to manufacturers and as stated in STC conditions, should be 1%-2% per year. Needless to say, the weather conditions weren't meeting the STC standards during the entire period of panels operation. Therefore, bearing in mind the crucial impact of extreme weather factors, the effect of aging progressed in tested photovoltaics considerably more than the manufacturers' expectations. Furthermore, such an increased aging affects both the internal resistance Rs and the electronic circuit, which is integrated inside the junction box. This phenomenon has been analyzed in section 3.1 dedicated to internal factor affecting the efficiency levels.

On the top of the long years of usage, the photovoltaic panels were also stored and transported in imperfect conditions. In section 3.1, the risk of improper handling has been thoroughly described. We may assume that the tested panels may not have been handled professionally enough in order to avoid the risk of micro-cracks, which in consequence leaded to their performance drop. Another factor leading to these micro-cracks might have been an intense hail which is not uncommon in Greece. Such a weather condition can easily damage a photovoltaic panel. The micro-cracks are not visible to the naked eye as the frame may have been micro-cracked but the glass may not be broken. Taking the above into consideration we may assume that the micro-cracks occurred due to the climate particularities of the country and the improper transportation along with installation held with unprofessional means. Especially, the Sunearth panel seemed to have a higher level of damage that potentially might have been caused by exceptionally incorrect handling, such as for example an unexpected drop or extreme mechanical stress imposed on the panel during unprofessional transportation. Numerous related studies have investigated the crucial impact of micro-cracks on photovoltaics efficiency. Relevant researches were undertaken for example by RWTH Aachen University (Germany) or University of Huddersfield (United Kingdom). Worth taking into consideration is also the Portugese study of Santos, Torres, Fernandes and Lameirinhas, stating that micro-cracks have considerable input in progressive aging. Bibliography [47, 48, 49]

Furthermore, visual losses were noted. Not on a high scale as the photovoltaic panel was thoroughly cleaned, although still such condition cannot be considered “perfect” as per manufacturers’ testing, as also analyzed in section 3.1.

The Potential Induced Degradation (PID) of the photovoltaic panels, as presented in section 3.3 related to key factors of panels’ degradation, can be considered another common issue which caused the power leakage and finally the decrease in the performance of the tested panels. This phenomenon of current leakage might be enhanced by humid winters being an important feature of the local climate. All of examined panels, especially the Sunearth’s, suffer from the above mentioned issues. Similar correlation between increased temperature and humidity conditions along with progressed aging towards the loss in efficiency has been observed in several analogous studies, as for example the research of Gang Sun, Xiaohe Tu, Rui Wang investigating the potential-induced degradation (PID) of PV modules running in two different local climate areas in China. Bibliography [46]

Overall, the four Suntech panels proved to be more productive than the Sunearth photovoltaic. Except of the internal and external factors affecting the efficiency, it is crucial to underline that the monocrystaline technology used in Suntech offers much more durable structure, as described in section 1.1. The polycrystalline Sunearth cannot reach such level of endurance. The lower temperature coefficient is another feature making the polycrystaline panels less efficient in high temperature conditions, what is clearly seen on the obtained readings. Being more durable and efficient in rough weather conditions, the monocrystaline panels have longer lifespan than the other types.

To sum up, based on the performed measurements it is self-evident that the used photovoltaic panels don't meet the manufacturers' specifications. We may assume that the reason for such a low performance might be the strength of all the negative external and internal factors to which the photovoltaic panels were exposed during their long years of service. As explained previously, the rough weather conditions along with the aging, the PID and the micro-cracks caused by improper storage and transportation have distinctively affected power output of the panels. If the overall amount of unfavorable factors was lower or their intensity was more moderate, in the obtained measurements, levels much closer to manufacturers' nominal results might have been achieved. In particular, on the example of the examined Sunearth the observed performance was dramatically disappointing. This panel's measurements were on purpose included in this research, in order to show how an excessively increased level of micro-cracks along with various negative factors may affect the overall performance of a photovoltaic panel.

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FOREWORD

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This second edition cancels and replaces IEC 60904-2 (1989), its Amendment 1 (1998) and IEC 60904-6 (1994) and its Amendment 1 (1998). It constitutes a technical revision. The main technical changes with regard to the previous edition are as follows:

– Added subclause on “Calibration traceability”.

– Added subclause on “Construction” to differentiate the various types of reference devices.

– Added guidance on use of a built-in shunt resistor.

– Increased data sheet requirements. In particular, added requirement for either a mismatch correction or an estimate of uncertainty due to the mismatch of the reference device.

– Added Clause on “Calibration of working solar reference devices”.

60904-1 © IEC:2006 – 9 – PHOTOVOLTAIC DEVICES – Part 1: Measurement of photovoltaic current-voltage characteristics

1 Scope and object

This part of IEC 60904 describes procedures for the measurement of current-voltage characteristics of photovoltaic devices in natural or simulated sunlight. These procedures are applicable to a single photovoltaic solar cell, a sub-assembly of photovoltaic solar cells, or a photovoltaic module.

NOTE 1 This standard may be applicable to multi-junction test specimens, if each sub-junction generates the same amount of current as it would under the reference AM1,5 spectrum in IEC 60904-3.

NOTE 2 This standard may be applicable to photovoltaic devices designed for use under concentrated irradiation if they are irradiated using direct normal irradiance and a mismatch correction with respect to a direct normal reference spectrum is performed.

The purpose of this standard is to lay down basic requirements for the measurement of current-voltage characteristics of photovoltaic devices, to define procedures for different measuring techniques in use and to show practices for minimizing measurement uncertainty.

60904-2 © IEC:2007 – 5 – INTERNATIONAL ELECTROTECHNICAL COMMISSION PHOTOVOLTAIC DEVICES – Part 2: Requirements for reference solar devices

1 Scope and object

This part of IEC 60904 gives requirements for the classification, selection, packaging, marking, calibration and care of reference solar devices. This standard covers solar reference devices used to determine the electrical performance of solar cells, modules and arrays under natural and simulated sunlight. It does not cover solar reference devices for use under concentrated sunlight.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60891, Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic devices

IEC 60904-1, Photovoltaic devices – Part 1: Measurements of photovoltaic current-voltage characteristics

IEC 60904-5, Photovoltaic devices – Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method

IEC 60904-7, Photovoltaic devices – Part 7: Computation of spectral mismatch error introduced in the testing of a photovoltaic device

IEC 60904-8, Photovoltaic devices – Part 8: Measurement of spectral response of a photovoltaic (PV) device

IEC 60904-9, Photovoltaic devices – Part 9: Solar simulator performance requirements

IEC 60904-10, Photovoltaic devices – Part 10: Methods of linearity measurement

IEC 61215, Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval

IEC 61646, Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval

60904-3 © IEC:2008

PHOTOVOLTAIC DEVICES

– Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data

1 Scope and object

This part of IEC 60904 applies to the following photovoltaic devices for terrestrial applications:

– solar cells with or without a protective cover;

– sub-assemblies of solar cells;

– modules;

– systems.

NOTE The term “test specimen” is used to denote any of these devices.

The principles contained in this standard cover testing in both natural and simulated sunlight. This standard is not applicable to solar cells designed for operation in concentrated sunlight or to modules embodying concentrators. Photovoltaic conversion is spectrally selective due to the nature of the semiconductor materials used in photovoltaic solar cells and modules. To compare the relative performance of different photovoltaic devices and materials a reference standard solar spectral distribution is necessary. This standard includes such a reference solar spectral irradiance distribution. This standard also describes basic measurement principles for determining the electrical output of photovoltaic devices. The principles given in this standard are designed to relate the performance rating of photovoltaic devices to a common reference terrestrial solar spectral irradiance distribution. The reference terrestrial solar spectral irradiance distribution given in this standard is required in order to classify solar simulators according to the spectral performance requirements contained in IEC 60904-9.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60891:1987, Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic devices Amendment 1 (1992)

IEC 60904-1, Photovoltaic devices – Part 1: Measurements of photovoltaic current-voltage characteristics

IEC 60904-2, Photovoltaic devices – Part 2: Requirements for reference solar devices

IEC 60904-7, Photovoltaic devices – Part 7: Computation of spectral mismatch error introduced in the testing of a photovoltaic deviceThis is a preview - click here to buy the full publication

IEC 60904-9, Photovoltaic devices – Part 9: Solar simulator performance requirements

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