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Master Thesis

Electrical characterization of standalone Solar Farm enabled by Graphene-Perovskite based PV panels under various environmental conditions



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Περιεχόμενα

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Abstract

This Thesis entitled “Electrical characterization of standalone Solar Farm enabled by Graphene-Perovskite based PV panels under various environmental conditions” was written to study the behavior of GRAPEs (Graphene Perovskite solar panels), a new emerging technology in photovoltaics, for the first time at panel size in real outdoor conditions.

To determine this behavior, they were studied and measured for the period from January to August 2021 to find out how different parameters and factors affect their electrical properties, efficiency, and long-term lifetime stability.

In the following chapters, the construction of the panels, the results of the measurements during this period under different outdoor conditions and all the factors that influence and change their electrical properties are analyzed.

Experiments on the light soaking effect were also carried out to study the behavior of the panels, and electrochemical impedance spectroscopy (EIS) measurements were carried out to determine the **EEC** of this category of photovoltaic (PV) technology and how it is affected by temperature.

In addition, the temperature coefficients of the electrical characteristics of this technology were investigated in indoor experiments by taking measurements in a room with controlled environmental conditions.

Furthermore, benchmarking between GRAPEs and other solar cells has been carried out to compare the behavior of this technology with other technologies already commercialized and to estimate the expected energy yields of each type of photovoltaic technology.

Finally, all the meteorological data for the solar park area recorded by the weather station for the period in which the measurements were taken per month are presented.

1. Renewable Energy Sources (RES)

Renewable energy sources (RES) or soft energy, or new energy sources or green energy are forms of exploitable energy that come from various natural processes, such as wind, geothermal, water circulation and others.

The term "mild" refers to two of their most important characteristics. First, their exploitation does not require any active intervention, such as extraction, pumping, or combustion, as is the case with previously used energy sources, but simply the exploitation of the already existing flow of energy in nature. Secondly, they are 'clean' forms of energy that are very 'environmentally friendly' as they do not release hydrocarbons, carbon dioxide or toxic or radioactive waste like other energy sources that are used on a large scale. Therefore, they are considered by many as a starting point for solving the earth's ecological problems.

"Renewable energy" is generally considered to be alternatives to traditional energy sources (e.g., oil or coal), such as solar and wind power. The term "renewable" is somewhat misused because some of these sources, such as geothermal energy, are not renewable over millennia. In any case, RES have been studied as a solution to the problem of the expected depletion of (non-renewable) fossil fuel supplies. Recently, new strategies for the use of renewable energy sources have been adopted by the European Union, but also by many individual countries, promoting such internal policies for the Member States as well.

1.1 Advantages of photovoltaic systems

Solar energy in general and especially photovoltaic systems have many advantages in order to use for energy production. PV is environmentally friendly technology: no pollution is caused by electricity generation. Solar energy is an inexhaustible source of energy, it is available everywhere and it costs absolutely nothing. With the appropriate geographical distribution, close to the respective energy consumers, the PV systems can be installed without

the need to strengthen the distribution network. The operation of the system is completely silent. They have almost zero maintenance requirements and have a long service life: the manufacturers guarantee the "crystals" for 20-30 years of operation.

In parallel, there is always the possibility of future expansion to meet the growing needs of users. They can be installed on existing structures, such as e.g. the roof of a house or the facade of a building,

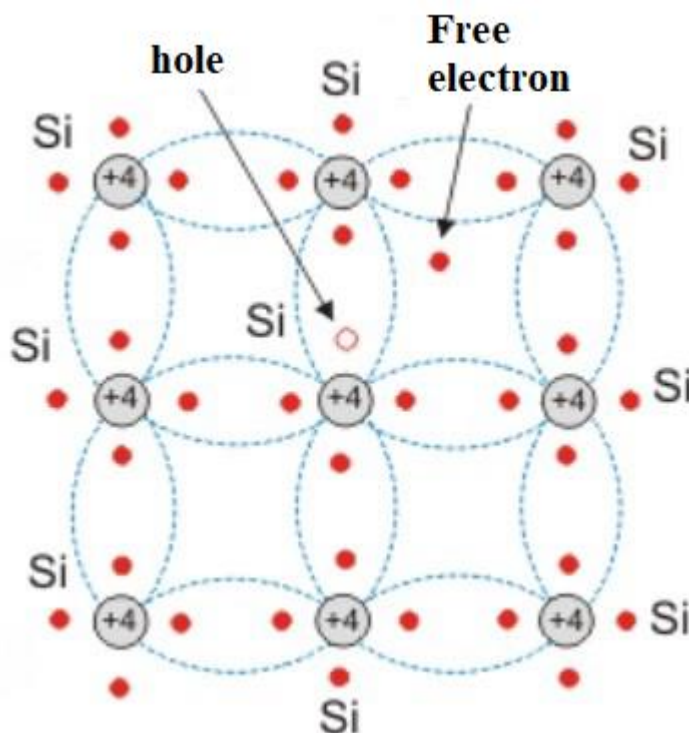
They have flexibility in applications: PV systems work perfectly both as stand-alone systems and as stand-alone hybrid systems when combined with other energy sources (conventional or renewable) and accumulators to store the energy produced. In addition, a major advantage of the PV system is that it can be interconnected to the power grid (interconnected system), thus eliminating the need for backup and also enabling the user to sell any excess energy to the grid operator.

1.2 The photovoltaic phenomenon and photovoltaic technology

The conversion of electromagnetic energy absorbed in a series of contact materials into electricity is called the photovoltaic effect, and the device is called a photovoltaic cell. Photovoltaic cells are made from semiconductor materials such as silicon (Si) and germanium (Ge), and also from compounds such as gallium arsenide (GaAs) and cadmium sulfide (CdS).

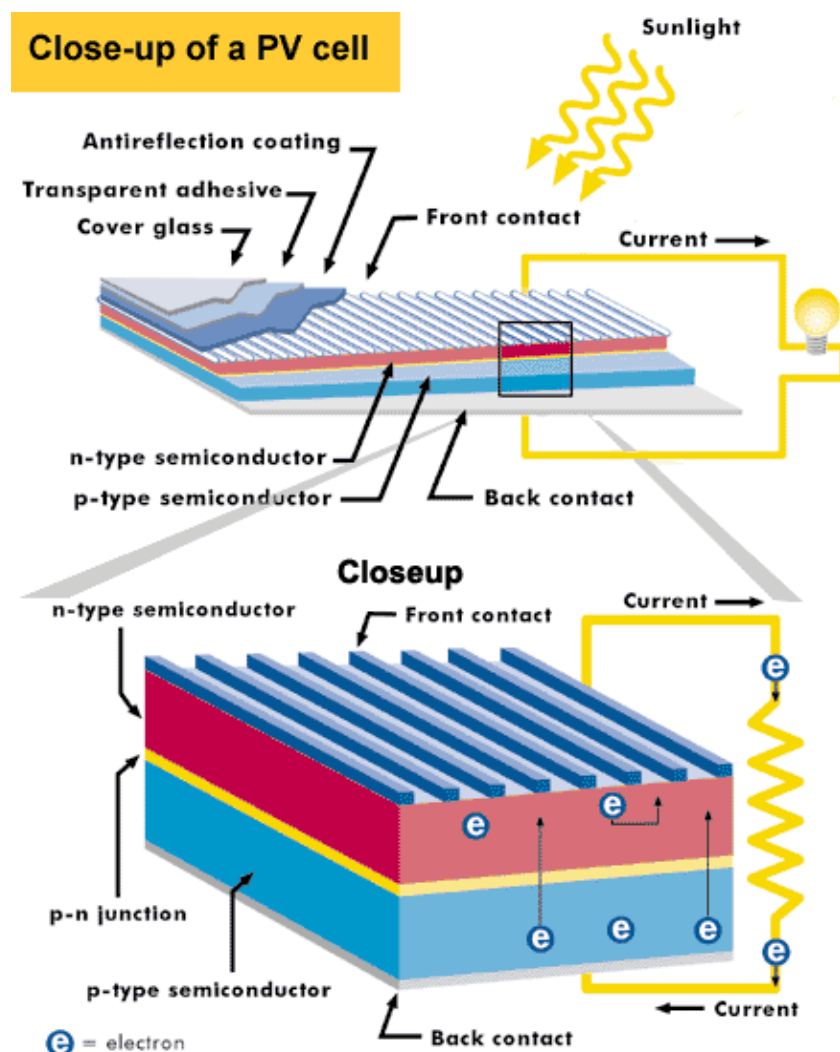
As in the manufacture of most electronic components, silicon is the main semiconductor material. In a silicon crystal, the four electrons in the outer layer of each atom form bonds with the electrons of neighboring atoms. If for some reason, such as thermal oscillations of the lattice or absorption of a photon, one of these electrons picks up an energy equal to the energy gap of the silicon ($E_g = 1.12\text{eV}$ for silicon at room temperature), it leaves the valence band and becomes excited in the conduction band (Figure 1), leaving a positively charged region called a hole. The probability of this happening depends on the size of the energy gap and the temperature T , and has a value proportional to the Boltzmann factor $e^{-E_g / 2kT}$. Each hole can be neutralized either when it receives an electron from the conduction band,

which loses its energy, or when it receives an adjacent electron from the valence band. In the second case, the hole actually moves because another hole is created next to the neutralized one. At room temperature, silicon has about 1.6×10^{10} electric current carriers, consisting essentially of electrons in the conduction band and holes per cm^3 . This means, in practical terms, that it behaves roughly like an insulator, as this number is on the order of about 10^{22} for metals by comparison. However, if impurities are present in the crystal of elements that have a different number of electrons in their outer layer than silicon, then the conductivity of the element increases. In particular, in a silicon crystal with arsenic impurities (pentavalent - five electrons in the outer layer), the extra electron in the arsenic atom acquires the role of the conductivity electron. Such a semiconductor is called a type n (from the word negative). Respectively in a crystal with a mixture of Boron (trivalent - three electrons in the outer layer), there is a position that can accept an electron, resulting in the formation of a hole. This semiconductor, in which the number of holes is greater than the number of conducting electrons, is called type p (from the word positive).



Εικόνα 1 When a photon breaks the Si - Si bond, an electron - hole pair is created

When an n-type semiconductor comes into contact with a p-type semiconductor, there is electron diffusion from the first to the second and of holes from the second to the former occurs. Around the interface formed at the point of contact between the two semiconductors, the holes and the electrons are reconnected, resulting in their neutralization. However, this creates an electric field (about 0.3-0.5 V) due to the presence of stationary ions, which prevents further diffusion. However, when the p-n contact is irradiated with photons whose energy is higher than the energy gap E_g , vectors are created which separate due to the electrostatic field. The result is a potential difference between the contact terminals. When the terminals are conductively connected, electricity is generated, which can also be seen in Figure 2.



Εικόνα 2 Basic structure of a solar cell.^[1]

1.3 Photovoltaic cell technologies

There are different categories of photovoltaic cells which are categorized depending on the materials used and the corresponding technologies with which they are manufactured. The result of this multitude of different elements is the existence of a great variety in their performance and electrical characteristics.

The main categories of photovoltaic cells (solar cells) are the following:

I. Monocrystalline silicon.

Monocrystalline silicon cells are made from a large crystalline silicon wafer by a process known as the "Czochralski" process. Their yield is in the range of 15-18% and could be considered relatively high. But they have a high cost. PV elements are manufactured in a circular or square shape. Circular solar cells are cheaper than the rest and the reason is that there is less during their production.

However, they are not often used in the construction of photovoltaic panels. The reason for this is that when they are lined up to create a wide surface there are large gaps between them and therefore the construction is not efficient. However, this is a good condition for integration into buildings when partial light transmission is required. Their color is usually deep blue to black if they have an anti-reflective coating, or gray if there is no such coating.

II. Polycrystalline Silicon.

Polycrystalline silicon elements are less expensive than those of monocrystalline silicon, but less efficient. As the name implies, they are made from slices (wafers) cut from square polycrystalline silicon rods. The method of making a polycrystalline element does not require great precision and the cost is much lower than single crystal elements. Their yield ranges from 13% to 16% and they are usually produced in square form. Their color is usually blue (with anti-reflective coating) or gray-silver (without anti-reflective coating).

III Thin-Film Solar Cell Technology.

In recent years, a great deal of research has been carried out to perfect the methods of manufacturing PV solar cells with semiconductors whose thickness does not exceed a few micrometers. The aim is to achieve relatively good performance using as little material as possible. The efficiency of these cells is lower compared to the elements made of crystalline silicon (in the order of 5-7%), but also much cheaper, which makes them quite competitive and very promising. The main reason for the lower cost is that they offer the possibility of building units in complete form, without the need for interconnections of independent cells together, which is quite expensive. Figure 3 shows the way an integrated interface to the thin film technology unit is made. They are usually characterized by their almost black color.

The following are the main representatives of this category:

1. amorphous silicon (amorphous-Si) elements.

They are the most common form and are widely used in consumer electronics (for example, in pocket computers). Amorphous silicon (the non-crystalline form of silicon) can be deposited onto a conductive substrate in the form of a thin film, creating a thin-film technology cell. Through the deposition process, the amorphous silicon can be less than 1% of the thickness of a crystalline cell. In addition, amorphous silicon cells offer the possibility of producing flexible photovoltaic modules.

2. Cadmium- telluride (CdTe).

Cadmium telluride (CdTe) is a stable crystalline compound composed of cadmium and tellurium.

The crystalline cadmium telluride compound (CdTe) has ideal properties for solar absorption. These properties make it an excellent material for the manufacture of photovoltaic cells. A very basic disadvantage is the use of the rare metal tellurium. Also, due to the use of cadmium, they have to be recycled at the end of their life and their construction is a difficult task. It is

usually interconnected with cadmium sulfide to form a PV solar cell with p-n junction

Direct band gap, $E_g=1.45\text{eV}$

- High production speed of the modules
- Very low cost
- 20.4 % efficiency

It is mainly used as semiconductor material in CdTe photovoltaics as well as in infrared optical window applications. [3].

3 Copper Indium Gallium Selenide (CIGS)

CIGS solar cells are manufactured by depositing a thin layer of copper, indium, gallium, and selenium on a glass or plastic substrate, along with electrodes on the front and back to collect current. Because the material has a high absorption coefficient and absorbs sunlight strongly, a much thinner layer is required than for other semiconductor materials.

These are cells made of a material that has direct optical absorption with an extremely high absorption coefficient. Its electrical properties depend mainly on the copper/indium ratio, but also on precise control stoichiometry during the production process. These data have shown efficiencies of 20%, which is the highest value for cells of this technology. [2]

Bandgap changes with x from 1 to 1.7.

High efficiency: 23.3%.

Expensive vacuum processing, but low material costs

High absorption coefficient, therefore thin films can be fabricated

IV. Other types of PVs.

In addition to the above, one can find the following types of cells that are used either on a small scale or at laboratory level:

2) Gallium arsenide (GaAs). They are high performance items (up to 36%) and degrade more slowly than silicon. Therefore, they are used for expensive applications such as spacecraft and satellites, but they are very expensive, which is their biggest disadvantage.

Unlike silicon, they have a direct band gap and improved charge transport properties, so they are more absorbent and thin films of this type of PVs can be made with high efficiencies.

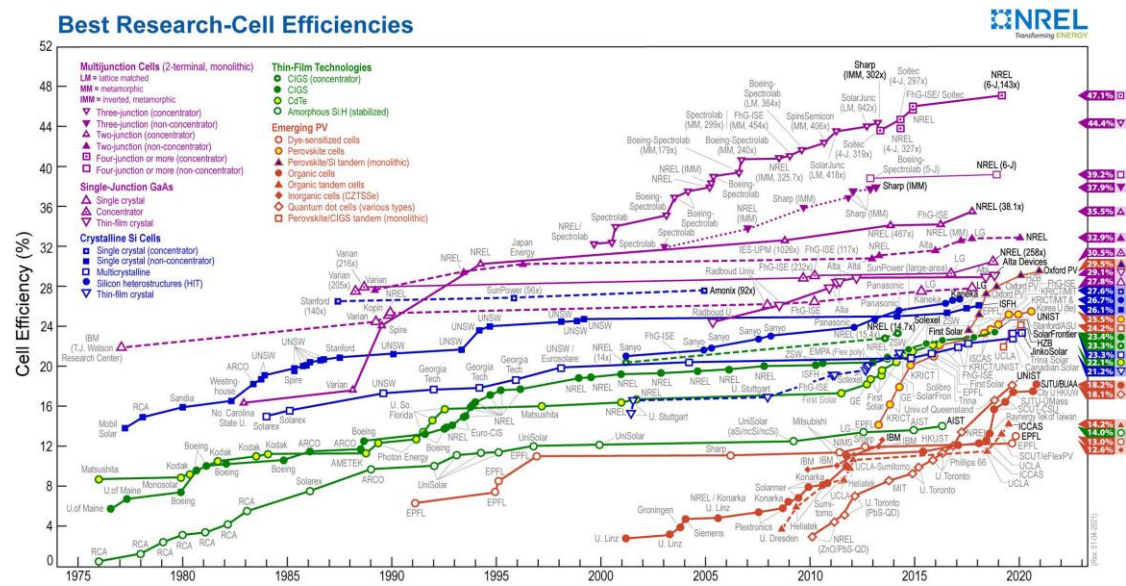
3) Elements that combine organic materials with polymers.

They are a relatively new technology. Organic PV cells use organic materials that act as electron receivers and donors instead of semiconductor p-n junctions. The major advantage of using organic materials is that they enable the construction of flexible low-temperature solar cells on plastic substrates on a large scale. The yield of organic cells today is in the range of 8-10%, but the increasing demand in the coming years is going to significantly reduce the production costs of organic PV cells.

3. Multi-junction (MJ) solar cells are solar cells with multiple p-n junctions made of different semiconductor materials. The p-n junctions of each material generate electric current in response to different wavelengths of light. The use of multiple semiconductor materials enables the absorption of a wider range of wavelengths, improving the cell's efficiency in converting sunlight into electrical energy.

Conventional cells with a single junction have a maximum theoretical efficiency of 33.16%. [2] Theoretically, an infinite number of junctions would achieve a limiting efficiency of 86.8% in highly concentrated sunlight. [3]

Cells composed of multiple layers of material can have multiple band gaps and therefore respond to multiple wavelengths of light, capturing and converting some of the energy that would otherwise be lost due to the relaxation described above. [4]

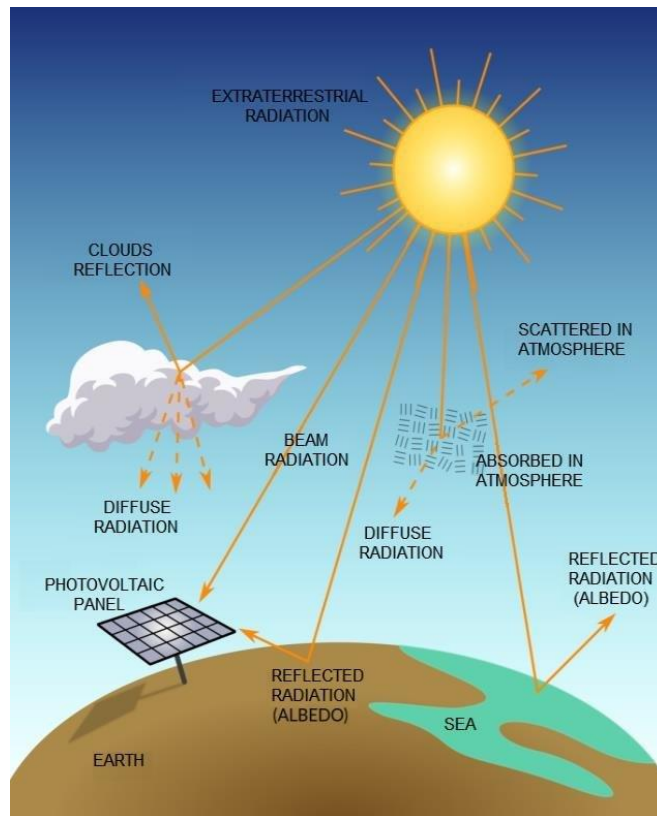


Εικόνα 3 The increase of efficiencies by type of photovoltaic technology over the years:[5]

1.4 The solar irradiance

After the analysis of the photovoltaic phenomenon and the characteristics that govern the operation of the photovoltaic elements, it is time to study the power of the irradiance that falls on their surface from the sun. Such a study is necessary for the optimization of the photovoltaic panel, since for the best possible efficiency it is required that as much solar irradiance as possible falls directly on the photovoltaic elements that make up the photovoltaic panel but also for the longest possible time in during the day and consequently over a year. The problem of the correct orientation of the photovoltaic unit has to do with its position in relation to the horizon, the latitude of the location, the position of the sun, the meteorological conditions, the altitude, the moisture content of the atmosphere, etc.

The analysis of solar irradiance that strikes a surface is quite complex. There are two types of problems in this work. One is the collection of meteorological data and the other is the selection, based on this data, of the most correct method of calculating irradiance. Figure 4. shows the different types of solar irradiance that hit the earth's surface.



Εικόνα 4 Types of solar irradiance^[6]

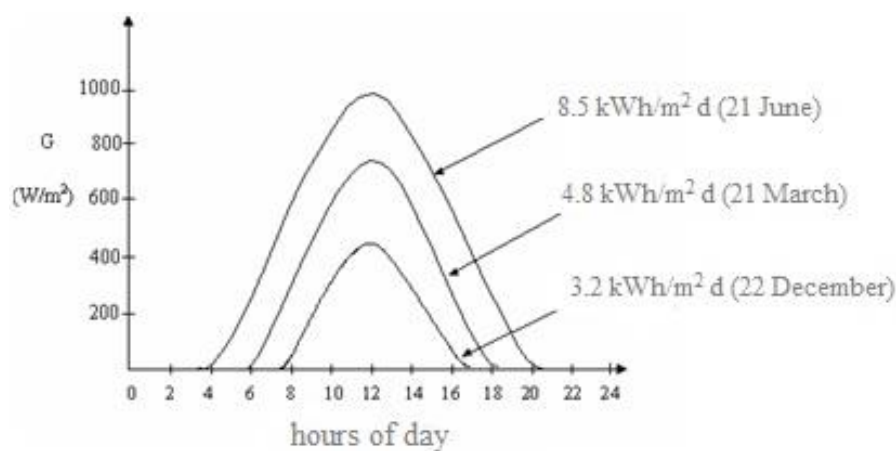
The irradiance that falls on the surface of a receiver located outside the Earth's atmosphere (extraterrestrial irradiance) consists exclusively of irradiance that travels in a straight line from the sun to this surface. This is because space is empty, that is, there are no materials on which irradiance is likely to be scattered or reflected. When the sun's irradiance enters the earth's atmosphere it is modified by various elements found in it. Some of them, such as clouds, reflect irradiance while others, such as ozone, carbon, oxygen, and evaporated water, absorb it. Also dust and water droplets scatter irradiance. Finally, some amount of irradiance as it reaches the ground is absorbed while another amount is reflected in the atmosphere. The result of all the above is the splitting of solar irradiance into different species:

1. Direct irradiance due to those rays of light that travel in a straight line from the sun to the earth's surface.
2. The diffuse irradiance that comes from the sky, but not from the solar disk, such as the rays that are scattered in the atmosphere.
3. The irradiance reflected on the ground (albedo irradiance).

The sum of these three types of irradiance gives the total irradiance that strikes a surface (global irradiance).

The properties of diffuse irradiance depend to a large extent on the shape, location and composition of the clouds. The angular distribution of diffuse irradiance is generally a complex function that varies with time. Diffuse irradiance is essentially anisotropic. However, in some special cases (for example, in a completely cloudy sky) it is almost isotropic. The nature of the soil plays a huge role in the percentage of irradiance reflected from the soil, which shows a great variety (eg snow, vegetation, water, etc.). In some cases the soil is intentionally painted white. This results in the increase of the percentage of irradiance reflected from the ground and thus contributes significantly to the increase in total irradiance.^[8]

One of the main problems in using solar irradiance to generate electricity is that it fluctuates sharply. This means abrupt but also unpredictable changes over time compared to other energy conversion systems. Figure 5 shows a diagram in which the fluctuation of the intensity of solar radiation can be observed on a horizontal surface under clear sky for different indicative dates (solstices and equinoxes).



Εικόνα 5 Fluctuation of the intensity of solar radiation during one day with the collector being in the horizontal plane. [8]

When the surface receiving the irradiance is tilted there is an increase in the intensity of the irradiance which is defined as the power per unit area and has units W / m^2 .

Another way that can be used to improve the intensity of the solar irradiance received by the photovoltaic unit is to place it on a movable frame device that

rotates at specific intervals, following the course of the sun in the sky. This ensures the vertical incidence of solar irradiance on the surface of the photovoltaic cells, which results in an increase in electricity generation. These provisions are called photovoltaic solar trackers. With the use of the photovoltaic sundial, the increase of the generated electric power is achieved, but significant power consumption is required for the movement of the solar monitoring. From the calculation of the difference of these power values it can be concluded if the use of photovoltaic solar panels is energy efficient. Of course there are other important criteria for choosing a solar system such as its cost, the frequency of need for maintenance and the ability to quickly amortize the extra costs that it introduces to the photovoltaic system.^[8]

1.5 I-V Curves

Photovoltaic cells have a complex relationship between their operating environment and the maximum power they produce. The **fill factor**, abbreviated **FF**, is a parameter that characterizes the non-linear electrical behavior of the solar cell. The filling factor is defined as the ratio of the maximum power from the solar cell to the product of the open circuit voltage **Voc** and the short circuit current **Isc**. In table data it is often used to estimate the maximum power that a cell with an optimal load can deliver under given conditions,

$$P = FF * Voc * Isc. (1)$$

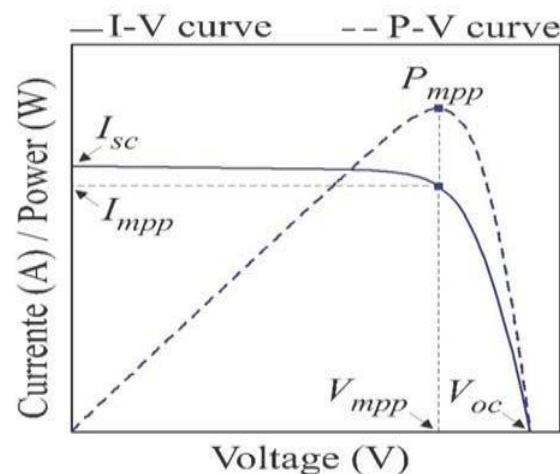
For most purposes, FF, Voc, and Isc are sufficient information to provide a useful approximation model of the electrical behavior of a photovoltaic cell under typical conditions.

For each given set of operating conditions, the cells have a single operating point where the values of current (I) and voltage (V) of the cell result in maximum output power. These values correspond to a specific load resistance, which is equal to V / I as determined by Ohm's law. The power P is given as $P = V * I$.(2)

A photovoltaic cell, for most of its useful curve, acts as a constant current source. However, in the MPP region of photovoltaic cells, its curve has an almost inverse exponential relationship between current and voltage. From

basic circuit theory, the power delivered by or to a device is optimized where the derivative (graph, slope) dI/dV of curve IV is equal to and opposite to the I/V ratio (where $dP/dV = 0$). This is known as the maximum power point (MPP) and corresponds to the "knee" of the curve.

A load with resistance $R = V/I$ equal to the inverse of this value draws maximum power from the device. This is sometimes called the "characteristic resistance" of the element. This is a dynamic quantity that changes depending on the level of irradiance, as well as other factors such as the temperature and age of the cell. If the resistance is lower or higher than this value, the power to be drawn will be less than the maximum available and so the cell will not be used as efficiently as it could. MPPTs use different types of control or logic circuitry to look for this point and thus allow the inverter circuit to extract the maximum available power from a cell.



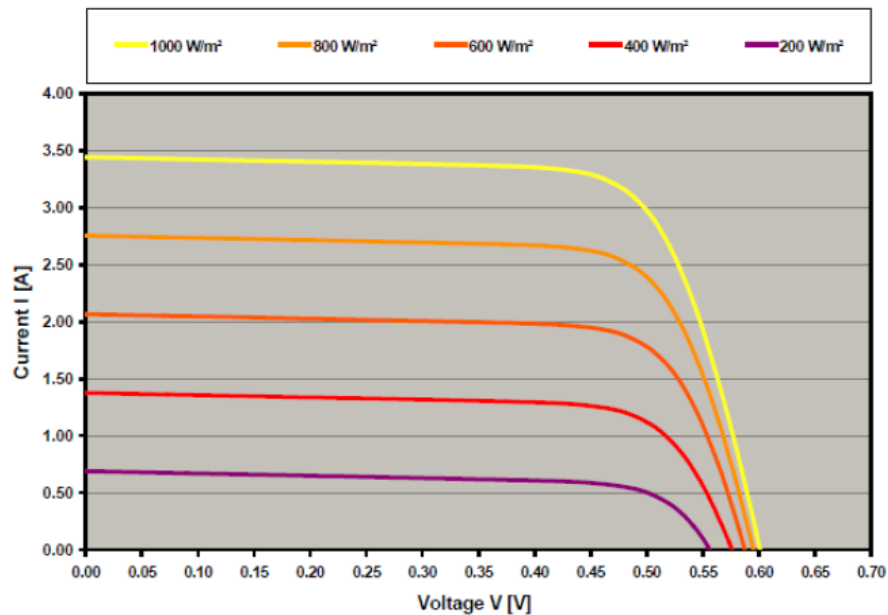
Εικόνα 6 The IV, PV curves of photovoltaic solar cells^[7]

1.6 Factors affecting the performance of photovoltaic systems

There are many factors that can affect the performance of a photovoltaic system. The three main ones are the intensity of the solar irradiance, the temperature and the shading (or otherwise the effect of the clouds).

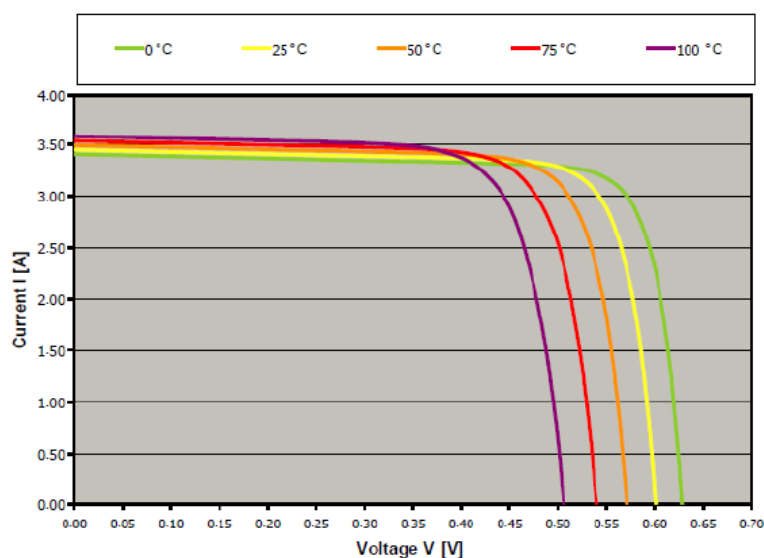
With increasing intensity of solar irradiance is observed intense, almost linear, increase in the cell short-circuit current, while the open-circuit voltage increases slightly but not linearly. The result of all this is the almost

proportional relationship that there is between the power of the cell and the intensity of the sunlight, when of course the cell temperature is kept constant as shown in Figure (8)



Εικόνα 7 Effect of solar irradiance on the characteristic I - V of a solar cell [8]

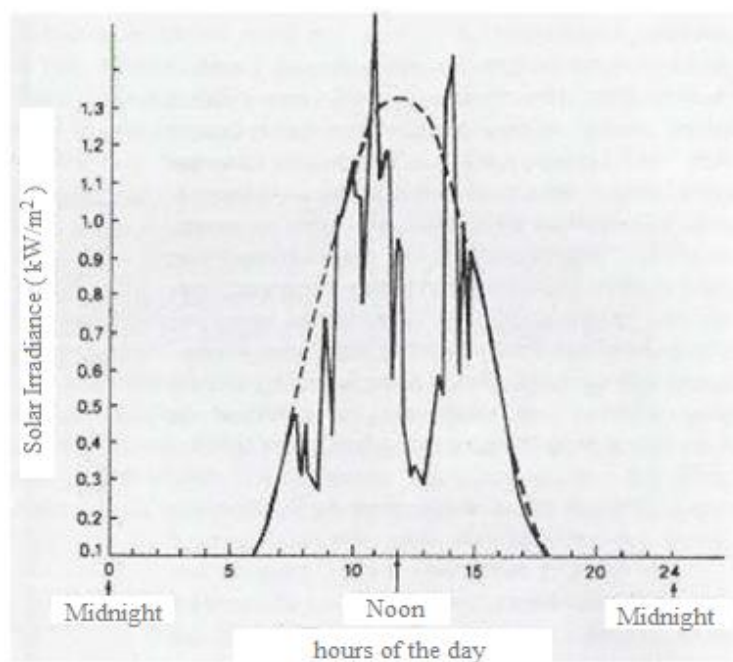
Temperature mainly affects the voltage of the solar cell. More specifically, with temperature drop there is a significant reduction in open circuit voltage (negative temperature-temperature coefficient, $\beta\% / ^\circ\text{C}$), while the short-circuit current (positive current temperature coefficient $\alpha\% / ^\circ\text{C}$). Overall, the power of the solar cell decreases as the temperature increases, as shown in Figure 8, a fact that must be taken into account when designing a system. [8]



Εικόνα 8 Effect of temperature on the characteristic I - V of a solar cell. [8]

Shading is usually created either by the presence of natural obstacles (eg trees, poles, etc.), or by temporary phenomena (eg clouds) or due to the limited extent of the installation. The consequences of shading can be very important and for this reason it is necessary to determine in detail the losses that they can cause. The choice of the place where the photovoltaic array will be based should be done in a way that will ensure the absence of shadows as much as possible throughout the year and especially during the hours of high solar irradiance.

The presence of clouds, as is logical, has a catalytic effect on the intensity of solar irradiance which enters and falls on the earth's surface. More specifically, the presence of relatively sparse clouds in the atmosphere attenuates the direct irradiance that enters the atmosphere but partially increases the diffuse. In cases of dense clouds it is possible to cut off most of the irradiance. Figure 9 shows the effect of clouds on the intensity of irradiance.



Εικόνα 9 Fluctuation of the intensity of sunlight during a day with partly cloudiness (continuous curve) - Fluctuation of the intensity of solar irradiance during a day with clear sky (discontinuous curve). ^[8]

Other factors that can significantly affect the performance of photovoltaic systems are speed combined with wind direction, air pollution, aging and losses of the photovoltaic system.

Wind speed and direction are directly related to the operating temperature of photovoltaics. Higher speeds imply, logically, lower temperatures. Also the

north winds imply lower temperatures, while the opposite happens with the south.

Pollution reduces the efficiency of photovoltaics due to the deposition of various pollutants on the surfaces of the panels. For this reason, regular cleaning of photovoltaic panels is necessary.

It is expected that the photovoltaic components of a photovoltaic system will deteriorate over time due to aging, which can lead to a decrease in electricity generation of up to about 1% per year.

When we refer to the losses of the photovoltaic system, we mean essentially the electrical losses in the conductors of the various connections, but also the connections with various other parts of the system. These losses can account for up to 30% of the electricity generated. ^[8]

2. Graphene Perovskite solar cells technology (GRAPEs)

The term graphene first appeared in 1987 to describe single sheets of graphite.

Successive attempts were made to make very thin graphite strips by mechanical peeling (from 1990 to after 2004) but none of them produced was thinner than 50 to 100 layers.

In 2004 at the University of Manchester, Andre Geim and Kostya Novoselov were able to isolate a single-dimensional two-dimensional crystallite called graphene. This discovery was honored with the Nobel Prize in Physics in 2010. In this two-dimensional crystal, strong intra-atomic bonds do not allow relatively large displacements of atoms in the lattice, even at high temperatures. ^[9]

The incorporation of graphene into perovskite-based solar cells was naturally proposed, and significant work is taking place on this matter. Graphene-based perovskite solar cells are studied in many ways, including hole and electron transport media (HTM and ETM), electrodes, and various approaches aiming

at improving the stability of the device. Tandem architectures based on graphene interlayers are also of great interest.^[22]

2.1 Graphene and derivatives

Graphene is an allotrope of carbon consisting of a single layer of atoms arranged in a two-dimensional honeycomb lattice nanostructure. The name is derived from "graphite" and the suffix -ene, reflecting the fact that the graphite allotrope of carbon contains numerous double bonds.^[10]

Graphene is technically a non-metal but is often referred to as a quasi-metal due to its properties being like that of a semi-conducting metal. As such, it has many unique properties that you don't find with other non-metallic materials.

Graphene has many unique properties, making it an ideal material for use in electronic applications when compared to conventional materials.

Electrical conductivity the most prevalent and important property of graphene. Graphene doesn't have an electronic band-gap (meaning that it can't be switched on or off) as the valence and conduction bands have a small overlap and the electrons act as massless relativistic particles.^[9]

There are several methods that have been used for graphene production, some of which have been abandoned and others are many promising. The following are the most common methods of producing graphene.^[10]

- Mechanical Exfoliation from natural Graphite(Scotch tape technique)
- Liquid Phase Exfoliation (LPE)
- Chemical Vapor Deposition(CVD)

As it is mentioned earlier graphene is a quasi-metal but there are some techniques that, while oxygen atoms are added in the graphene layer, can transform it into an insulator Graphene Oxide(GO)) or a semiconductor material (Reduced Graphene Oxide(rGO)).^[13]

This new material, thanks to its groups, becomes hydrophilic and thus can be dissolved in organic solvents very easily. This property seems to be particularly useful in the field of organic photovoltaics as well since GO in

addition to its use as an electrode, can be used to replace the PEDOT: PSS layer. Finally, GO can be used in the active layer of organic photovoltaics as a powerful electron receiver, instead of PC60BM.

The main methods of oxidation of graphite are:

1. The De Brodie method
2. The Staudenmaier method
3. The Hummers method

As we have seen, graphene oxide is an insulator, so it is not conductive at all. So the scientists tried to make a new molecule based on graphene, so that it retains all the mechanical properties of graphene, while also being extremely conductive, but also soluble in organic solvents, due to the reduction of oxygen groups never do not leave rGO completely. Modifying the GO was the ideal solution. ^[13]

The reduction methods that are mainly used:

1. Chemical: GO is reduced by the use of chemical reducing agents, such as hydrazine, hydrogen gas, vitamin C, etc. It is the most common method of reduction.
2. Thermal: Oxygen groups "burn" when we ignite GO at a very high temperature ~ 900 °C.
3. Photochemistry: With the use of laser the bonds of the oxygen groups are broken and so the GO is reduced to rGO.

2.2. Perovskite technology

Perovskites are a family of materials with a particular crystal structure that was discovered by a German scientist Gustav Rose in 1839^[12].

Perovskites are named after the mineral CaTiO_3 and generally refer to the crystal structure $\text{A}^+\text{M}_2^+\text{X}_3^-$

A is a nonbonding cation (+1)

M is a bonding metal ion (+2)

X is a halide(-1) ion

Any type of material that has the same as Calcium Titanium Oxide (CaTiO_3) is considered a perovskite.

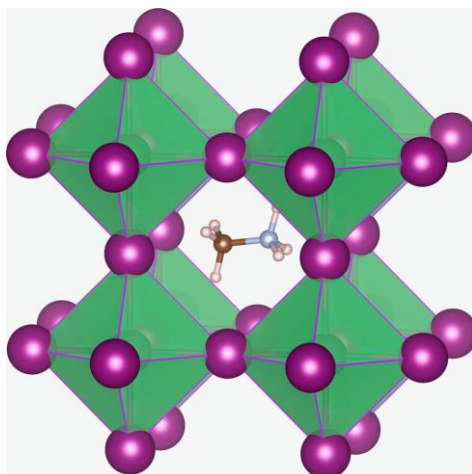
An empirical rule that determines whether an element fits in the perovskite structure is the Goldschmidt Tolerance Factor that expressed as :

$$t = \frac{R_A + R_X}{\sqrt{2}(R_M + R_X)} \quad (3)$$

where R_A, R_M, R_X are the ionic radii of A, B and X elements.

For halide perovskites, these parameters are typically in the following ranges:

$$0.81 < t < 1.11$$



Εικόνα 10 Perovskite crystal structure^[12]

It is one of the most common crystal structures found on the planet .it was originally discovered as a mineral and his shape shows up everywhere and it a common subject for cutting edge scientific research. Metal halide perovskites are a type of crystal that can act as a semiconductor so scientist are looking on how it on be incorporated in various technologies.

The tunability of the perovskite structure also makes these crystals attractive for catalysis and electrocatalysis. In solid oxide fuel cells, perovskites serve as oxygen ion conductors separating anodes and cathodes. For applications such as automotive pollution control, perovskite catalysts based on earth-abundant elements could provide alternatives to existing catalysts based on scarce precious metals^[23].

2.2.1 Perovskite solar cells

A perovskite solar cell (PSC) is a type of solar cell which includes a perovskite-structured compound, most commonly a hybrid organic-inorganic lead or tin halide-based material, as the light-harvesting active layer. Perovskite materials, such as methylammonium lead halides and all-

inorganic caesium lead halide, are cheap to produce and simple to manufacture^[14].

In 2009 researchers discovered that by emitting light on perovskite they were able to induce a small electric charge creating a mini scale solar cell^[16]. Solar cell efficiencies of laboratory-scale devices using these materials have increased from 3.8% ^[16]in 2009 to 25.5% in 2020 in single-junction architectures, and, in silicon-based tandem cells, to 29.15%^[5], exceeding the maximum efficiency achieved in single-junction silicon solar cells. These panels create electricity by a thin layer of lead halide perovskite film on top of a coating of conductive oxide .

Perovskite solar cells are therefore the fastest-advancing solar technology as of 2016. With the potential of achieving even higher efficiencies and very low production costs, perovskite solar cells have become commercially attractive. Core problems and research subjects include their short- and long-term stability.

Metal halide perovskites possess unique features that make them useful for solar cell applications. The raw materials used, and the possible fabrication methods (such as various printing techniques) are both low cost^[18]. Their high absorption coefficient enables ultrathin films of around 500 nm to absorb the complete visible solar spectrum^[17]. These features combined result in the possibility to create low cost, high efficiency, thin, lightweight and flexible solar modules. Perovskite solar cells have found use in powering low-power wireless electronics for the ambient powered internet of things applications ^[12].

One of the benefits to using perovskite in solar cells is their defect tolerance, unlike silicon cells where everything has to be aligned perfectly to work and any damage renders the entire device unusable ,perovskite cells can be simply layered onto a surface and generate an electric charge making manufacturing easier and cheaper but however engineers are hopeful that perovskite can help to break down the price of solar energy they have some disadvantages. The perovskite cells are fragile and degrade much faster than conventional silicon crystal panels

2.2.2 Architecture of perovskite solar cells

The methodology of photovoltaic cells fabrication with solutions described in this chapter.

A key factor in the construction of PV is the cleanliness of the surface but also the removal of moisture and oxygen, because there may be a problem in its coating since they are both factors that destroy the material and affect the efficiency of PV.

A "clean room" procedure is used to remove dust and other grease. The treatment is done with tweezers and contact with the photoactive mattress is prohibited so as not to scratch the mattresses and create a failed sample due to short circuit between anode and cathode.

The preparation and deposition of a photoactive layers is the most important which contains the donors and receivers.

Prior to the final step of deposition the cathode electrode is coated with a metal oxide coating for a better interface between the electrode and the photoactive layer and finally the deposition of the cathode electrode which is usually done by the evaporation method.

The most common and effective methods of coating solutions on thin substrates are:

- Drop casting
- Spin coating deposit
- Doctor blade
- Dip-coating
- Thermal evaporation deposition

Device configuration is one of the most important factors in evaluating the overall performance of perovskite solar cells. PSCs can be classified into regular (n-i-p) and inverted (p-i-n) structures, depending on which transport material (electrons/holes) is present on the exterior portion of the cell/encountered by incident light first. These two structures can be further divided into two categories: mesoscopic and planar structures. The mesoscopic structure includes a mesoporous layer, while the planar structure consists of all planar layers. Perovskite solar cells without electron and hole

transporting layers have also been tested. In summary, six types of perovskite solar cell architectures have been investigated by different researchers so far: the mesoscopic n-i-p configuration, the planar n-i-p configuration, the planar p-i-n configuration, the mesoscopic p-i-n configuration, the ETL-free configuration, and the HTL-free configuration^[49].

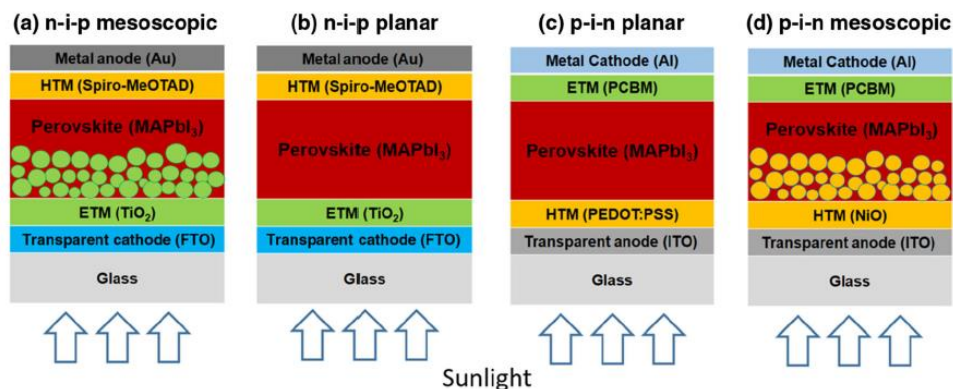
Normal n-i-p structure

The conventional mesoscopic n-i-p structure was the first tested arrangement of perovskite photovoltaics, where the light-collecting dye was replaced by lead halide perovskite semiconductors in a conventional DSSC architecture^[36]. The interest in perovskite solar cells further increased when so-called mesoscopic structures (Fig. 11a) were formed by replacing the liquid electrolyte with a solid-state hole conducting material^[37]. The structure starts with a transparent glass cathode followed by the electron transport material (ETM). The structure is then layered with a mesoporous metal oxide containing the perovskite, followed by the hole transport material (HTM), and capped with a metallic anode (Fig. 11a). This initial advance in PSCs created an important area of interest for photovoltaic researchers and subsequently led to the development of other PSC device configurations (Fig. 11b-d). The planar architecture is an evolution of the mesoscopic structure, in which the perovskite luminescent layer is embedded between the ETM and the HTM. The absence of a mesoporous metal oxide layer leads to an overall simpler structure. It is possible to achieve high efficiency without the mesoporous layer by carefully controlling the interfaces between the different layers that make up the PSC (the perovskite light absorber layer, the electron transport layer, the hole transport layer, the electrodes, and the perovskite layer itself)^[38]. Using the same materials and approach, a planar n-i-p PSC exhibited higher V_{oc} (open circuit voltage) and J_{sc} (short circuit current density) compared to a mesoscopic PSC device. However, the planar configuration also exhibited more J-V hysteresis, which questions the accuracy of the reported efficiencies^[39]. The grain and thickness of this buffer layer affect the behavior of J-V hysteresis^[40]. Also found that the J-V hysteresis problem depends significantly on the p-type hole transport materials and found that the

hysteresis behavior can become negligible with a reduced capacitance by replacing Spiro-OMeTAD with poly (3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) or other inorganic hole transport materials ^[41] . However, the J-V hysteresis behavior also depends on the direction of voltage sampling, sampling rate, and range ^[42] . To counteract this problem, a thin mesoporous buffer layer was integrated into the planar n-i-p PSC structure ^[43] . To date, the best mesoscopic n-i-p device ^[44] has achieved a PCE value of 21.6%, while the highest reported efficiency of a planar n-i-p cell is 20.7% ^[45] .

Inverted p-i-n structure

In the planar p-i-n perovskite architecture, the HTM layer is deposited first, followed by the ETM layer. It was discovered that perovskites are able to self-transport the holes ^[46] , which led Jeng et al. to develop the first planar heterojunction PSC with inverted structure design ^[47] . With this advancement, the inverted p-i-n configuration has expanded the possibilities to explore more for selective layers from organic to inorganic materials and the use of oxide HTM enables the construction of mesoscopic p-i-n device architectures ^[40] . Planar p-i-n PSCs offer low temperature processing, negligible hysteresis behavior and high efficiency of 18% ^[48] . The device configuration of the inverted planar and mesoscopic p-i-n PSC is shown in Fig. 11c, d.



Εικόνα 11 Schematic showing the layered structure four typical of perovskite solar cells (a) n-i-p mesoscopic, (b) n-i-p planar, (c) p-i-n planar, and (d) p-i-n mesoscopic^[50]

2.2.3 Fabrication and Operating Principle of GRAPEs

The most common methods to produce perovskite solar cells are:

- Sequential deposition
- Dual Vapor Evaporation
- Hot-casting
- Laser Ablation

When moving from single cell to module and panel configurations, several strategies should be employed to ensure the desired device reproducibility required for large-scale production.

Regarding the fabrication of PSMs, although laser patterning is nowadays the preferred technology for their fabrication in an industrial environment, the laser ablation process requires some precautions to ensure a high process yield. Monolithic integrated interconnects between adjacent cells can be achieved by the so-called P1, P2 and P3 scribing processes, which determine the final module layout. In particular, the P2 process should be able to remove the entire stack of ETL($\text{cTiO}_2/\text{mTiO}_2$)/perovskite/HTL without damaging the underlying FTO layer to ensure minimal contact resistance between the vertical gold interconnect and the removed area. In this regard, when using a mesoscopic PSC structure, a mask can be used to prevent the deposition of cTiO_2 over the contact areas, as the strong adhesion of this layer to the FTO would require a high laser fluence for the complete removal of the layer, which may affect the underlying FTO. Structured printing of CTiO_2 eliminates the likelihood of FTO damage by ensuring high module reproducibility in a high throughput production environment. Although structured printing of cTiO_2 slightly reduces the geometric fill factor ($\text{GFF}=82.18\%$) compared to optimized all-laser processes ($\text{GFF} \geq 90\%$), the larger contact area will reduce contact resistance with an improvement in FF. In addition, this enables accessible contact areas that can simplify module functional testing during in-line module production.

As for the module layout, the optimized cell width of 0.9 cm has several advantages in terms of industrial production. First of all, by reducing the total

number of sub-cells and possibly P2 ablation steps and interconnects, the production process is accelerated as the laser ablation time is reduced. At the same time, the lifetime of the module is extended since the total vertical area of the stack exposed to external influences is reduced. Second, the current in a module that uses a series connection between individual cells is limited by the cell with the worst performance. The deposition techniques based on perovskite solutions are usually affected by a crystallization process that is not fully controlled, which could contribute to the non-uniformity of the absorber layer. The higher the percentage of non-uniform morphology, the more limited is the power generation on the active area. Consequently, a larger active area of the cell guarantees a lower percentage of low-power areas by limiting the current distribution between the cells of the module.

The reduction of interconnection number is desirable even for the final P3 counter electrode ablation process. In this regard, the gold layer provides an ultimate protective barrier against external agents that cause cell degradation. Therefore, for the stability and reproducibility of perovskite-based modules, it is crucial to find a good compromise between the number of P3 scribes, the cell width and finally the aspect ratio of the perovskite-based module stability and reproducibility. Moreover, the P3 ablation width should also be optimized in terms of massive module fabrication for panel production. This is because the narrower the P3 ablation width, the higher the likelihood that residual gold flakes can re-connect and cause shunting of adjacent cells during the module lamination process where external pressure is applied.

All strategies used to ensure high throughput in device manufacturing aim to achieve a low reject rate in production. This is reflected in an overall cost reduction resulting from i) improved module fabrication yield and ii) the use of a cheaper nano-second pulsed laser for P2 ablation instead of a more expensive pico-second equipment required for the cTiO₂ removal.

The rationalization, as well as solving of module production problems, has allowed us to demonstrate perovskite solar modules with record-breaking efficiencies. Indeed, a maximum module efficiency of 16.4% was achieved on 81.9 cm² of active area (substrate area 121 cm²), which is above the state-of-the-art for this size, as shown in Fig. S1.

After encapsulating the modules, the sorting procedure and subsequent

distribution of the PSM aim to reduce the current mismatch between the series-connected modules and the voltage mismatch between the parallel-connected strings. In this way, the overall efficiency of the panel is improved by avoiding sources of inhomogeneous degradation of the PSMs during the lifetime of the panel. The panels consist of 5 strings connected in parallel, each of which is realised by connecting 8 modules in series, resulting in 40 PSMs per panel (Fig. S2). The PSM connections were made using pressure-sensitive copper conductor tapes and by gluing the tapes in place, the latter being placed between the tapes and the busbars. Finally, a commercial junction box with MC4 connectors was used to collect and protect the panel external contacts of the panel.

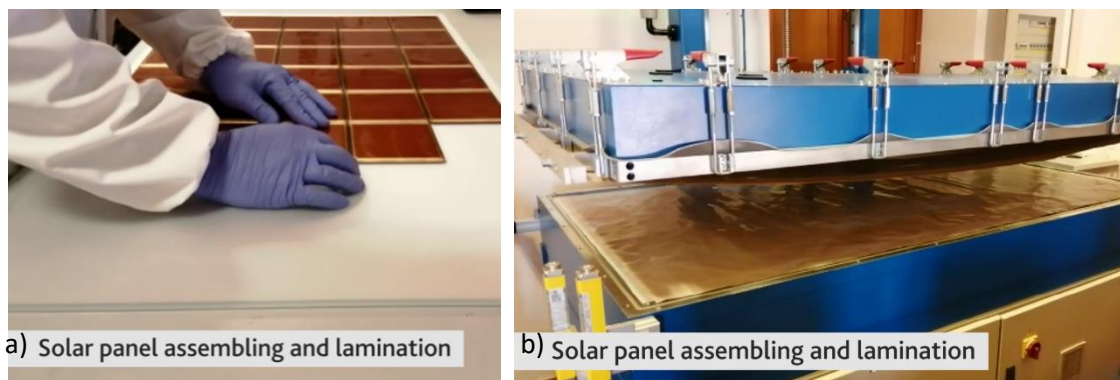


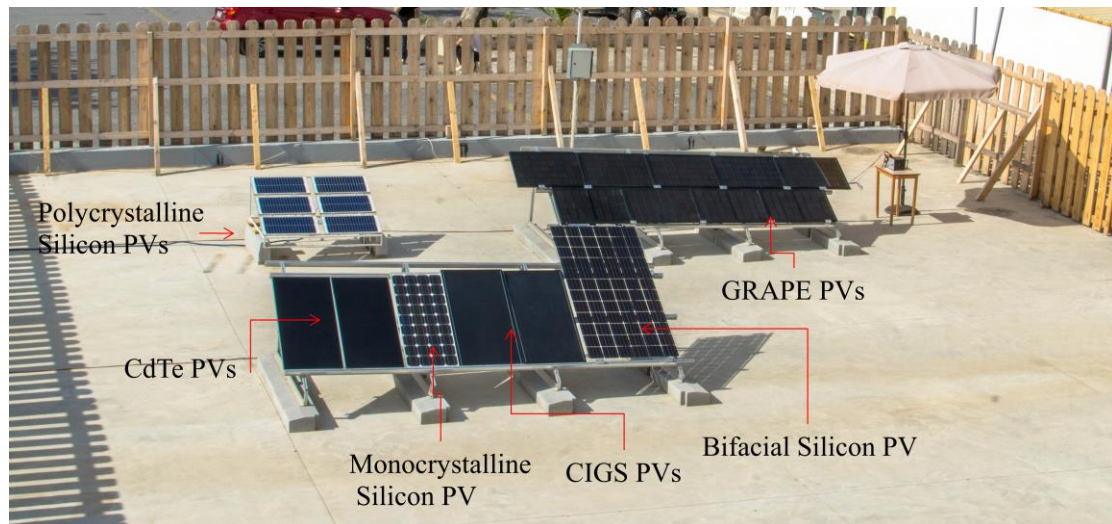
Figure S2. a) Assembling of the PSM into a GRAPE panel and b) lamination equipment.

3. Solar farm facilities

The solar farm project is located in Hellenic Mediterranean University in Heraklion of Crete Island in Greece and the reason that the specific area is ideal, for the study of photovoltaic systems, is due to the high value of solar radiation that occurs every year.

3.1.1 Solar park

The solar park is an outdoor facility equipped with solar panel stands on which there are several PV technologies both for the production of electricity and for reasons of benchmarking with new technologies that are under research.



Εικόνα 12 PV technologies of the solar farm

The solar park is equipped with a weather station in order to keep track of the weather conditions of the environment in general and during measurements.

The weather station that is installed is the **CR1000X** from Campbell Scientific which is a low-powered device that measures sensors, drives direct communication and telecommunications, analyzes data, controls external devices, and stores data and programs in onboard, nonvolatile storage. The electronics are RF-shielded by a unique sealed, stainless-steel canister. A battery-backed clock assures accurate timekeeping.

Furthermore it is equipped with an onboard, BASIC-like programming language that supports data processing and analysis routines.



On this board are connected sensors that can measure:

Temperature sensors for measuring the temperature of the solar panels
(Four)

Temperature sensor for the temperature of the environment(one)

Pyranometer in order to measure the solar irradiance

Anemometer (wind speed and wind direction)

Hygrometer (relative humidity)

Barometer (atmosphere pressure)

Data received from the sensors is recorded and stored with intervals of 1 minute, 5 minutes, 10 minutes, one hour and one day.

The intervals show the average value of the measurements taken in the time period concerning each of them respectively.

All the data presented in this work is about one minute record measurements in order to achieve better accuracy and more realistic results of weather conditions during the experiments.

3.1.2 Dark room

In this work, when we speak of a dark room, we refer to a room that serves to isolate some of the factors that normally exist in outdoor conditions.

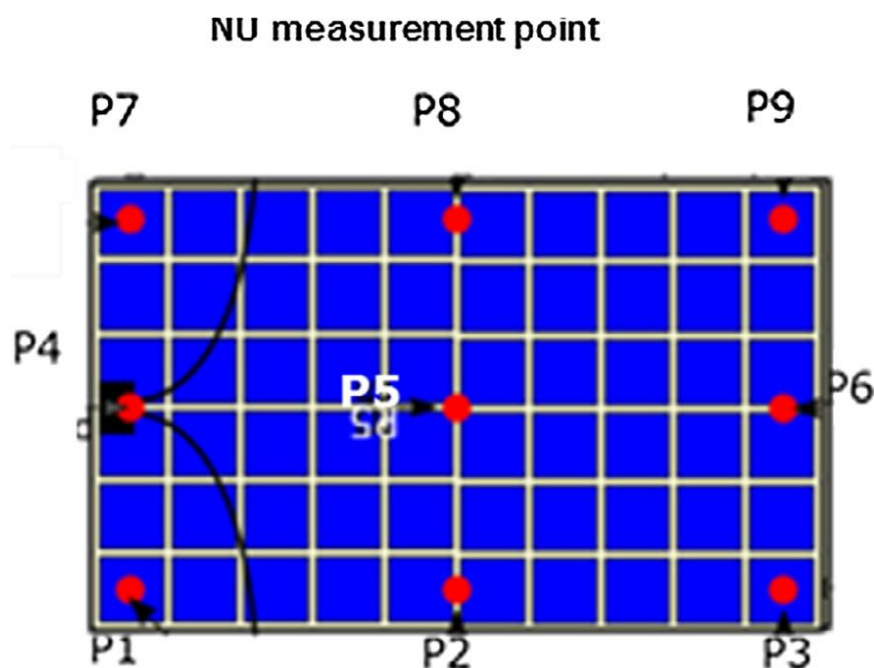
The goal was to study the effects of factors such as temperature in a room with controlled radiation, humidity and wind. These are factors that affect the performance of photovoltaic systems.

These experiments took place in the darkroom to determine the temperature coefficient of all electrical characteristics of GRAPEsc at different scales (panel, single and double module).

As part of conducting the temperature experiment, an array of lamps were placed opposite the photovoltaic panel so that they illuminated its entire surface.

Then, using a pyranometer, the irradiance values at 5 points on the panel were recorded using the 5-point irradiance non-uniformity method [15] and the average irradiance value of the 5 points was considered as the total irradiance value that fell on the surface of the panel.

Either the average of points P1, P7, P9, P3, P5 or P4, P8, P6, P2, P5 as shown in Figure 12 can be used to estimate the non-uniformity irradiance using this technique [15]. Points P1, P7, P9, P3 and P5 were used in all experiments in the darkroom and in the results shown below.



Εικόνα 13 the 5 point method to measure the non-uniformity (NU) of irradiance. [15]

Then characterization experiments were performed via i-v curves measurements at each temperature change per degree Celsius in order to determine the behavior of each electrical characteristic of the PV panel/module, with the change of temperature.

Five Halogen lamp were used to irradiate the panels during the experiments with a total power of 1.8 kilowatts, pointing directly at the panel under testing, with the alignment shown in figure 13.



Εικόνα 14 light set up of the dark room experiments

3.2 Equipment of solar farm & Setup used for characterization measurements

In this chapter are going to be presented the devices and their specifications that were used in order to perform the experiments, during the research period, whose results are analyzed in the following chapters.

3.2.1 I-V Tracer equipment

As it was already mentioned in **chapter 1.5**, the I-V curves are crucial for extracting the electrical characteristics of a solar cell such as **I_{sc}** , **V_{oc}** , **I_{max}** , **V_{max}** , **P_{max}** , **FF** and **PCE**.

In order to perform these measurements there where two machines used, the "I-V 400w" and "P-V BLOCKS".

- I-V 400



I-V 400w is a I-V Curve tracer from HT instruments which is equipped with a wi fi chip on board and a PC cable connection which makes it easy to download an analyze the DATA in **HT analysis software**.

The I-V400w allows on-site measurement of the I-V curve and the main characteristic parameters of both a single module and module strings for PV systems up to a maximum voltage of 1000V and 15A. For the measurement of the I-V curve, the I-V400w manages an internal database of the modules, which can be updated by the user at any time. The comparison of the measured data with the nominal values allows an immediate assessment of

whether the string or module meets the efficiency parameters specified by the manufacturer. The I-V curve can also be measured by decentralized measurement of irradiance and temperature using the optional SOLAR02 remote unit connected to the master unit via a radio link (RF).

The irradiance is measured with a reference cell, which is able to measure as a mono or multi panel.

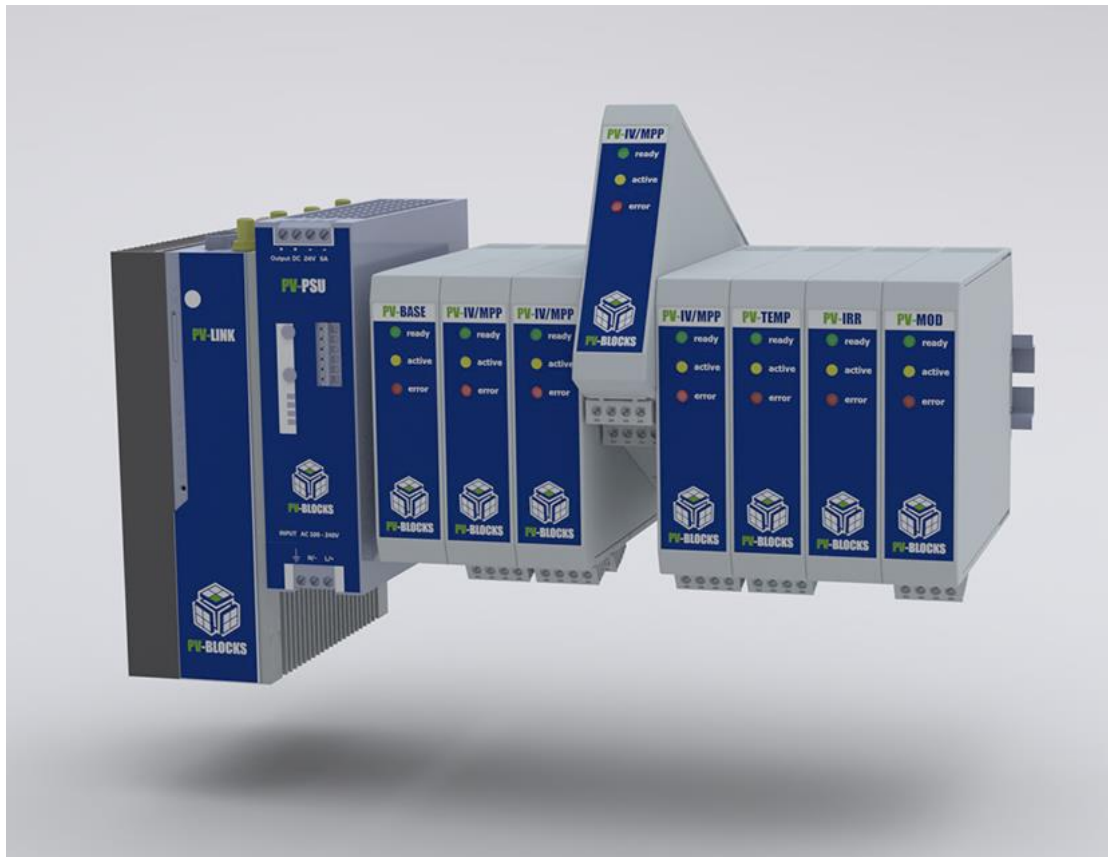
Also for the I-V400w, the display of the I-V curve at the end of the test is a clear indication of compliance with the specifications given by the panel manufacturer [25].

In addition, the I-V400w can also measure capacitive panels by changing the PV panel type setting.

The I-V400w has 4 terminals that can be connected in pairs. Two of them are connected to the positive end of the module and two to the negative end. One of the pairs measures the panel's voltage and current.

Finally, the I-V400w can easily detect any deviation of the I-V curve measured in operation from the estimated curve, which should be consistent with the manufacturer's specifications of the PV panel under test.

▪ P-V BLOCKS



ReRa Solutions has developed a completely new productline: PV Blocks. The modular PV-Blocks system is a unique and universal solution for testing any type of experimental PV technology like perovskite and hybrid solar modules, organic PV modules and high power Bi-facial modules. The system is also suited for single cell measurements^[24].

The modular PV Blocks system consists of the following blocks:

- PV Base: base system PV Blocks
- PV IV/MPP: performing several measurements of PV Modules (IV-Curves, MPPT, Voltage Biasing, Open Circuit)
- PV MON: monitoring of PV Modules
- PV IRR: Irradiance measurement
- PV TEMP: Temperature measurement
- PV MOD: connection to external instruments

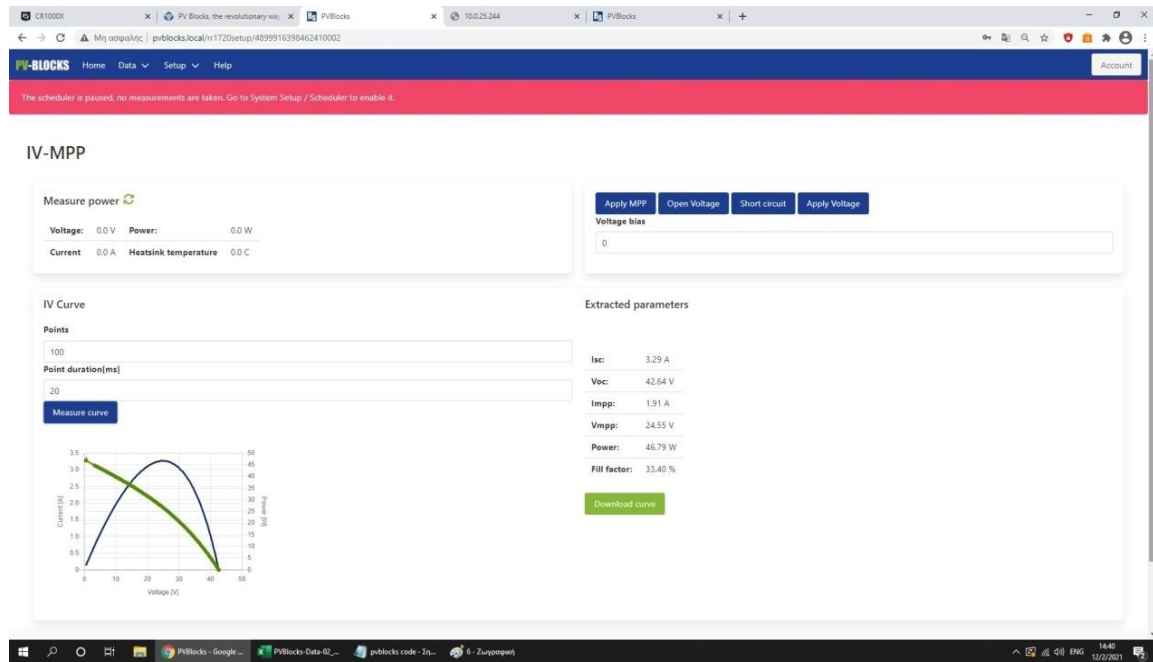
The measurements can be performed either live or with a programmed scheduler through the company's software.

In both manual and scheduled measurements there are several parameters that should be adjusted.

- The number of points to be taken for each curve
- The duration of each measuring point of the curve

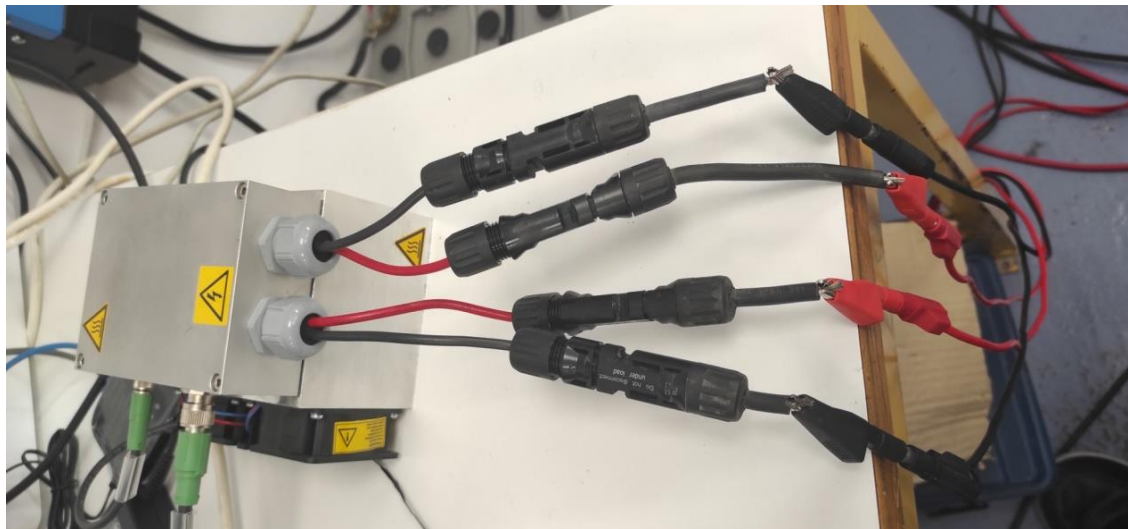
Furthermore for the scheduled measurements it's also needed to indicate

- The start and finish time of the measurements
- The intervals between each measurement



Εικόνα 15 software interface of pv blocks by RERA SOLUTIONS

The load used with the PV blocks is the 350W with a maximum input current of 20 amps and a maximum input voltage of 200 volts, which makes it ideal for the GRAPE solar panels that were examined. Just like the I-V400w, it has four terminals, two red terminals connected to the positive end of the panel and two black terminals for the negative end as shown in figure (15). One terminal is for measuring the voltage and the other one the current of the DUT.



Εικόνα 16 connection of pv-load terminal with a pv panel

3.3 Capacitance measurements (NYQYIST PLOTS)

One way to understand electrochemical or electrical differences in a system is to measure capacitance with electrochemical impedance spectroscopy (EIS). While performing EIS, a small current is applied to the device under test (DUT). The current applied is an alternating current or AC and during EIS the voltage is kept constant, typically around five to ten millivolts, so the current response is linear with the voltage and the variable that changes is the frequency. In this way, the ions of the specimen move and as they move through the different layers of the materials of the specimen, they respond. Impedance prevents the ions from moving freely through the materials because of the energy barriers they have to overcome.

If the frequency of the signal applied to the DUT was varied, the areas of energy barriers for the ions can be highlighted. At high frequencies only fast processes can be observed and at low frequencies the slow processes of the ions. The fast processes are usually chemical reactions and the slow processes are diffusion.

In EIS, a very high frequency is first applied and then swept to a low frequency.

In a Nyquist plot, we have imaginary impedance on the y-axis and real impedance on the x-axis.

There are a few areas in a Nyquist plot that are most important when

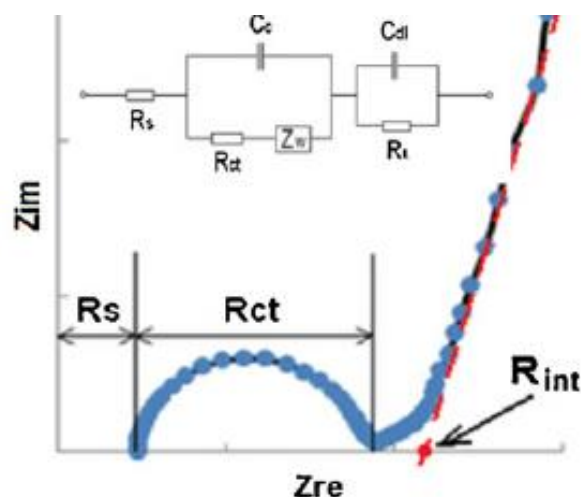
interpreting EIS data.

The first part is the gap between the zero point and the beginning of the semicircle, the second part is the semicircle itself. The highest frequencies are shown on the left side of the graph and the lower frequencies are shown on the right side.

It is important to know that it is not possible to understand everything about the DUT from a Nyquist chart, but it can show some important areas to consider when doing research.

The first intercept is called solution resistance (R_s) and can be related to transport properties.

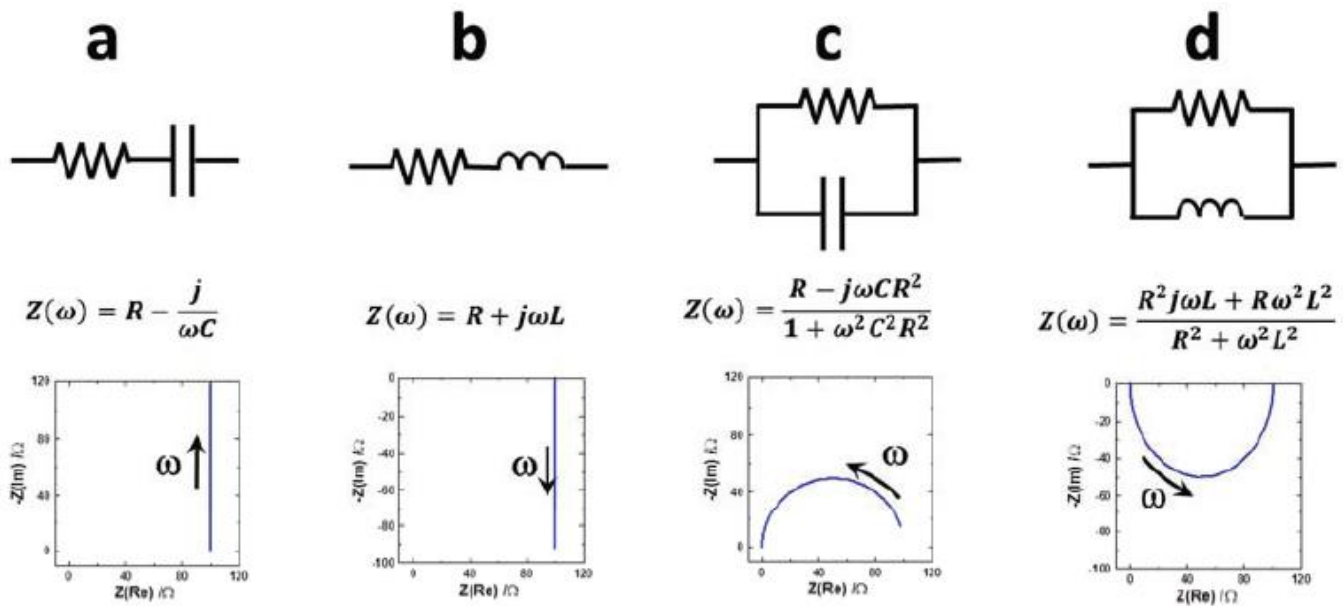
The other feature of a Nyquist diagram is where the semicircle crosses the x-axis, and is called charge transfer resistance (R_{ct}).



Εικόνα 17 the most important points of the Nyquist plot from which the impedance information can be extracted ^[19]

One way to understand the inter working of the DUT is to construct an equivalent circuit from the Nyquist plot.

From the various forms of the plot, the information about the equivalent and the electrical components to which they correspond can be extracted, as shown in Fig. ^[13]



Εικόνα 18 Nyquist representation (top graph) along with the direction of increasing frequency, of the impedance of resistor and capacitor in series (a), resistor and inductor in series (b), resistor and capacitor in parallel (c), and resistor and inductor in parallel (d). [20]

The equipment used to carry out the capacity measurement experiments is the «**Agilent B1500A Semiconductor Device Analyser**»

Keysight B1500A Semiconductor Device Analyzer of Precision Current-Voltage Analyzer Series is an all in one analyzer supporting IV, CV, pulse/dynamic IV, Nyquist plots and more, which is designed for all-round characterization from basic to cutting-edge applications. It provides a wide range of measurement capabilities to cover the electrical characterization and evaluation of devices, materials, semiconductors, active/passive components, or virtually any other type of electronic device with uncompromised measurement reliability and efficiency.



The B1520A Multi-frequency capacitance measurement unit (MFCMU)
Can perform the several measurements with the following specifications.

- AC impedance measurement (C-V, C-f, C-t)
- 1 kHz to 5 MHz frequency range with minimum 1 mHz frequency resolution
- 25 V built-in DC bias and 100 V DC bias with SMU and SCUU (SMU CMU Unify Unit)
- Easy and fast yet accurate IV and CV automated connection change by SCUU

As it appears from the characteristics of the machine there is a big limitation in terms of the minimum frequency that can perform a measurement since the lowest frequency is limited to 1kHz which has as result that in some cases the Nyquist plot cannot be fully mapped due to the lack of the desired low frequency range.

3.4 Temp coefficients

Dark room

In this scenario, experiments were performed in order to understand the effects that temperature has on GRAPEsc.

These experiments took place in the dark room in order to determine the temperature coefficient of all electrical characteristics of GRAPEsc at different scales (panel, single and double module).

As part of the implementation of the temperature experiment, an array of lamps were placed opposite the photovoltaic panel so that they illuminated its entire surface.

Then, using a pyranometer, the radiation values at 5 points on the panel were recorded, as shown in the reference paper, and the average radiation value of the 5 points was considered as the total radiation value that fell on the surface of the panel.

Then characterization experiments were performed via i-v curve measurements at each temperature change per degree Celsius to determine the behavior of each electrical characteristic of the PV panel/module with the change of temperature.

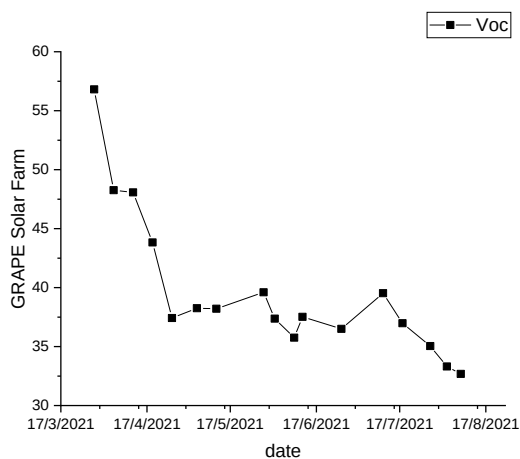
4.1. Electrical Characteristics for GRAPE Solar Farm

As it was mentioned in a previous chapter, from the I-V characterization curve can be extracted all the information concerning the electrical characteristics of a photovoltaic panel, such as I_{sc} , V_{oc} , I_{max} , V_{max} , P_{max} , PCE and FF.

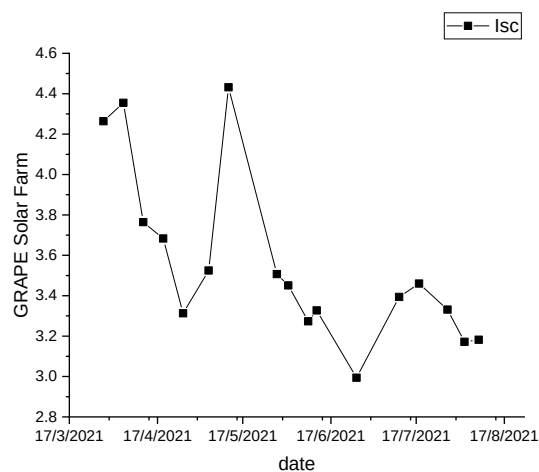
This chapter presents the results of characterization measurements that were implemented in each panel individually but also in the total of the panels during the day.

In this chapter are presented the electrical characteristics of GRAPE panels individually but also as a whole. all nine panels are connected with its other in parallel in all measurements so that they can be rightly compared over time

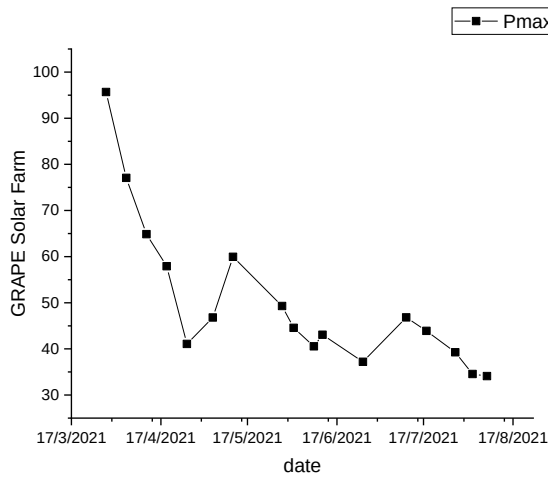
Date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Panel
	(V)	(A)	(V)	(A)	(W)	(%)	(%)	(h:m)	(W/m ²)	(°C)	(%)	(m/s)	deg	(°C)
29/3/2021	56.8	4.26	35.8	2.7	95.7	39.5	3.6	11:30	928.9	13.9	55.2	1.6	212.6	26.7
5/4/2021	48.3	4.36	28.9	2.7	77.1	36.7	2.7	12:30	1000.0	17.7	71.7	1.7	11.7	46.9
12/4/2021	48.1	3.76	29.4	2.2	64.9	35.8	2.3	11:30	998.0	17.1	57.3	2.6	244.7	39.2
19/4/2021	43.8	3.68	26.0	2.2	57.9	35.9	2.0	11:28	1000.0	14.8	51.8	1.1	255.5	43.0
26/4/2021	37.4	3.31	21.6	1.9	41.1	33.1	1.4	12:13	998.0	16.3	66.1	3.0	343.9	41.1
5/5/2021	38.2	3.53	23.1	2.0	46.8	34.7	1.6	10:54	1000.0	17.0	31.9	1.7	6.1	47.0
12/5/2021	38.2	4.43	22.9	2.6	60.0	35.4	2.0	11:07	1018.0	13.1	51.6	2.2	298.6	40.3
29/5/2021	39.6	3.51	23.4	2.1	49.3	35.5	1.7	11:53	1002.0	16.6	55.7	2.2	355.9	44.5
2/6/2021	37.4	3.45	21.8	2.0	44.6	34.6	1.5	11:54	1001.0	16.1	49.8	1.7	333.7	44.1
9/6/2021	35.8	3.27	20.9	1.9	40.6	34.7	1.4	11:05	984.0	12.4	45.6	3.6	44.2	27.8
12/6/2021	37.5	3.33	21.0	2.0	43.1	34.5	1.5	11:46	1001.0	15.8	57.4	2.7	353.2	42.8
26/6/2021	36.5	2.99	21.3	1.7	37.2	34.0	1.3	11:50	1004.0	18.0	51.9	4.3	288.2	42.1
11/7/2021	39.5	3.39	23.6	2.0	46.8	34.9	1.6	11:55	1001.0	20.1	55.7	4.4	277.8	44.2
18/7/2021	37.0	3.46	22.0	2.0	43.9	34.3	1.5	12:09	1000.0	30.8	31.5	1.2	330.0	58.4
28/7/2021	35.0	3.33	20.2	1.9	39.3	33.6	1.4	12:34	999.0	25.3	50.7	2.5	51.7	50.2
3/8/2021	33.3	3.17	18.8	1.8	34.6	32.7	1.2	12:18	1001.0	22.9	47.0	2.2	24.4	43.8
8/8/2021	32.7	3.18	18.5	1.8	34.1	32.8	1.2	13:12	984.0	30.4	29.9	1.7	325.9	64.1



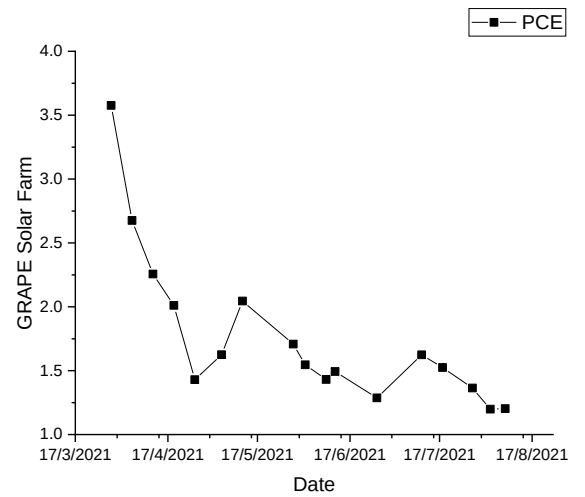
a)



b)



c)



d)

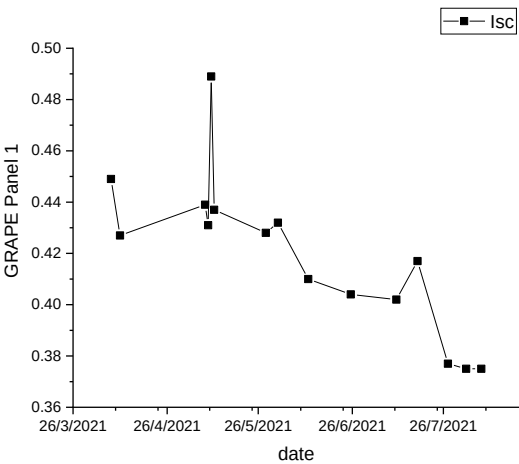
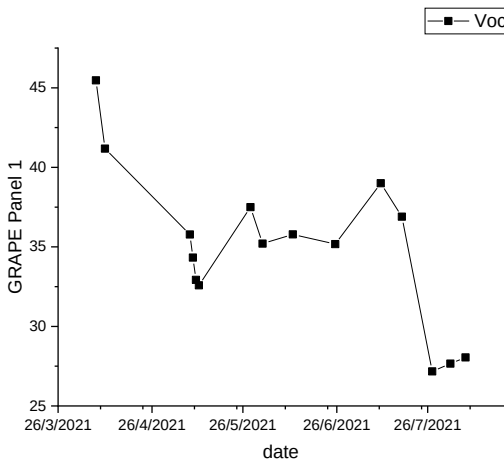
Εικόνα 19 The change of the electrical characteristics of the GRAPE panels with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

4.2. Electrical characteristics for individual GRAPEsc

Panel 1

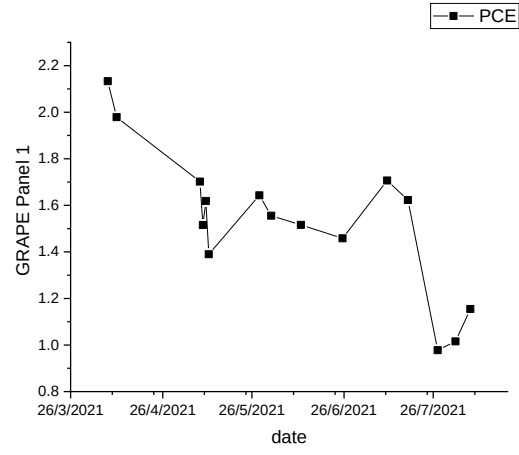
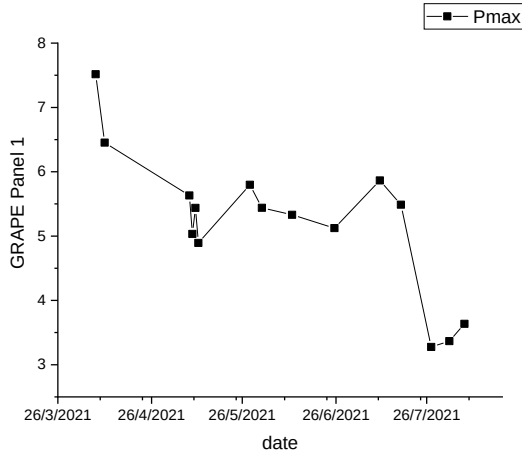
Date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Pan.
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m ²)	(°C)	(%)	(m/s)	deg	(°C)
8/4/2021	45.5	0.4	28.9	0.3	7.5	36.8	2.1	13:58	1101	20.6	53.3	3.9	183.0	37.7
11/4/2021	41.2	0.4	26.3	0.2	6.5	36.7	2.0	13:58	1019	21.6	35.8	6.0	205.7	39.4
9/5/2021	35.8	0.4	20.6	0.3	5.6	35.8	1.7	12:57	1034	19.5	57.1	2.4	26.5	44.7
10/5/2021	34.3	0.4	19.9	0.3	5.0	34.0	1.5	11:59	1038	18.1	81.0	2.0	337.9	48.6
11/5/2021	32.9	0.5	18.3	0.3	5.4	33.8	1.6	12:57	1050	17.7	50.5	3.0	352.6	36.3
12/5/2021	32.6	0.4	19.0	0.3	4.9	34.4	1.4	12:01	1100	13.1	53.5	2.8	344.0	43.8
29/5/2021	37.5	0.4	20.7	0.3	5.8	36.1	1.6	13:09	1103	17.0	58.0	2.3	311.6	49.5
2/6/2021	35.2	0.4	21.9	0.2	5.4	35.8	1.6	13:24	1093	17.1	48.5	1.4	350.3	52.3
12/6/2021	35.8	0.4	19.5	0.3	5.3	36.3	1.5	12:53	1099	16.3	56.6	2.3	341.7	45.8
26/6/2021	35.2	0.4	21.9	0.2	5.1	36.1	1.5	13:02	1098	18.8	53.2	3.2	2.4	43.8
11/7/2021	39.0	0.4	23.9	0.2	5.9	37.4	1.7	13:30	1074	20.6	54.8	4.1	9.2	45.6
18/7/2021	36.9	0.4	20.8	0.3	5.5	35.7	1.6	13:16	1057	30.0	34.5	2.5	29.0	57.3

28/7/2021	27.2	0.4	16.0	0.2	3.3	32.0	1.0	13:46	1047	24.8	54.0	3.3	21.6	51.1
3/8/2021	27.7	0.4	15.0	0.2	3.4	32.5	1.0	13:23	1036	22.7	51.5	2.1	291.0	53.6
8/8/2021	28.0	0.4	16.0	0.2	3.6	34.6	1.2	13:18	984	30.2	31.1	2.0	11.2	62.6



a)

b)



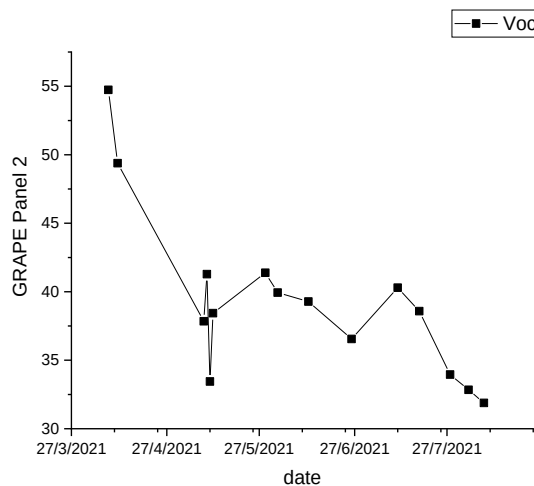
c)

d)

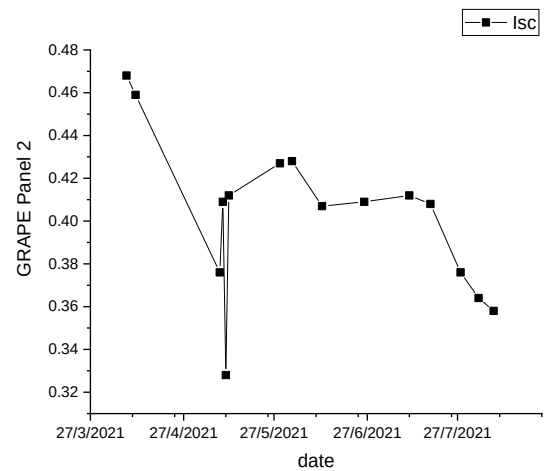
Εικόνα 20 The change of the electrical characteristics of the GRAPE panel 1 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

Panel 2

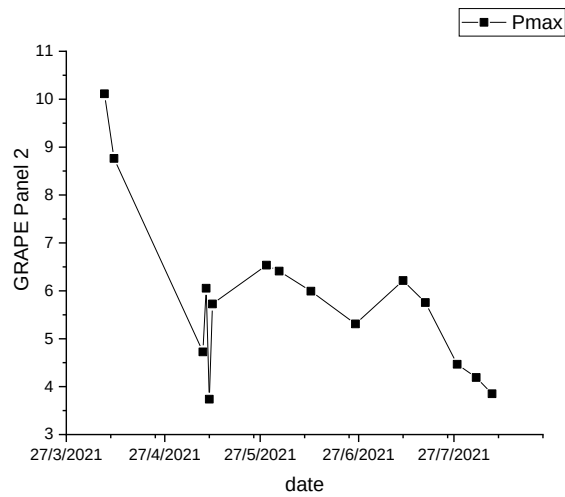
date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	T_Panel
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m2)	(°C)	(%)	(m/s)	deg	(°C)
8/4/2021	54.7	0.5	33.2	0.3	10.1	39.5	3.0	14:02	1044	20.9	53.3	2.9	191.7	39.4
11/4/2021	49.4	0.5	29.9	0.3	8.8	38.7	2.6	14:02	1042	21.6	36.2	4.2	149.1	38.0
9/5/2021	37.8	0.4	21.7	0.2	4.7	33.2	1.6	13:01	934	19.5	55.5	2.5	13.2	46.6
10/5/2021	41.3	0.4	24.7	0.2	6.1	35.9	1.8	12:01	1037	17.9	81.2	2.2	30.4	49.7
11/5/2021	33.4	0.3	20.2	0.2	3.7	34.1	1.3	15:09	902	16.3	48.2	3.6	10.1	28.5
12/5/2021	38.4	0.4	23.4	0.2	5.7	36.2	1.6	12:02	1096	13.3	53.5	1.9	2.2	44.4
29/5/2021	41.4	0.4	25.0	0.3	6.5	37.0	1.8	13:10	1105	16.9	59.5	3.3	322.8	48.5
2/5/2021	39.9	0.4	23.8	0.3	6.4	37.5	1.8	13:25	1096	17.2	48.4	1.4	27.3	52.5
12/6/2021	39.3	0.4	24.3	0.2	6.0	37.5	1.7	12:49	1097	16.4	54.8	2.2	262.1	44.9
26/6/2021	36.6	0.4	22.8	0.2	5.3	35.5	1.5	13:04	1098	19.0	54.1	3.3	352.4	44.4
11/7/2021	40.3	0.4	25.2	0.2	6.2	37.4	1.8	13:30	1074	20.6	54.8	4.1	9.2	45.6
18/7/2021	38.6	0.4	24.0	0.2	5.8	36.6	1.7	13:19	1056	29.7	35.7	1.6	331.9	56.9
28/7/2021	34.0	0.4	20.0	0.2	4.5	35.0	1.3	13:46	1047	24.8	54.0	3.3	21.6	51.1
3/8/2021	32.8	0.4	21.1	0.2	4.2	35.1	1.3	13:23	1036	22.7	51.5	2.1	291.0	53.6
8/8/2021	31.9	0.4	18.8	0.2	3.9	33.7	1.2	13:15	981	30.0	31.1	1.3	317.9	63.1



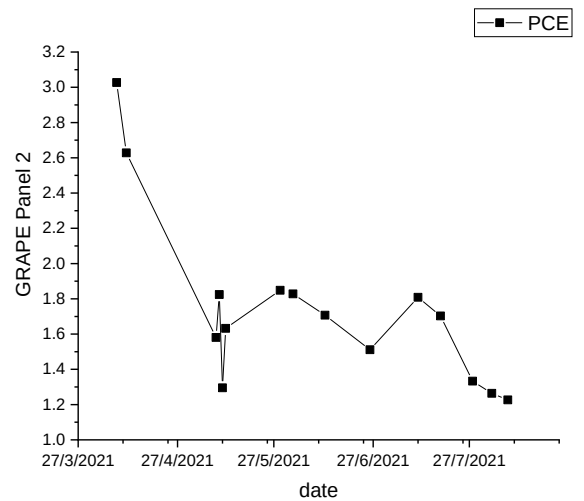
a)



b)



c)

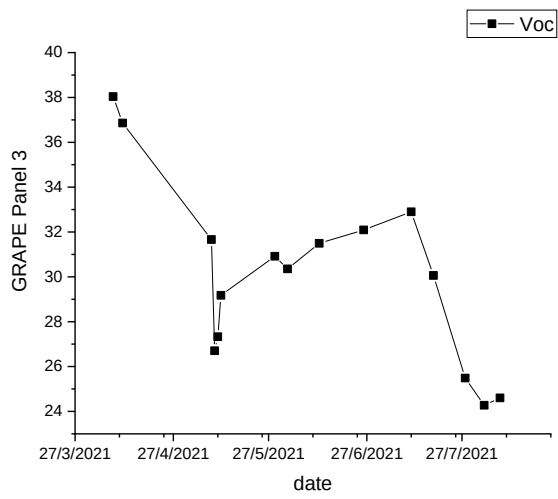


d)

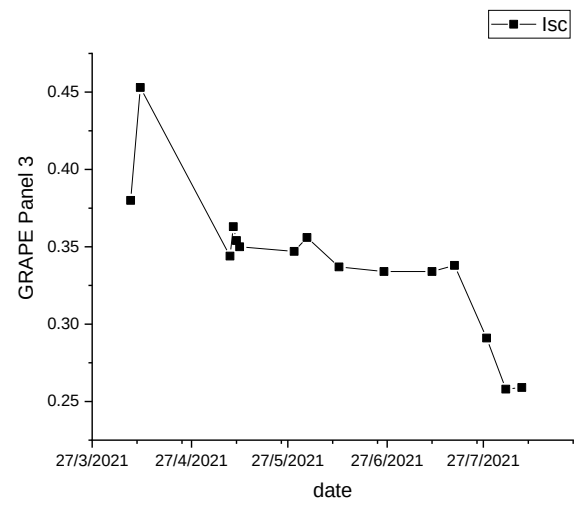
Εικόνα 21 The change of the electrical characteristics of the GRAPE panel 2 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

Panel 3

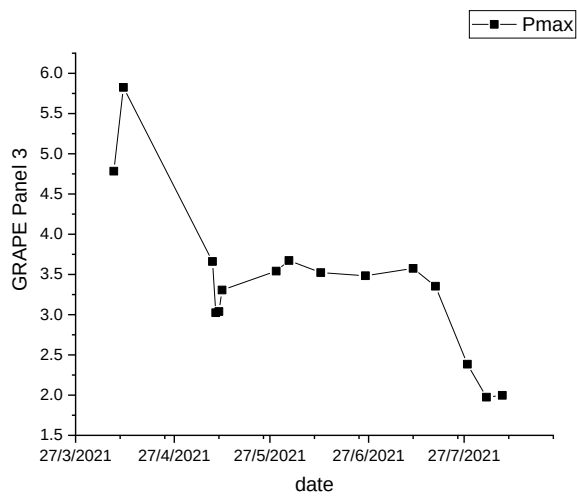
date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Panel
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m2)	(°C)	(%)	(m/s)	deg	(°C)
8/4/2021	38.0	0.4	22.4	0.2	4.8	33.1	1.5	14:05	978	20.8	53.1	3.5	162.3	37.7
11/4/2021	36.9	0.5	21.8	0.3	5.8	34.9	1.6	13:03	1108	22.3	29.3	3.9	145.0	46.5
9/5/2021	31.7	0.3	18.1	0.2	3.7	33.6	1.2	13:03	980	19.8	56.0	0.8	318.9	46.6
10/5/2021	26.7	0.4	15.3	0.2	3.0	31.2	0.9	12:02	1028	18.0	81.4	1.8	351.9	52.3
11/5/2021	27.3	0.4	15.9	0.2	3.0	31.4	0.9	13:59	1068	17.3	44.5	2.8	29.1	39.7
12/5/2021	29.2	0.4	14.6	0.2	3.3	32.4	0.9	12:00	1102	13.2	52.6	3.0	4.1	43.4
29/5/2021	30.9	0.3	18.5	0.2	3.5	33.0	1.0	13:11	1104	16.8	61.1	2.1	322.2	48.9
2/6/2021	30.4	0.4	16.1	0.2	3.7	34.0	1.0	13:27	1096	17.1	48.4	1.2	325.4	52.4
12/6/2021	31.5	0.3	17.5	0.2	3.5	33.2	1.0	12:52	1099	16.2	57.1	2.9	10.0	45.7
26/6/2021	32.1	0.3	17.6	0.2	3.5	32.5	1.0	13:05	1107	19.0	50.5	4.0	356.4	44.2
11/7/2021	32.9	0.3	18.1	0.2	3.6	32.5	1.0	13:32	1072	20.7	56.0	3.9	80.4	47.6
18/7/2021	30.1	0.3	17.6	0.2	3.4	33.0	1.0	13:17	1058	29.9	35.3	2.3	345.9	57.1
28/7/2021	25.5	0.3	13.5	0.2	2.4	32.2	0.7	13:47	1038	24.8	54.4	3.0	68.7	51.2
3/8/2021	24.3	0.3	14.5	0.1	2.0	31.5	0.6	13:21	1039	22.9	49.3	3.0	320.6	51.7
8/8/2021	24.6	0.3	13.8	0.1	2.0	31.4	0.6	13:16	985	30.2	30.4	1.7	314.7	62.9



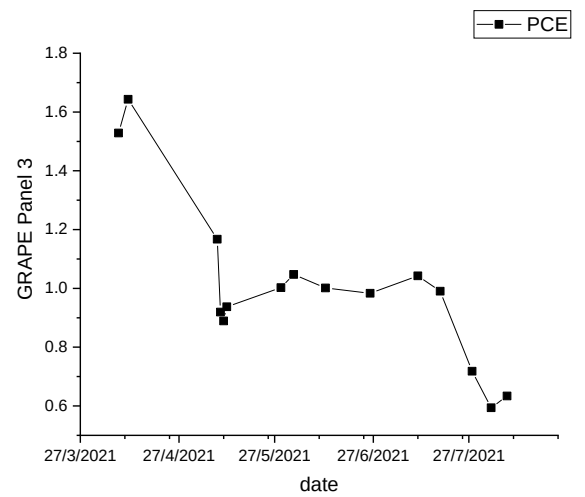
a)



b)



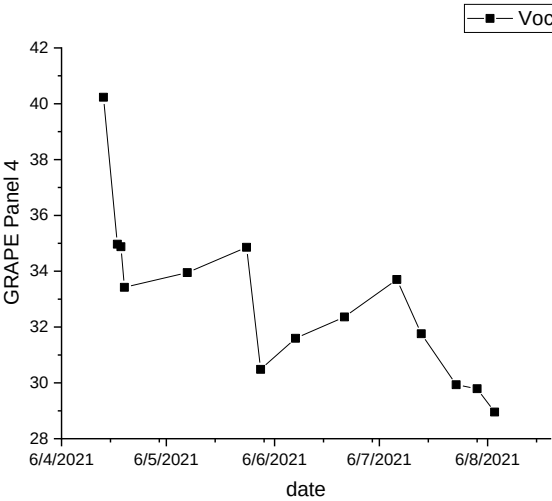
c)



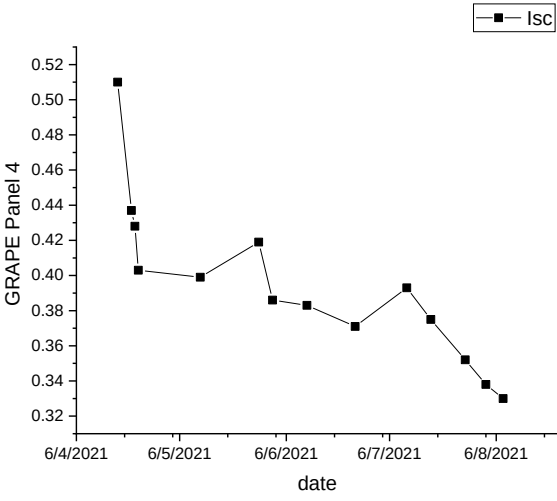
d)

Εικόνα 22 The change of the electrical characteristics of the GRAPE panel 3 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

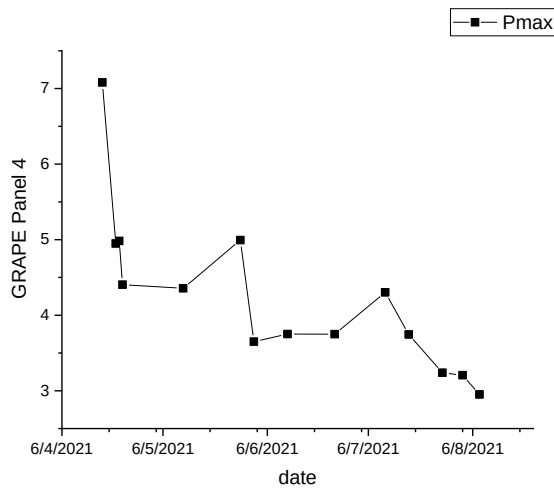
date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Panel
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m2)	(°C)	(%)	(m/s)	deg	(°C)
18/4/2021	40.2	0.5	21.5	0.3	7.1	34.5	1.9	12:57	1145	13.3	60.9	1.3	302.5	35.9
22/4/2021	35.0	0.4	20.0	0.2	4.9	32.4	1.5	12:58	1051	14.6	61.8	3.0	344.8	40.6
23/4/2021	34.9	0.4	20.4	0.2	5.0	33.4	1.5	11:58	1027	15.7	60.5	2.7	312.3	43.3
24/4/2021	33.4	0.4	20.1	0.2	4.4	32.7	1.3	11:58	1053	18.7	41.5	2.2	32.8	47.8
12/5/2021	34.0	0.4	18.7	0.2	4.4	32.2	1.2	12:01	1100	13.1	53.5	2.8	344.0	43.8
29/5/2021	34.9	0.4	20.0	0.3	5.0	34.2	1.4	13:11	1104	16.8	61.1	2.1	322.2	48.9
2/6/2021	30.5	0.4	18.3	0.2	3.7	31.0	1.0	13:27	1096	17.1	48.4	1.2	325.4	52.4
12/6/2021	31.6	0.4	17.8	0.2	3.8	31.0	1.1	12:52	1099	16.2	57.1	2.9	10.0	45.7
26/6/2021	32.4	0.4	17.8	0.2	3.7	31.2	1.1	13:04	1098	19.0	54.1	3.3	352.4	44.4
11/7/2021	33.7	0.4	20.1	0.2	4.3	32.5	1.3	13:30	1074	20.6	54.8	4.1	9.2	45.6
18/7/2021	31.8	0.4	19.2	0.2	3.7	31.5	1.1	13:18	1059	29.8	36.0	2.1	163.8	54.4
28/7/2021	29.9	0.4	17.2	0.2	3.2	30.7	1.0	13:47	1038	24.8	54.4	3.0	68.7	51.2
3/8/2021	29.8	0.3	17.6	0.2	3.2	31.8	1.0	13:19	1037	23.2	48.5	1.9	340.5	53.4
8/8/2021	29.0	0.3	16.2	0.2	3.0	30.9	0.9	13:21	988	30.0	31.2	2.0	326.2	62.5



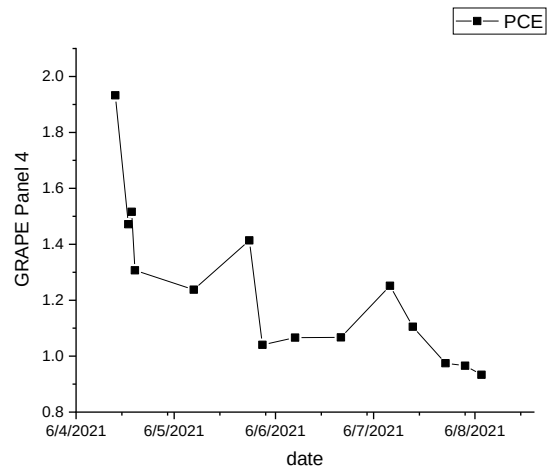
a)



b)



c)

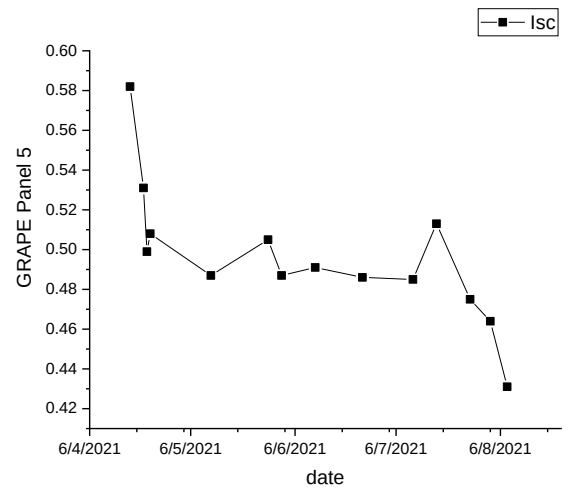
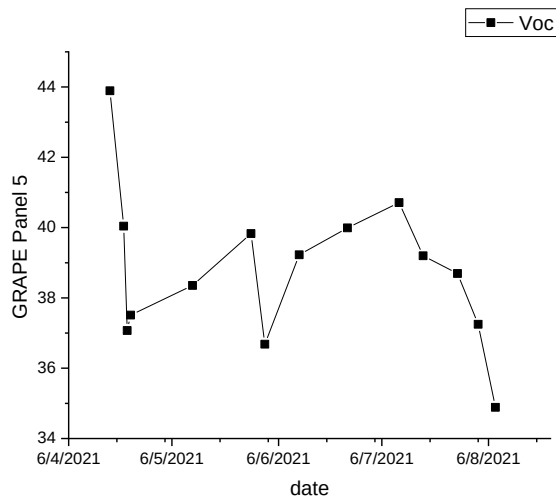


d)

Εικόνα 23 The change of the electrical characteristics of the GRAPE panel 4 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

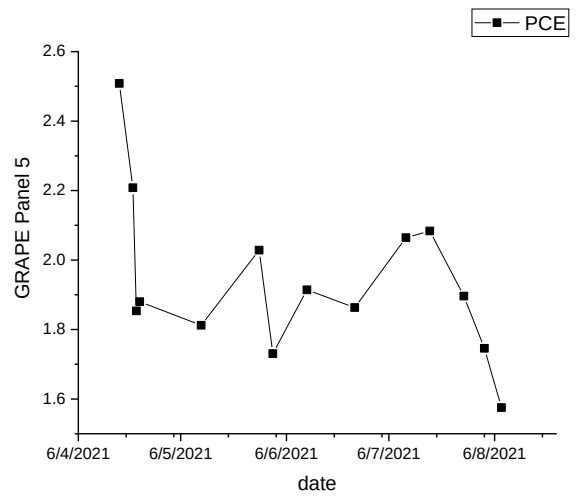
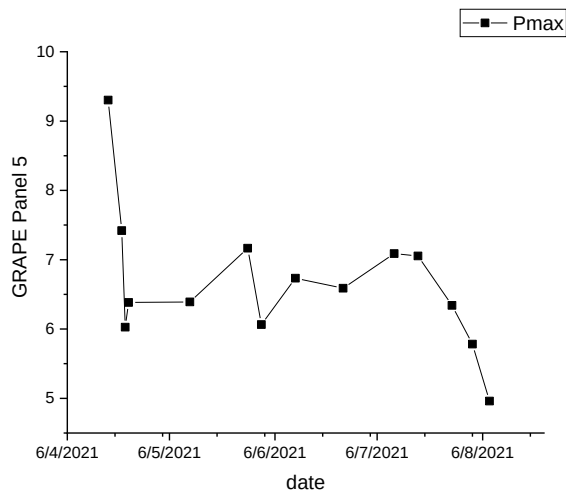
Panel 5

date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Panel
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m2)	(°C)	(%)	(m/s)	deg	(°C)
18/4/2021	43.9	0.6	27.8	0.3	9.3	36.4	2.5	12:59	1159	13.4	62.1	0.9	81.5	37.2
22/4/2021	40.0	0.5	22.2	0.3	7.4	34.9	2.2	13:01	1050	14.8	62.9	2.4	310.9	42.1
23/4/2021	37.1	0.5	22.2	0.3	6.0	32.6	1.9	12:02	1016	15.4	58.9	2.6	308.5	42.9
24/4/2021	37.5	0.5	22.3	0.3	6.4	33.5	1.9	12:01	1061	18.9	34.4	2.0	346.8	45.4
12/5/2021	38.4	0.5	25.7	0.2	6.4	34.2	1.8	12:00	1102	13.2	52.6	3.0	4.1	43.4
29/5/2021	39.8	0.5	24.3	0.3	7.2	35.6	2.0	13:11	1104	16.8	61.1	2.1	322.2	48.9
2/6/2021	36.7	0.5	22.9	0.3	6.1	33.9	1.7	13:28	1095	17.1	49.8	2.3	307.1	51.2
12/6/2021	39.2	0.5	22.2	0.3	6.7	35.0	1.9	12:53	1099	16.3	56.6	2.3	341.7	34.2
26/6/2021	40.0	0.5	23.8	0.3	6.6	33.9	1.9	13:01	1105	18.8	53.3	2.5	84.4	43.2
11/7/2021	40.7	0.5	24.4	0.3	7.1	35.9	2.1	13:33	1073	20.7	56.3	3.6	304.9	47.9
18/7/2021	39.2	0.5	23.8	0.3	7.1	35.1	2.1	13:17	1058	29.9	35.3	2.3	345.9	57.1
28/7/2021	38.7	0.5	23.3	0.3	6.3	34.5	1.9	13:48	1045	24.9	54.4	3.1	298.9	51.3
3/8/2021	37.3	0.5	22.8	0.3	5.8	33.5	1.7	13:22	1035	22.7	51.2	1.9	317.8	53.7
8/8/2021	34.9	0.4	21.7	0.2	5.0	33.0	1.6	13:22	984	29.9	31.5	1.7	318.8	63.1



a)

b)



c)

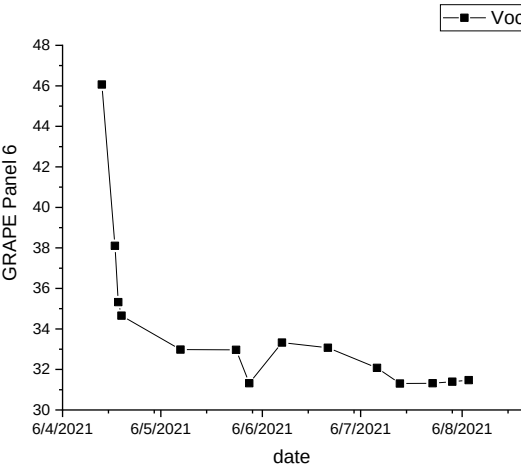
d)

Εικόνα 24 The change of the electrical characteristics of the GRAPE panel 5 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

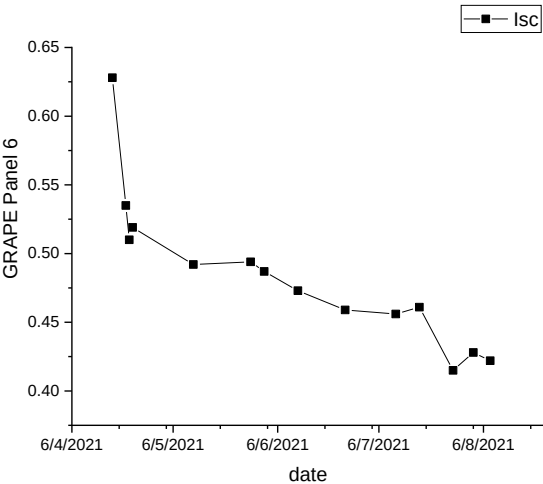
Panel 6

date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Panel
------	-----	-----	------	------	------	----	-----	------	------------	------	----	----	----	------------

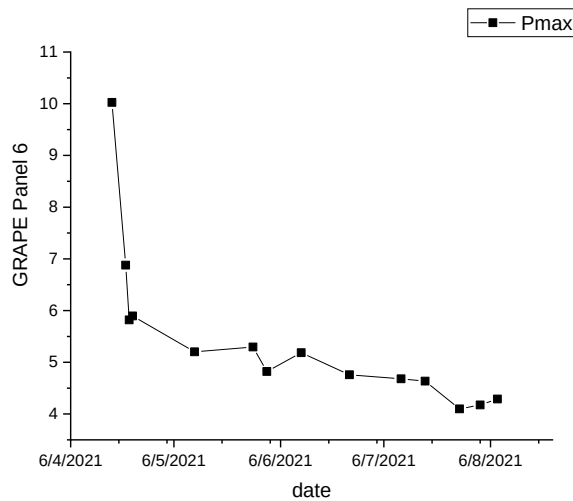
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m2)	(°C)	(%)	(m/s)	deg	(°C)
18/4/2021	46.1	0.6	25.4	0.4	10.0	34.7	2.7	13:00	1164	13.5	60.5	1.0	343.2	39.5
22/4/2021	38.1	0.5	22.2	0.3	6.9	33.7	2.0	13:02	1052	14.8	63.7	2.8	4.8	42.7
23/4/2021	35.3	0.5	21.3	0.3	5.8	32.3	1.8	12:03	1025	15.5	58.7	1.7	313.5	43.5
24/4/2021	34.7	0.5	19.7	0.3	5.9	32.8	1.7	12:02	1060	19.0	36.2	2.5	268.6	49.3
12/5/2021	33.0	0.5	19.1	0.3	5.2	32.1	1.5	12:04	1104	13.3	53.1	2.8	26.5	43.7
29/5/2021	33.0	0.5	19.8	0.3	5.3	32.5	1.5	13:12	1102	16.8	60.8	1.8	356.4	49.0
2/6/2021	31.3	0.5	18.1	0.3	4.8	31.6	1.4	13:24	1093	17.1	48.5	1.4	350.3	52.3
12/6/2021	33.3	0.5	20.9	0.2	5.2	32.9	1.5	12:51	1098	16.2	56.0	3.0	251.3	45.4
26/6/2021	33.1	0.5	21.1	0.2	4.8	31.3	1.3	13:06	1104	18.6	48.7	3.2	315.1	44.7
11/7/2021	32.1	0.5	17.1	0.3	4.7	32.0	1.4	13:32	1072	20.7	56.0	3.9	80.4	47.6
18/7/2021	31.3	0.5	18.8	0.2	4.6	32.1	1.4	13:18	1059	29.8	36.0	2.1	163.8	54.4
28/7/2021	31.3	0.4	17.8	0.2	4.1	31.5	1.2	13:48	1045	24.9	54.4	3.1	298.9	51.3
3/8/2021	31.4	0.4	18.4	0.2	4.2	31.1	1.3	13:19	1037	23.2	48.5	1.9	340.5	53.4
8/8/2021	31.5	0.4	17.5	0.2	4.3	32.3	1.4	13:17	989	30.1	30.6	2.2	32.8	62.8



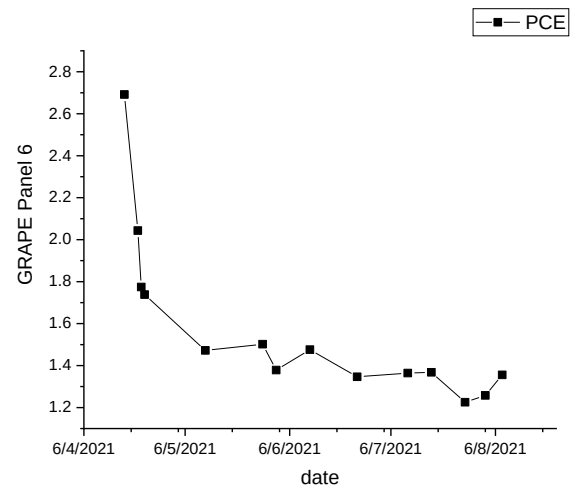
a)



b)



c)

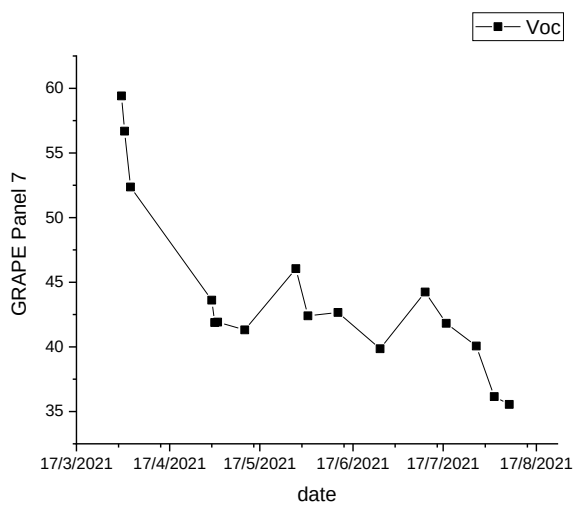


d)

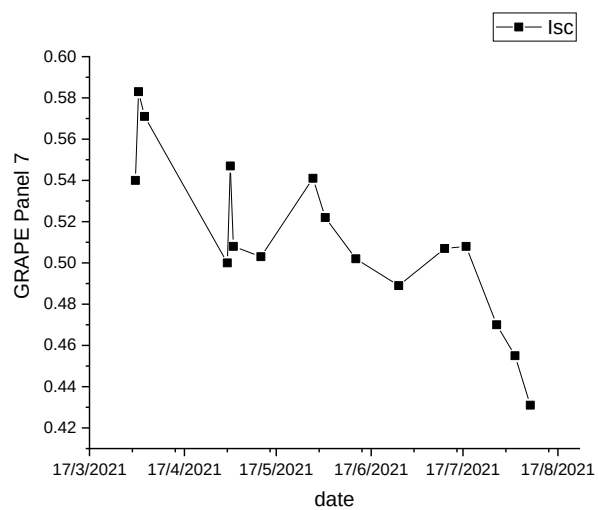
Εικόνα 25 The change of the electrical characteristics of the GRAPE panel 6 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

Panel 7

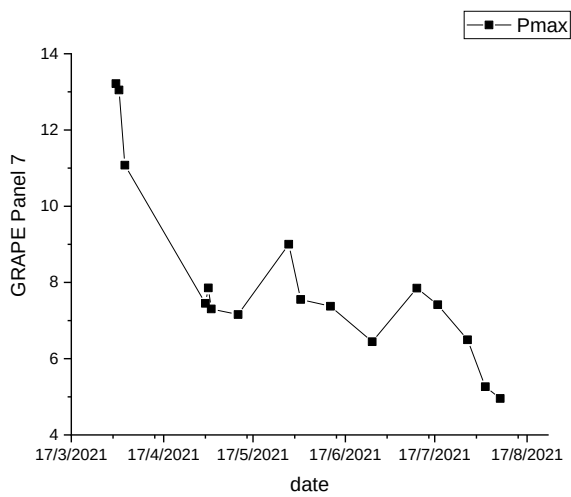
date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Panel
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m2)	(°C)	(%)	(m/s)	deg	(°C)
1/4/2021	59.4	0.54	37.33	0.35	13.2	41.2	4.06	11:00	1018.05	21.2	41.4	4.2	212.5	39.6
2/4/2021	56.7	0.58	36.15	0.36	13.1	39.5	4.15	13:58	982.00	18.2	67.1	1.4	333.1	47.7
4/4/2021	52.4	0.57	31.38	0.35	11.1	37.0	3.46	12:58	999.00	17.9	67.5	1.3	6.9	47.7
1/5/2021	43.6	0.50	25.88	0.29	7.5	34.2	2.17	13:58	1073.00	14.2	48.2	3.4	303.0	40.5
2/5/2021	41.9	0.55	26.91	0.29	7.9	34.3	2.09	12:53	1176.00	13.1	51.4	3.8	261.4	32.2
3/5/2021	41.9	0.51	23.80	0.31	7.3	34.3	2.11	11:57	1084.00	13.4	54.0	5.4	344.9	32.9
12/5/2021	41.3	0.50	26.22	0.27	7.2	34.4	2.03	12:03	1102.00	13.3	52.7	3.0	303.3	43.1
29/5/2021	46.0	0.54	26.95	0.33	9.0	36.1	2.56	13:13	1100.00	16.9	60.4	2.8	30.8	48.7
2/6/2021	42.4	0.52	26.05	0.29	7.6	34.1	2.15	13:25	1096.00	17.2	48.4	1.4	27.3	52.5
12/6/2021	42.7	0.50	24.43	0.30	7.4	34.4	2.10	12:50	1099.00	16.4	55.3	3.2	324.9	45.2
26/6/2021	39.8	0.49	22.94	0.28	6.4	33.1	1.83	13:03	1099.00	18.8	53.2	3.2	58.2	43.7
11/7/2021	44.2	0.51	27.07	0.29	7.9	35.0	2.29	13:31	1072.00	20.6	55.4	3.7	29.9	47.6
18/7/2021	41.8	0.51	24.97	0.30	7.4	34.9	2.19	13:16	1057.00	30.0	34.5	2.5	29.0	57.3
28/7/2021	40.1	0.47	23.04	0.28	6.5	34.5	1.94	13:48	1045.00	24.9	54.4	3.1	298.9	51.3
3/8/2021	36.2	0.46	21.23	0.25	5.3	32.0	1.59	13:22	1035.00	22.7	51.2	1.9	317.8	53.7
8/8/2021	35.5	0.43	20.40	0.24	5.0	32.4	1.57	13:19	986.00	30.1	30.6	2.4	13.9	62.5



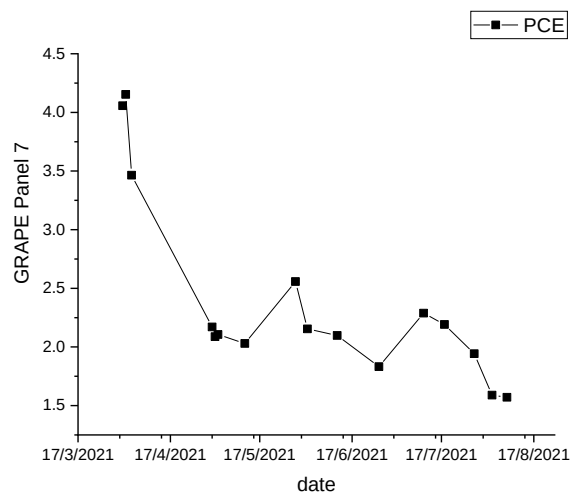
a)



b)



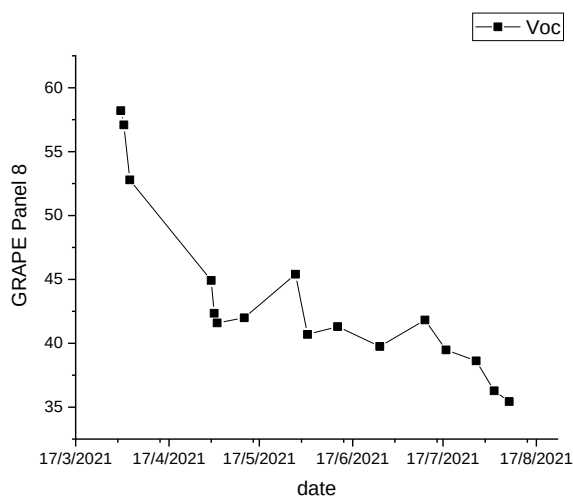
c)



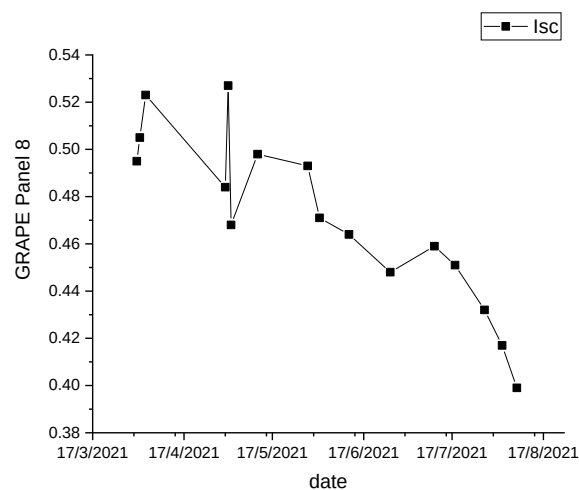
d)

Εικόνα 26 The change of the electrical characteristics of the GRAPE panel 7 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

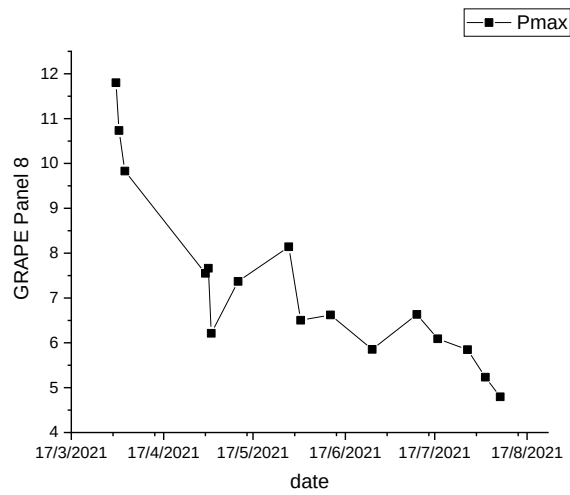
date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Panel
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m2)	(°C)	(%)	(m/s)	deg	(°C)
1/4/2021	58.2	0.50	39.60	0.30	11.8	41.0	3.5	11:02	1042.2	21.1	41.0	5.0	159.8	38.3
2/4/2021	57.1	0.51	31.48	0.34	10.7	37.2	3.6	14:03	944.0	18.2	68.1	1.4	7.9	43.7
4/4/2021	52.8	0.52	32.12	0.31	9.8	35.6	3.1	13:02	997.0	18.3	66.0	1.5	16.8	46.0
1/5/2021	44.9	0.48	27.26	0.28	7.5	34.7	2.2	14:02	1088.0	14.1	49.1	3.1	349.9	38.1
2/5/2021	42.3	0.53	26.98	0.28	7.7	34.3	2.1	12:04	1165.0	12.8	55.9	3.9	32.0	25.1
3/5/2021	41.6	0.47	24.75	0.25	6.2	31.9	1.8	12:02	1069.0	13.5	55.0	4.8	33.5	32.1
12/5/2021	42.0	0.50	26.04	0.28	7.4	35.2	2.1	12:04	1104.0	13.3	53.1	2.8	26.5	43.7
29/5/2021	45.4	0.49	27.88	0.29	8.1	36.4	2.3	13:13	1100.0	16.9	60.4	2.8	30.8	48.7
2/6/2021	40.7	0.47	23.82	0.27	6.5	33.9	1.9	13:26	1097.0	17.2	49.3	1.9	303.4	52.7
12/6/2021	41.3	0.46	26.92	0.25	6.6	34.6	1.9	12:50	1099.0	16.4	55.3	3.2	324.9	45.2
26/6/2021	39.7	0.45	21.21	0.28	5.9	32.9	1.7	13:02	1098.0	18.8	53.2	3.2	2.4	43.8
11/7/2021	41.8	0.46	26.86	0.25	6.6	34.6	1.9	13:28	1075.0	20.7	56.3	4.0	314.4	47.8
18/7/2021	39.5	0.45	23.33	0.26	6.1	34.2	1.8	13:15	1056.0	30.0	35.1	2.2	347.3	56.6
28/7/2021	38.6	0.43	22.93	0.26	5.8	35.1	1.7	13:49	1047.0	24.9	53.3	3.0	311.3	50.8
3/8/2021	36.3	0.42	21.45	0.24	5.2	34.6	1.6	13:20	1041.0	23.2	48.6	2.1	302.0	53.6
8/8/2021	35.4	0.40	22.63	0.21	4.8	33.9	1.5	13:20	983.0	30.0	31.5	1.5	339.7	62.8



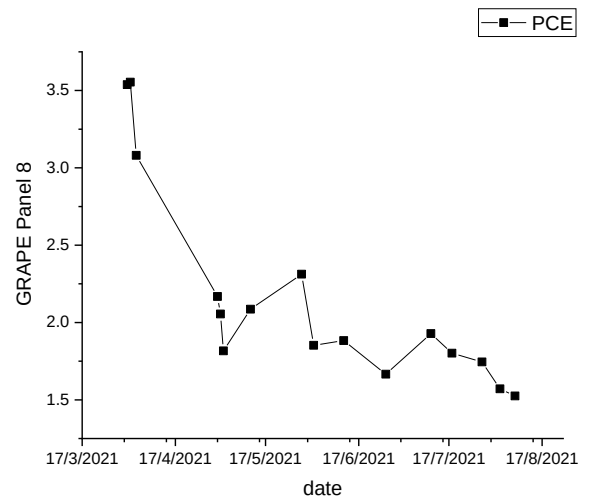
a)



b)



c)

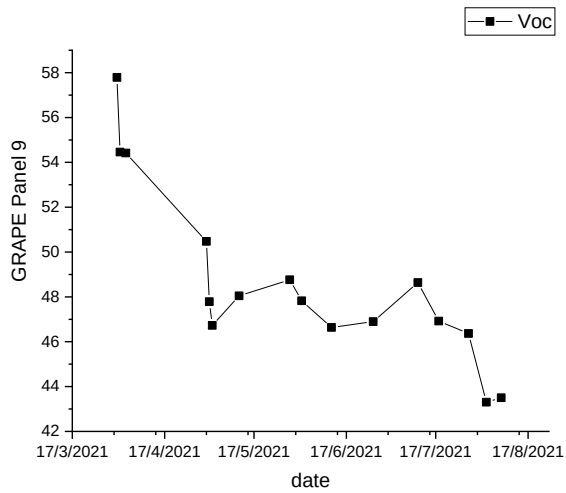


d)

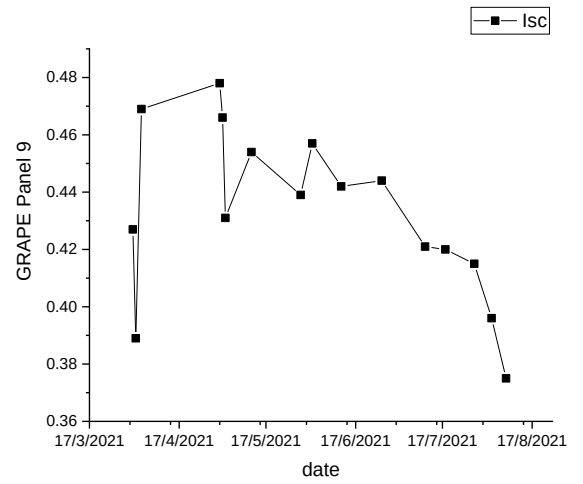
Εικόνα 27 The change of the electrical characteristics of the GRAPE panel 8 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

Panel 9

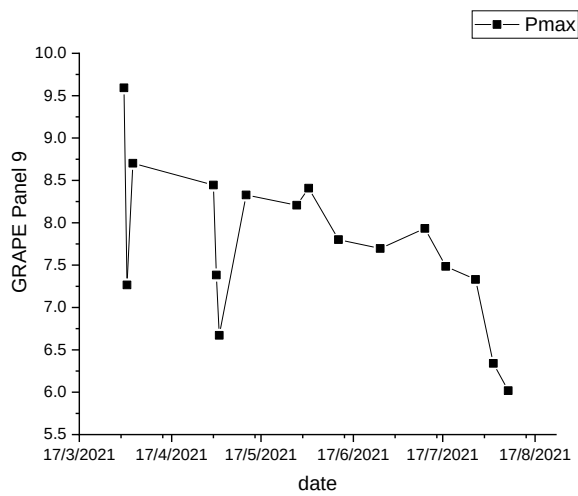
date	Voc	Isc	Vmax	Imax	Pmax	FF	PCE	Time	Irradiance	Tair	RH	WS	WD	Temp_Panel
	(V)	(A)	(V)	(A)	(W)	(%)	(%)		(W/m2)	(°C)	(%)	(m/s)	deg	(°C)
1/4/2021	57.8	0.4	35.3	0.3	9.6	38.9	3.1	12:04	980	20.5	47.3	3.9	167.9	33.2
2/4/2021	54.5	0.4	32.2	0.2	7.3	34.3	2.4	14:04	927	18.2	67.3	1.8	61.8	42.9
4/4/2021	54.4	0.5	33.7	0.3	8.7	34.1	2.7	13:05	995	18.1	66.1	1.7	313.6	48.3
1/5/2021	50.5	0.5	33.9	0.2	8.4	35.0	2.7	14:04	982	14.1	49.4	2.9	26.0	39.4
2/5/2021	47.8	0.5	29.1	0.3	7.4	33.2	2.0	12:57	1161	13.5	48.4	4.6	345.5	35.0
3/5/2021	46.7	0.4	28.0	0.2	6.7	33.1	1.9	12:03	1070	13.5	55.2	4.5	5.7	35.8
12/5/2021	48.0	0.5	30.4	0.3	8.3	38.2	2.4	12:03	1102	13.3	52.7	3.0	303.3	43.1
29/5/2021	48.8	0.4	31.3	0.3	8.2	38.3	2.3	13:14	1105	16.8	60.2	2.7	307.8	48.7
2/6/2021	47.8	0.5	30.4	0.3	8.4	38.5	2.4	13:26	1097	17.2	49.3	1.9	303.4	52.7
12/6/2021	46.6	0.4	30.7	0.3	7.8	37.8	2.2	12:51	1098	16.2	56.0	3.0	251.3	45.4
26/6/2021	46.9	0.4	29.7	0.3	7.7	37.0	2.2	13:02	1098	18.8	53.2	3.2	2.4	43.8
11/7/2021	48.6	0.4	29.7	0.3	7.9	38.7	2.3	13:31	1072	20.6	55.4	3.7	29.9	47.6
18/7/2021	46.9	0.4	29.4	0.3	7.5	38.0	2.2	13:19	1056	29.7	35.7	1.6	331.9	56.9
28/7/2021	46.4	0.4	29.7	0.2	7.3	38.1	2.2	13:46	1047	24.8	54.0	3.3	21.6	51.1
3/8/2021	43.3	0.4	26.6	0.2	6.3	37.0	1.9	13:21	1039	22.9	49.3	3.0	320.6	51.7
8/8/2021	43.5	0.4	27.5	0.2	6.0	36.9	1.9	13:15	981	30.0	31.1	1.3	317.9	63.1



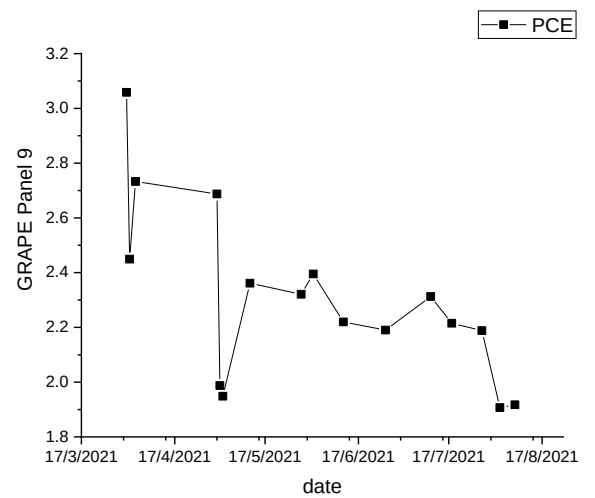
a)



b)



c)



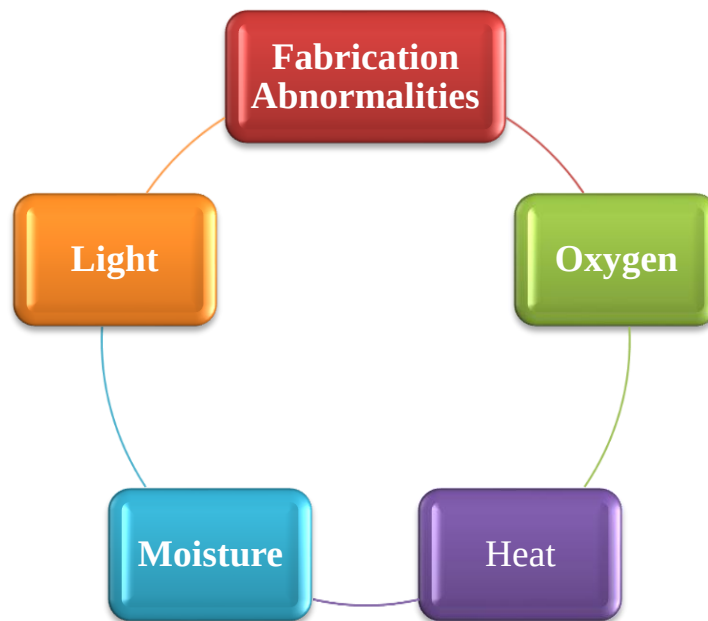
d)

Εικόνα 28 The change of the electrical characteristics of the GRAPE panel 9 with respect to the period of measurements a)Voc, b)Isc, c)Pmax, d)PCE

5.Degradation for GRAPE panels

Many research articles have been published highlighting different aspects of the stability related issues of perovskite solar cells.

The most common degradation factors are:



From those factors, the ones dependent on fabrication can be limited by improving our fabrication environment.

Degradation Mechanisms commonly met due to fabrication environment:

- Abnormalities in morphologies of layer or interfaces due to deposition
- Contamination through remaining molecules from fabrication ^[21]

HEAT DEGRADATION

Operating temperatures of solar panels can vary from -20 up to >85 °C depending on where they are located. The most important concern with regards to thermal stability is the chance of thermal decomposition

It is well known that when heated to or above 85 °C, a temperature approximately equal to that attained during normal operation in full sunlight, the performance deteriorates rapidly, and that this instability is aggravated by

the action of moisture. Changes occur in both the organic and inorganic components of the cells.

Not much work has been done to understand the impact of high operating temperatures on PSC performance. It is important to note that degradation in complete PSC devices is more complicated than degradation of the perovskite absorption layer, possibly due to multiple degradation pathways. Clarification of these issues is of paramount importance and a clear understanding of the degradation mechanism is necessary to improve the long-term thermal stability of PSC.^[29].

OXYGEN INDUCED DEGRADATION

Of the external factors that affect semiconductor performance, oxygen and moisture are among the most damaging. All PV technologies deployed to date suffer from degradation in the presence of these two ubiquitous stressors, which can oxidize and dissolve many of the functional components in solar cells.

Any deployed solar cell will benefit from thorough encapsulation, usually in the form of a laminated plastic/glass or glass/glass package. Nevertheless, improving the intrinsic stability of non-encapsulated solar cells is a first step in relaxing the encapsulation requirements for perovskite solar cells and ensuring that the encapsulation used for commercial crystalline Si and thin film PV is also adequate for perovskite solar cells.

One advantage of perovskite solar cells is that they can be made into flexible PV modules. Here, thorough encapsulation is more difficult, and the best atmospheric barrier layers can be prohibitively expensive. Again, the more stable the unencapsulated solar cell, the less stringent the requirements for encapsulation, making flexible perovskite modules possible.^[26].

MOISTURE INDUCED DEGRADATION

While oxygen decomposes perovskite only when exposed to light, exposure to moisture causes perovskite to decompose rapidly even in the dark. This was one of the first degradation pathways to be investigated, and much work has gone into elucidating the degradation mechanism of MAPbI₃ in the presence of moisture, as well as the synergistic effects of moisture, heat, and

electrical bias.

Essentially, water can penetrate the perovskite lattice and form hydrated perovskite phases in which the organic species can be readily mobilized and evolved, eventually leaving only lead iodide. The crystal structures derived for the hydrated phases show that although some hydrogen bonding may occur with the lead halide octahedra, by far the strongest interactions arise from hydrogen bonding with the organic methylammonium cation, forming cation-water cation chains. [26].

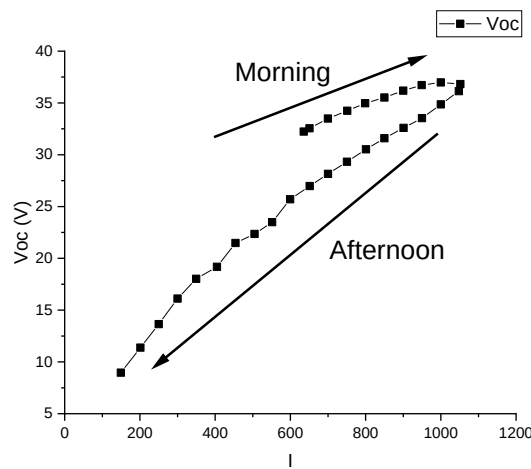
UV DEGRADATION

Perovskite solar cells typically use compact TiO₂, sometimes together with mesoporous TiO₂ layers, to transport electrons generated by light. TiO₂ is a popular photocatalyst that can catalyze the degradation of perovskite in the presence of UV radiation. A rapid decrease in photocurrent and PCE is observed for the PSCs exposed to UV compared to the PSCs protected from UV by an optical filter. The formation of deep traps at the oxygen vacancies of the surface was proposed as the main reason for the degradation. The degradation due to UV radiation is explained by the fact that TiO₂, as an n-type semiconductor, has many oxygen vacancies on the surface. These deep electron donating sites combine with oxygen adsorbed on the oxygen vacancies on the surfaces. Upon exposure to UV radiation, an electron-hole pair is formed in TiO₂. The hole in the valence band (VB) combines with the electron at the oxygen surface, leading to the desorption of O₂ and the formation of an oxygen vacancy. These oxygen vacancies act as trap states for photoinduced electrons generated in the perovskite layer. These trapped electrons recombine with holes from the hole transporting materials. The creation of the active trap sites is responsible for the degradation of the photocurrent in the solar cell. The rate of oxygen desorption is low and reversible. At the same time, the number of deep empty traps depends on the partial pressure of oxygen in the pores, and in the presence of oxygen there are fewer empty traps, hence in this case, oxygen serves to pacify these electron trap sites on TiO₂ surfaces^[28].

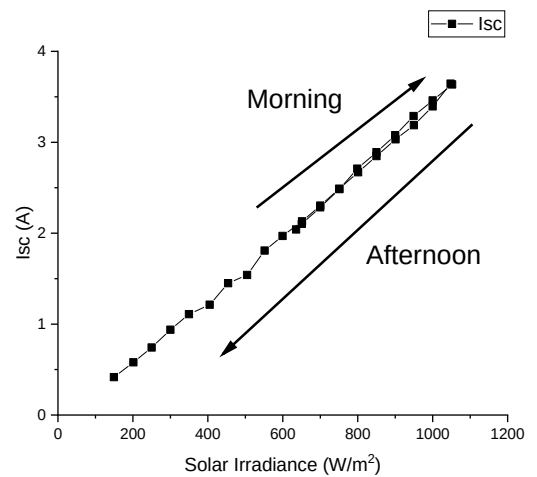
Besides, the limited ultraviolet (UV) light absorption of TiO₂ ETLs makes the perovskite structure easy to degradation under long-term illumination, which significantly destroys the photostability of PSCs^[27].

5.1. Degradation observed during day.

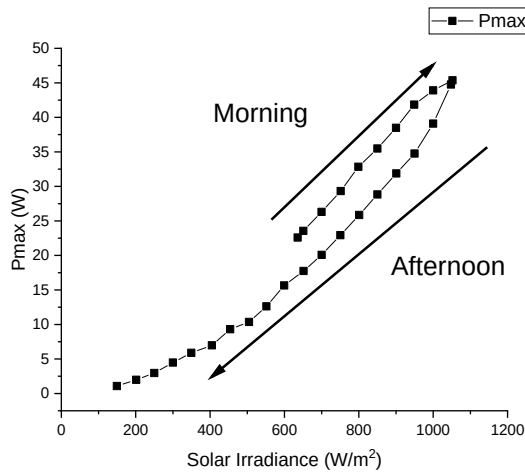
During the period that the GRAPE photovoltaic panels were studied, a degradation was observed in their electrical characteristics. In the following chapters will be examined the parameters to which this degradation is due as well as the factor that causes it.



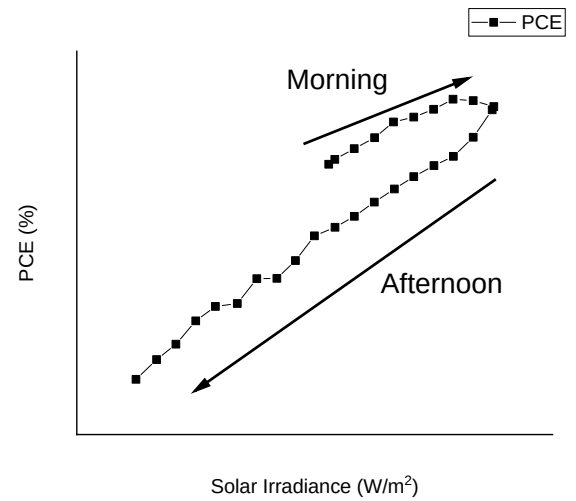
a)



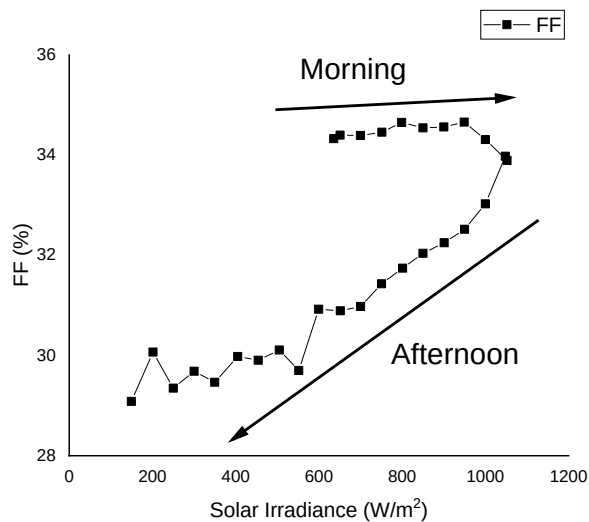
b)



c)



d)



The graphs above present the change in the electrical characteristics of GRAPE photovoltaics in measurements taken during a day. The characterization measurements were taken at each change of solar radiation by 50 W/m^2 so that the alteration they present in relation to it can be observed.

It is evident from the above diagrams that, as the day progresses, the values from the morning to the peak of irradiance differ markedly from those in the afternoon

These changes mainly affect the open circuit voltage, which decreases significantly for the same irradiance values in the afternoon compared to the values in the morning.

The decrease observed in the V_{oc} had a direct impact on the reduction of the

FF and consequently on the overall performance in terms of PCE of the modules.

It is important to mention that the short-circuit current (I_{sc}) shows an identical behavior as well as a linear dependence on it both in the morning and in the afternoon for the same values of solar irradiance.

Therefore, we can easily conclude that the solar irradiation causes in the photovoltaic panels of the GRAPE technology panels due to continuous irradiance exposure explained in degradation chapter.

5.2. Open circuit Voltage dependence of Irradiance

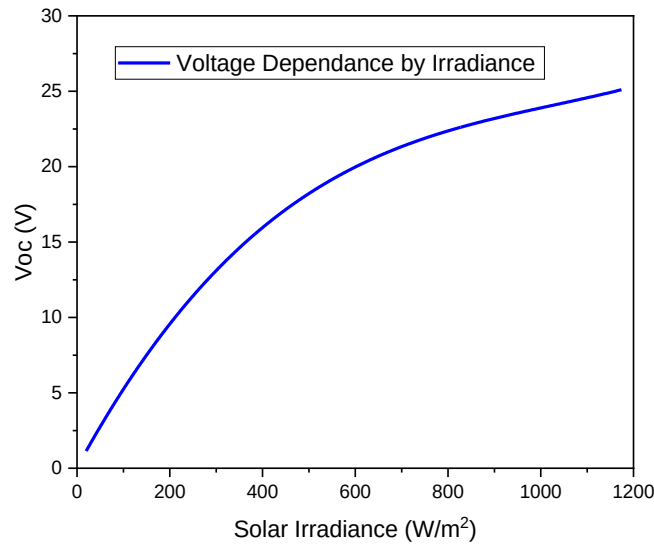
Another feature that distinguishes these photovoltaic systems from those of other technologies is the dependence of the open circuit voltage on solar irradiance.

During the characterization measurements during the day, a behavior before the open circuit voltage was observed that is different from other technologies. While for conventional technologies it is known that the open circuit voltage has a logarithmic variation with respect to the solar irradiance, GRAPE photovoltaic is much more dependent on it, especially at low irradiance values.

To further investigate this behavior, experiments were conducted under cloudy sky so that the solar irradiance remains at a low level.

During the experiment, the values of V_{oc} were continuously measured and recorded so that this behavior is evident.

As can be seen in the graph below, the open circuit voltage shows an almost linear variation, especially at low irradiation values ($\sim 400 \text{ W / m}^2$)



5.3 Visual display of GRAPEs solar panels degradation

The easiest way to observe degradation is the visual change they show over time. This chapter presents photographs that show visual defects that either existed from the beginning due to Fabrication Abnormalities or were created during the measurements due to the factors mentioned earlier.

Upon receipt of the panels all the cells were dark in color while during the period studied there was a gradual change in the color of some cells for various reasons.

On the cells of the panels there are various forms of discoloration that indicate that degradation has occurred such as :

Red circles that show the moisture inside the modules,

Orange circles shows the discoloration of the perovskite

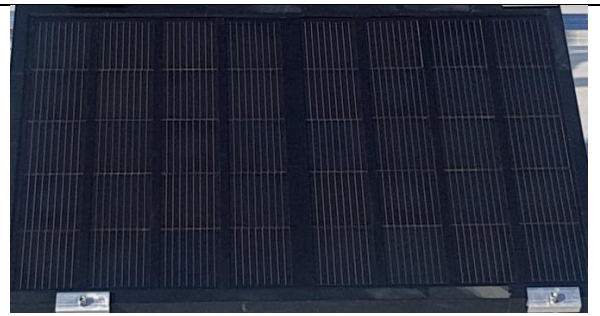
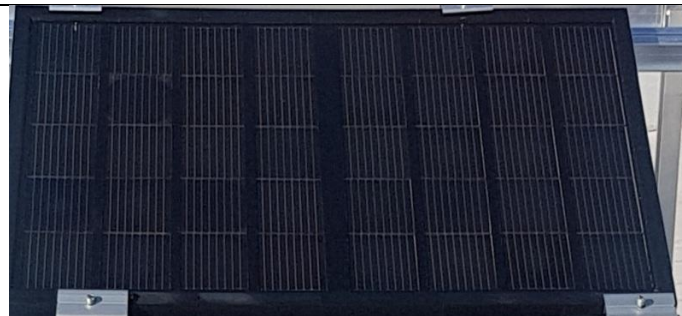
Yellow circles shows the relaxation of the lamination between modules

Blue circles shows morphological defects of the cells

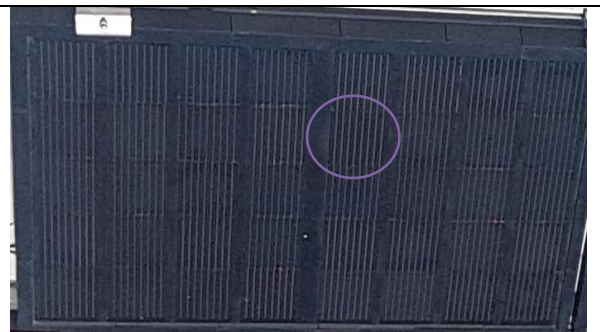
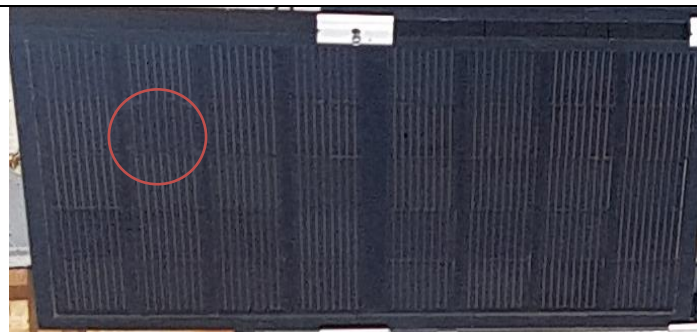
All these optical defects can explain the failure of the lamination process and the rapid degradation in months 9 to 12 of operation.

It is important to note that this color change was observed at different rates in each panel, which is due to the different series of experiments and the possible difficulties in accurately repeating the construction process. This also contributes to the observation of the different rate at which the electrical properties of each panel presented earlier. the panels that present these signs to a greater extent are also those in which more stressful experiments were performed because they were exposed to environmental conditions for a longer period of time.

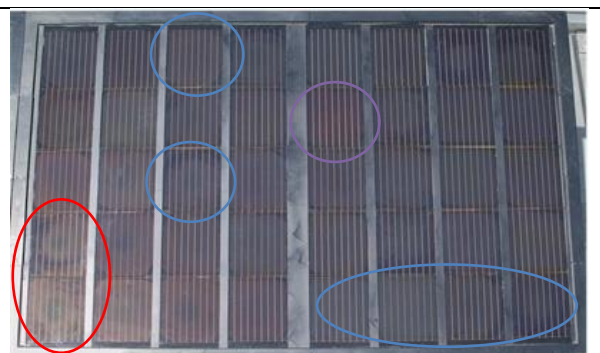
10 - 06 - 2020 GRAPE Panels no 1 & no 2



01 - 03 - 2021 GRAPE Panels no 1 & no 2



29 - 03 - 2021 GRAPE Panels no 1 & no 2



10 - 06 - 2021 GRAPE Panels no 1 & no 2

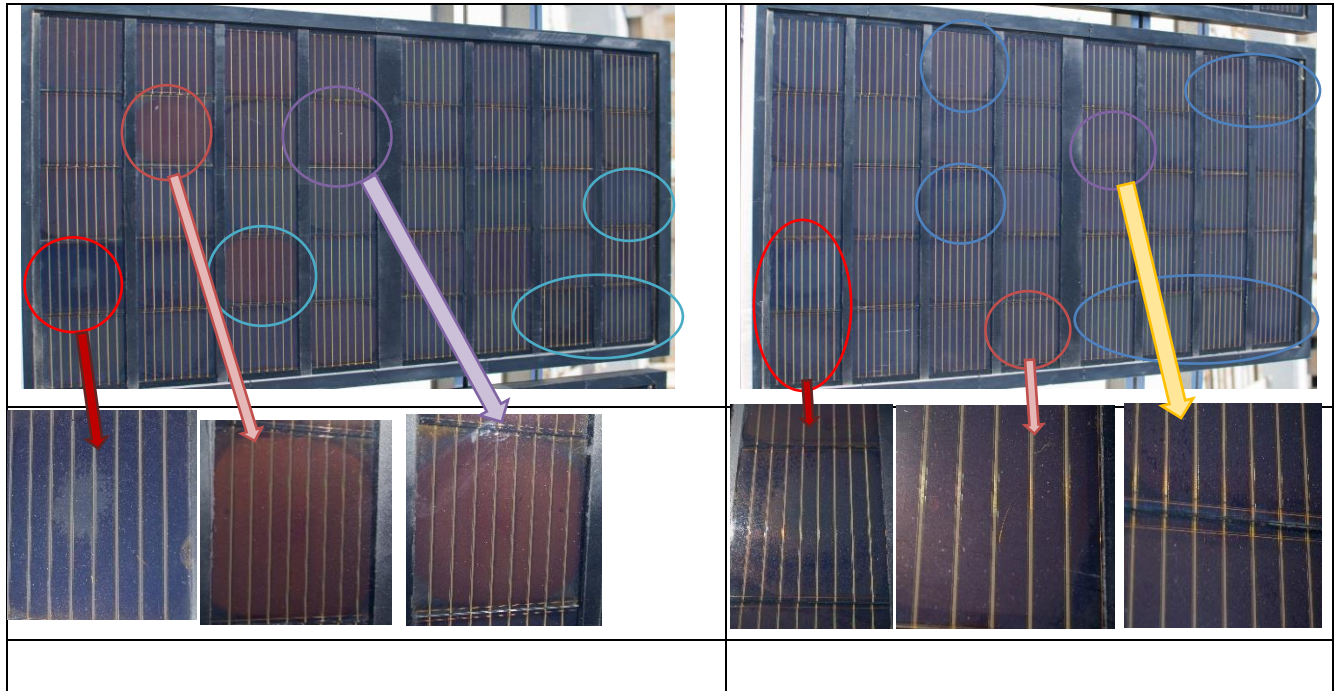
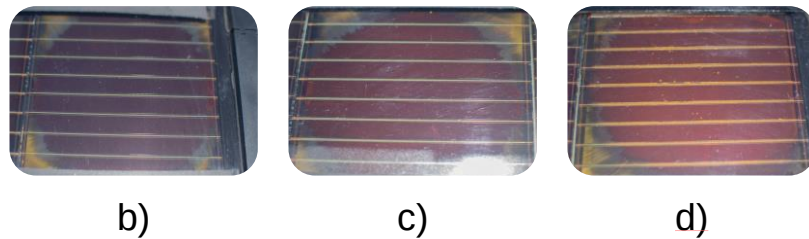


Figure. a) to d) Photo of GRAPE panels no1 & 2 in different timing periods a) in 10 - 06 – 2020, c) in 01 - 03 – 2021, c) in 29 - 03 – 2021, d) 10 - 06 – 2021.

GRAPE panel #3 was one of the panels which was submitted to many sets of measurements and it may not have had as good an encapsulation as the rest during its manufacturing process and that is why it presents very strongly these phenomena of discoloration.

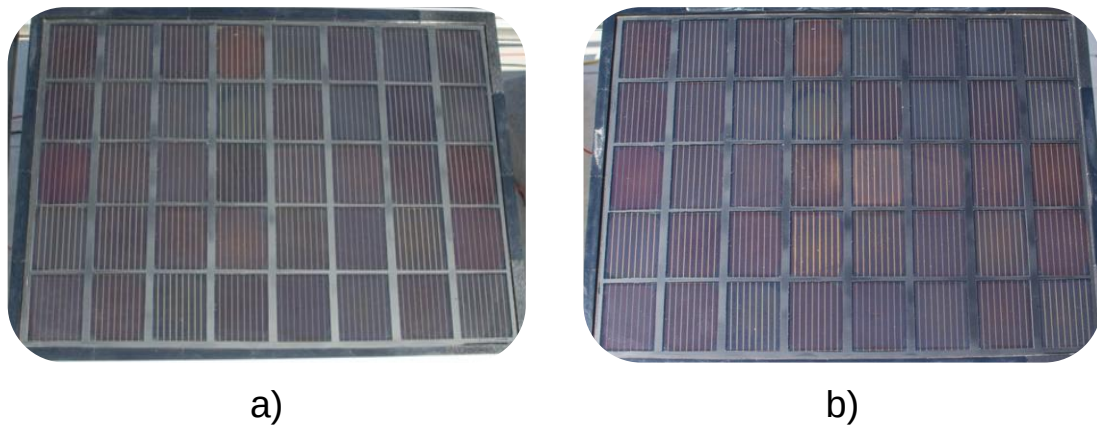


a)



Εικόνα 29 a) to d) visual display of degradation of GRAPE panel 3 a) and close up in the most affected cells b),c),d) in 24 - 08 – 2021

On the other hand panel #9 , although this too has suffered a discoloration, shows a sublime endurance through the time period of this research presenting less visible changes and a smaller reduction in PCE and electrical characteristics.



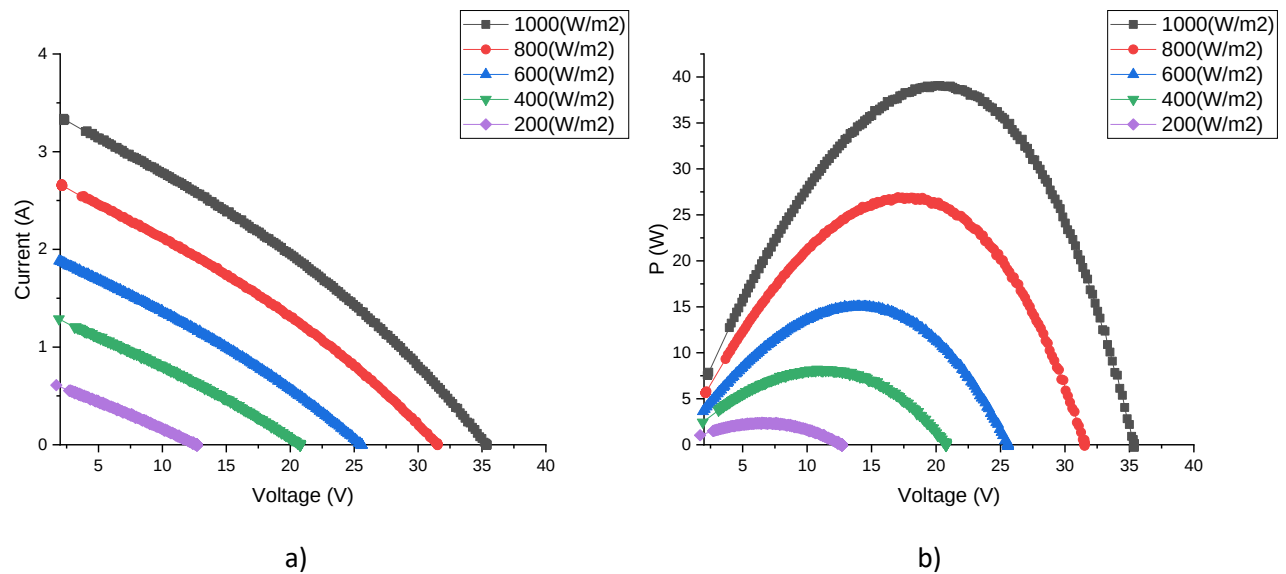
Εικόνα 30 visual display of degradation of GRAPE panel 9 a) 12-3-21 and b) 24 - 08 – 2021

6. I-V curves for different PV technologies (benchmarking)

This chapter will analyze the differences between GRAPE photovoltaics and other conventional photovoltaic technologies.

Characterization graphs are presented for each PV technology at different radiation (200,400,600,800,1000 W/m²) values so that differences can be observed through the method of benchmarking.

As it was mentioned in the previous chapter, GRAPE photovoltaics are highly dependent on solar radiation, something that is also evident from the graph [31]

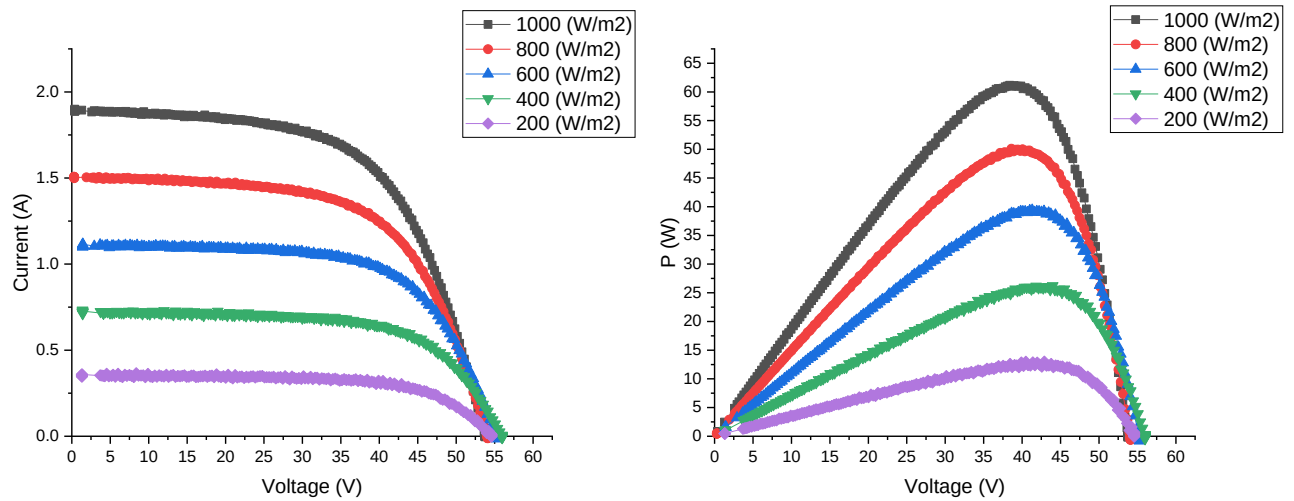


Εικόνα 31. I-V & P-V at different radiation values(200,400,600,800,1000 W/m²) for GRAPE PVs

6.1 CdTe

The CdTe PV panel that was used for the benchmarking purposes in this thesis is the FS-382 model of first solar. In the table below are presented its electrical characteristics based on the datasheet of the manufacturer in STC conditions .

Nominal Power(+/-5%)	Pmpp(W)	82.5
Voltage at PMAX	Vmpp(V)	48.3
Current at PMAX	Impp(A)	1.71
Open Circuit Voltage	Voc (V)	60.8
Short Circuit Current	Isc(A)	1.94

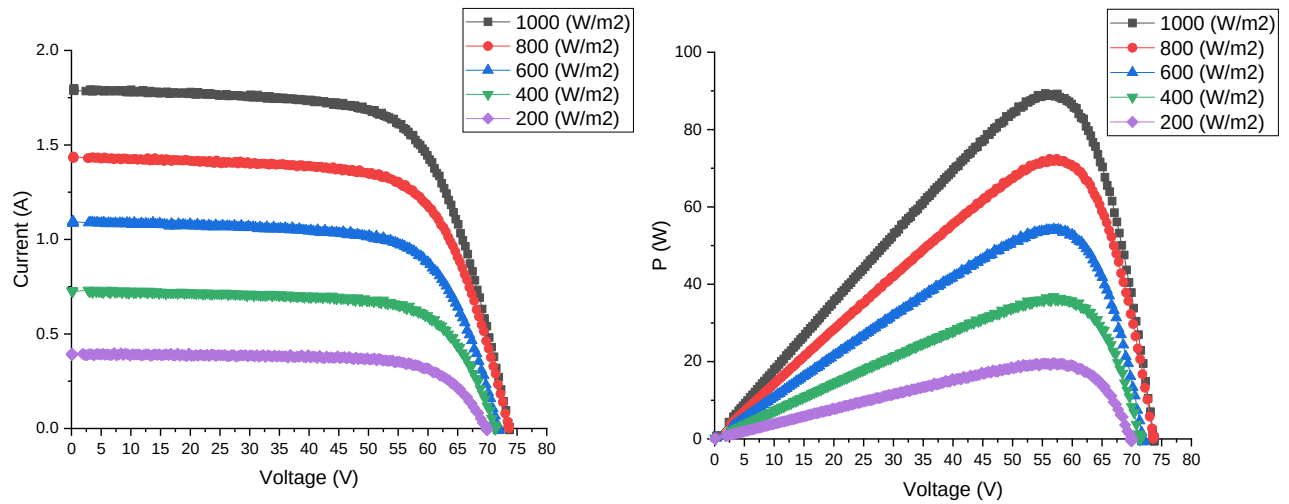


Εικόνα 32. I-V & P-V at different radiation values (200,400,600,800,1000 W/m²) for CdTe Panel

6.2 CIGS

The CiGs PV panel that was used for the benchmarking purposes in this thesis is the CdF -1000E1 model of solartech Power. In the table below are presented its electrical characteristics based on the datasheet of the manufacturer in STC conditions .

Nominal Power(+/-5%)	Pmpp(W)	100
Voltage at PMAX	Vmpp(V)	54.6
Current at PMAX	Impp(A)	1.83
Open Circuit Voltage	Voc (V)	73
Short Circuit Current	Isc(A)	2.1

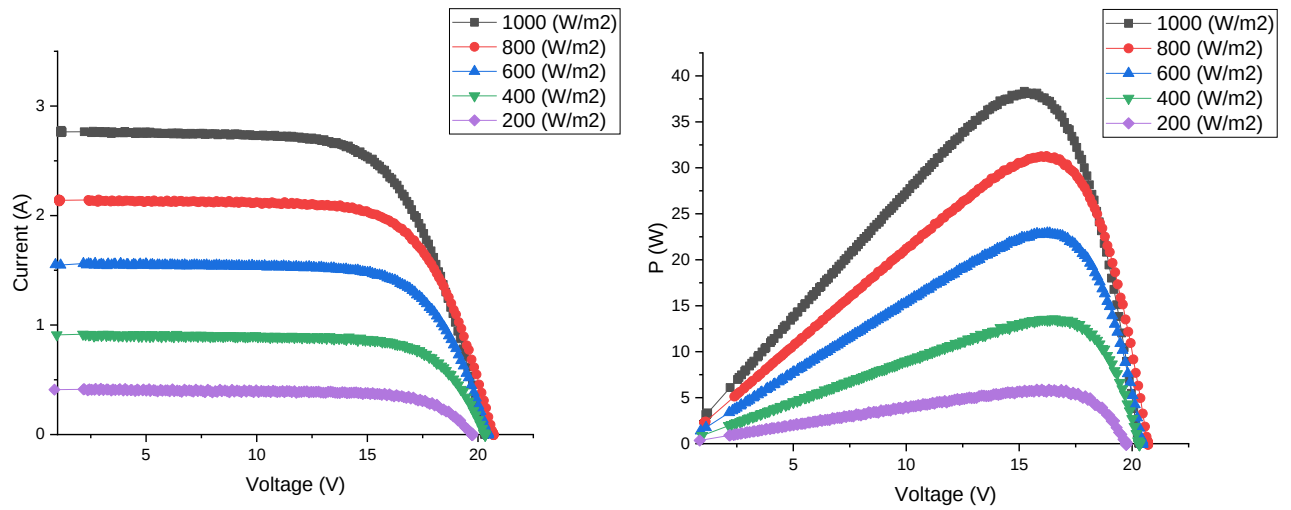


Εικόνα 33. I-V & P-V at different radiation values (200,400,600,800,1000 W/m²) for CIGS Panel

6.3 Polycrystalline Silicon

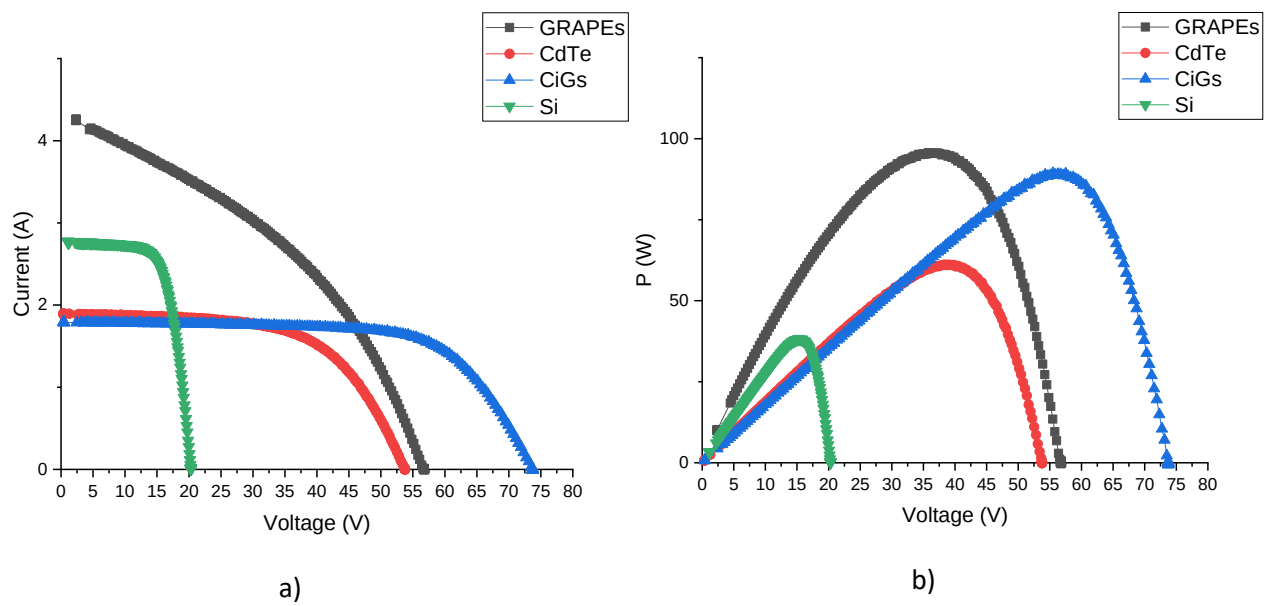
The Polycrystalline Silicon PV panel that was used for the benchmarking purposes in this thesis is the LX - 50P/156 x 52-36 model of Luxor. In the table below are presented its electrical characteristics based on the datasheet of the manufacturer in STC conditions .

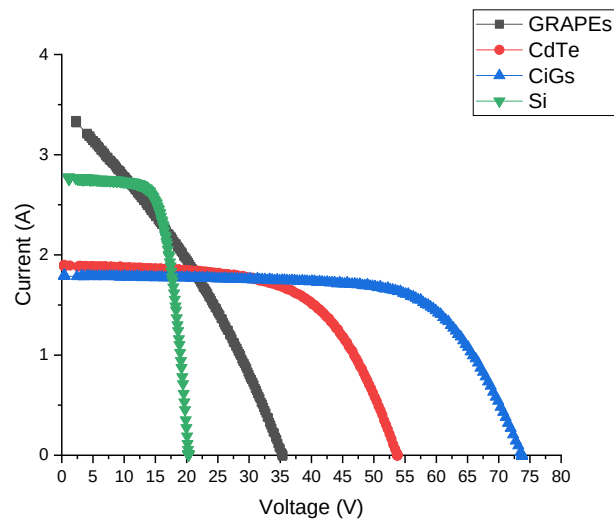
Nominal Power(+/-5%)	Pmpp(W)	50
Voltage at PMAX	Vmpp(V)	17.44
Current at PMAX	Ippp(A)	2.88
Open Circuit Voltage	Voc (V)	21.6
Short Circuit Current	Isc(A)	3.24



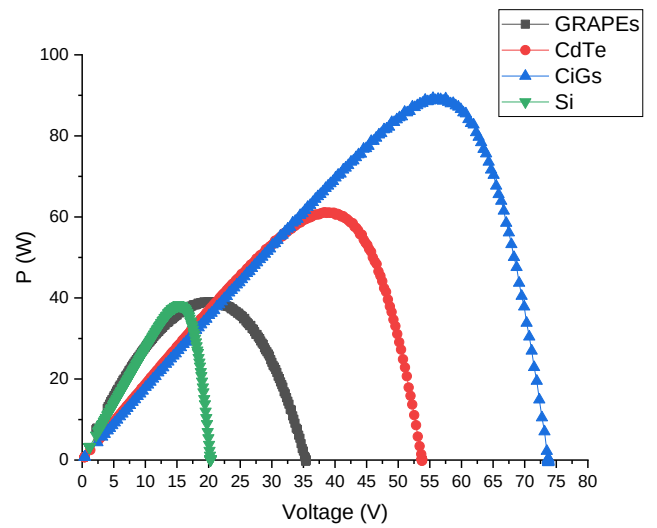
Εικόνα 34. I-V & P-V at different radiation values (200,400,600,800,1000 W/m²) for Si Panel

6.4 Benchmarking at 1000 watt/m²

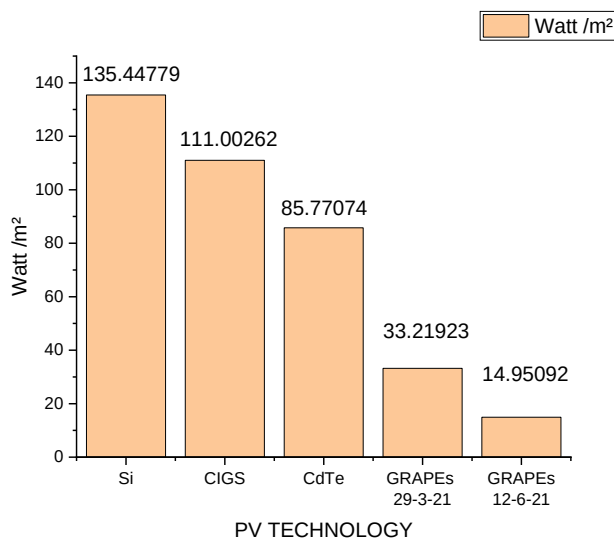




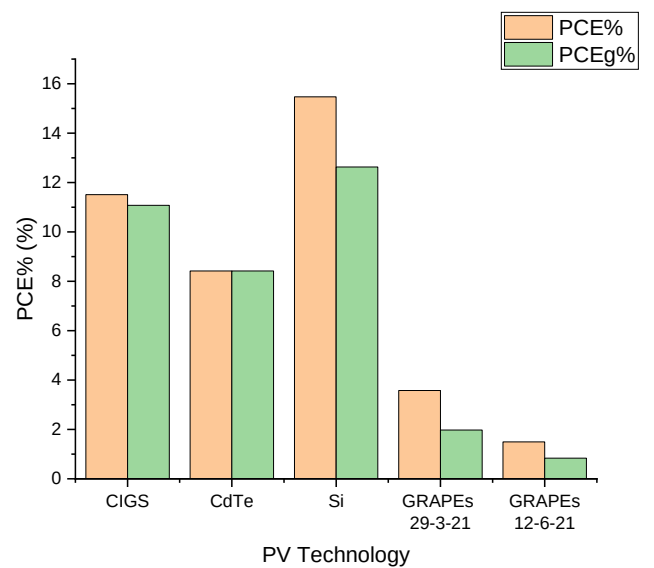
c)



d)



e)



f)

Εικόνα 35. I-V & P-V Benchmarking at 1000 watt/m² between different PV technologies a)-b)29-3-21 c)-d)12-6-21,e)maximum power produced per m² for each PV technology f)comparison between active(PCE%) and geometrical (PCEg%)area PCEs of each PV Technology

7. Capacitance measurements for GRAPEs

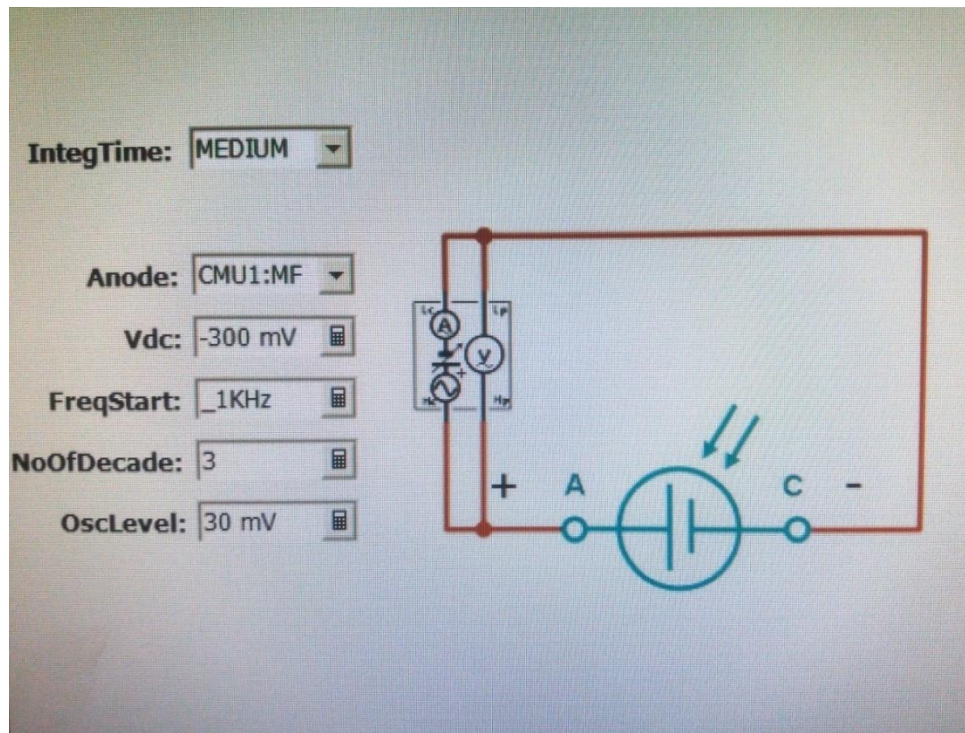
To understand the performance degradation as a function of temperature, electrochemical impedance spectroscopy (EIS) measurements were carried out to study the interfacial charge transport dynamics under variable frequencies (equipment available range is between 1kHz and 200kHz) and DC biases.

The B1520A port of the machine and the easyEXPERT software were used to extract the Nyquist curves.



This port has 4 outputs and can measure $\pm 25V$ Max, which is restrictive for measuring the capacity of the panels in the sun due to the much higher voltage value they are able to produce.

It is important to note that the machine has default values in terms of frequency, with a minimum starting frequency value of 1KHz and a maximum of 5 MHz which is restrictive for measuring capacity for frequencies below 1KHz.



Here is the wiring harness used to extract the Nyquist curves according to the machine instructions.

The High POT terminal along with the High CUR were connected to the positive end of the frame and respectively the LOW POT parallel to the LOW CUR were connected to the negative, as shown in the example in the picture.

The parameters used for the measurements are:

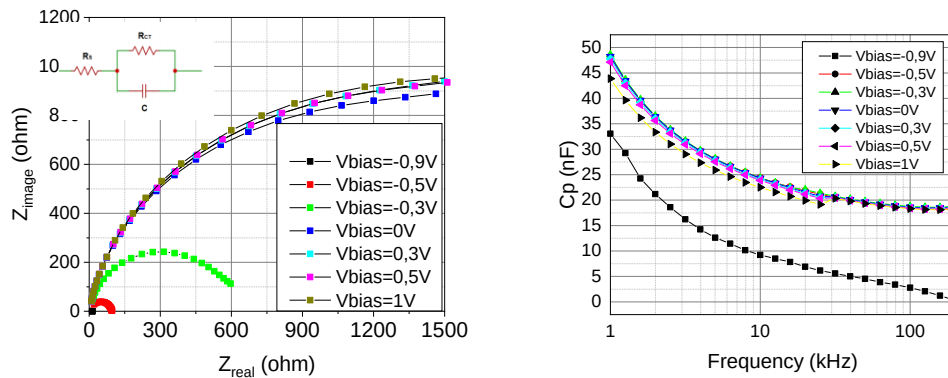
- Vdc: -300mV
- Initial frequency: 1KHz
- AC signal amplitude: 30 mV

This experiment was carried out with the aim of observing the change in the capacitive behavior of photovoltaics at different temperatures.

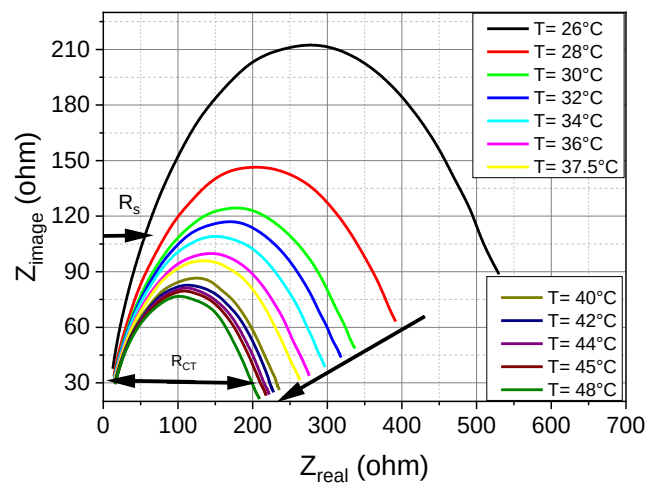
Initially the panel was placed in the sun to develop a temperature higher than 45 ° C and then repeated measurements per ~ 1 ° C were performed indoors in the shade as the temperature of the panel decreased.

As shown in **Fig.S15a & b**, for applied voltages (V_{bias}) less than -0.5 V, the bypass diodes of the panel are activated and a reverse electrical current pass through the device. Capacitance measurements versus frequency as depicted

in **Fig. S15b**, indicate an increasing capacitance value for decreasing frequency with maximum value reported at 1KHz. When the V_{bias} is equal to -0.3 V (green curves in **Fig. S15**), the semicircle radius decreases and reaches almost the axis of real part of the impedance (Z_{real}). According to this data, $V_{bias} = -0.3V$ was selected as the voltage condition to further investigate Nyquist plots depicted in **Fig. S16**. The Nyquist plots of the best panel (**Fig. S16**, panel No.7) under dark conditions reveal that the series resistance (R_s) (given by the intercept of the Nyquist plot on the real axis at high frequency) remains almost constant (12.5-15.7 ohm) over temperatures ranging from 26 to 48 °C, while the charge transfer resistance (R_{CT}) (given by the arc diameter) decreases (from 530 to 206 ohm) with increasing the temperature.



Εικόνα 36. a) Nyquist plots of a representative GRAPE panel (No 7) as a function of dc bias voltage (V_{bias}), ranging from -1V to 1V. Inset: the electrical equivalent circuit of the GRAPE panel that includes the series resistance (R_s) and the charge transfer resistance (R_{CT}) connected in parallel with a capacitor. b) Apparent capacitance, calculated as $\text{Im}(1/Z)/\omega$ of the panel as function of the frequency.



Εικόνα 37 Nyquist plots of a representative GRAPE panel (panel no. 7) at applied bias -0.3V and at different temperatures (from 26 to 48.5 °C)

Figs.S37 show the electrochemical impedance spectroscopy (EIS)spectra in the form of Nyquist and apparent capacitance versus frequency plots of a representative GRAPE panel at V_{bias} of -0.3 V and as a function of the temperature. The Nyquist plots measured at V_{bias} of -0.3V exhibit a similar arc shape(with variable radius) upon increasing temperatures, which indicates that the electronic properties of the investigated panels are stable under probed temperature ranges. The semicircle radius of the Nyquist plots monotonically decrease with increasing the temperature from 26 to 48.5 °C. Moreover, the resonance frequency shifts toward higher frequencies with increasing temperature. The observed shift suggests that there is a temperature-activated process that affects the performance of GRAPE panels.

8. Light soaking phenomenon

Another phenomenon that was observed was that of light soaking. As soon as the photovoltaic perovskite panels are exposed to sunlight this phenomenon occurs.

The light soaking effect is a drastic change in optical properties under illumination and is usually observed in hybrid perovskite materials. It should be resolved to achieve long-term operational stabilities in optoelectronic hybrid perovskite devices^[32]

It is well known that perovskite solar cells often exhibit light soaking effects and hysteresis phenomena under operating conditions: continuous illumination can gradually change the device performance The experimental studies have shown that the light soaking and hysteresis phenomena are related to the electrode interfaces in planar-heterojunction perovskite solar cells. In general, the light soaking and hysteresis effects can be attributed to the realignment of ferroelectric organic cations, polarization caused by lattice distortions, carrier trapping/interception, and ion migration in perovskite solar cells.

The light soaking phenomenon has been observed in perovskite solar cells with different device structures, which raises concerns about the instability of the power output of this type of solar cell. However, the severity of the light

soaking effect varies from laboratory to laboratory and has been the subject of intense discussions on the underlying mechanism. ^[31]

One of the proposed scenarios is the trap-filling/detrapping mechanism,^[33] in which the traps are filled under illumination. However, the long time scale observed in this process leads to controversial discussions about the location, properties of the trap states, and the role of light-generated charge carriers and mobile ions in the trap filling process.

The second scenario assumes some kind of doping mechanism in which the mobile ions drift to the opposite electrode under a photogenerated electric field, causing p- and n-doping at the anode and cathode, respectively.^[34] This last mechanism does not consider the role of traps in the light-soaking phenomenon. Moreover, the mobile species and their drift directions are controversial.

The third scenario proposed to explain the light-soaking effect considers variations in the crystal structure of the perovskite due to the alignment of the methylammonium cations under light and bias.^[35] However, it is difficult to draw conclusions from these studies due to the different device structures and perovskite morphology obtained in different research laboratories.^[31]

Moreover, optical measurements have revealed that carrier trapping (bulk trapping) can strongly affect the photoconductivity response and consequently generates photocurrent hysteresis phenomena. In addition, impedance and ultraviolet photoemission spectroscopy (UPS) studies suggest that energy level alignment and trap filling can also lead to "light soaking" behavior.^[30]

During this phenomenon changes in the electrical sizes of the panels were observed as well.

In order to examine the behavior of GRAPE photovoltaics during this phenomenon, the following experiments were performed:

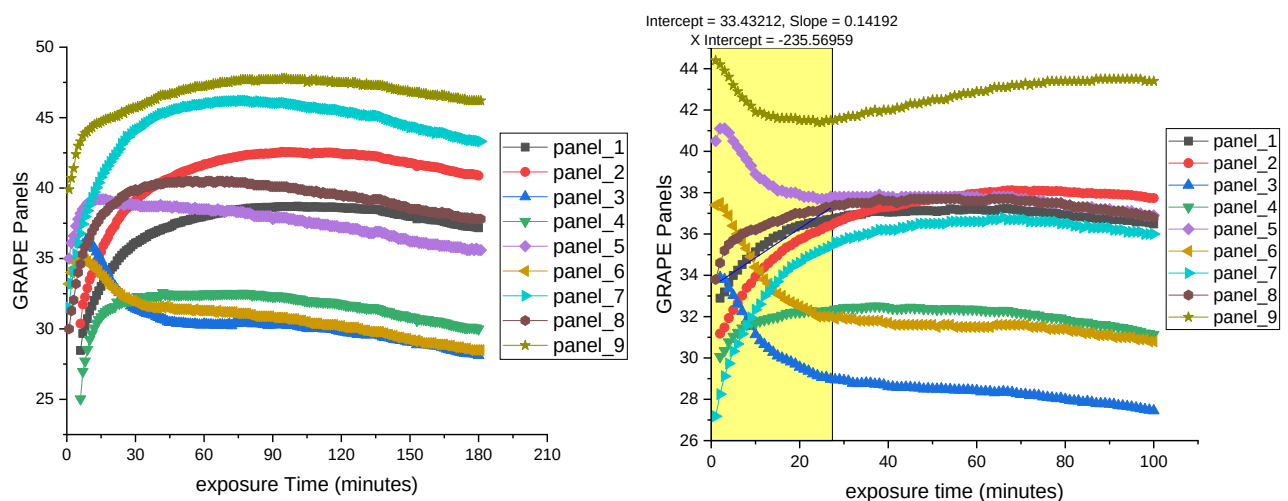
All panels were measured individually using multimeters at the same time so that the same environmental conditions apply to all of them during the experiment.

The panels were covered with aluminum foil to prevent exposure to light until the experiment began. Once the solar irradiance reached its peak, the aluminum foil was removed and Voc measurements were recorded at 1

minute intervals to observe the duration of the phenomenon as well as the changes in voltage.

The aim of these experiments were carried out at the time of peak solar irradiation was to obtain none or very little change in the irradiance parameter, which has already been reported to play an important role in changing the electrical characteristics of photovoltaic systems.

The goal of this experiment was to observe the changes in open circuit voltage in each panel separately and to record the time during which the phenomenon persists in GRAPE photovoltaics.



Εικόνα 38 light soaking experiments for Voc behavior observation performed a) 23-4-21 and b) 27-8-21

This experiment was performed twice at different time periods(a) 23-4-21 and b) 27-8-21), while the characterization measurements continued normally in between, to determine if and to what extent they are affected by them, but also if the degradation contributes to the change in the behavior of the panels during the light soak phenomenon.

Comparing the two sets of experiments, it was first noted that the nine panels can be classified into two behavioral scenarios based on the change in open circuit voltage.

In the first scenario, the open circuit voltage starts to increase as soon as they are exposed to direct sunlight until it reaches a level where it stabilizes.

In the second scenario, the open circuit voltage first increases and then begins to decrease until it reaches the level at which it stabilizes.

After a mean time of 45 minutes exposure the V_{oc} gradually decreases for most of the panels (apart from panel no3 ,no5 and no6 that have begun to degrade after 10 minutes). Extended light soaking effect cause light-activated degradation effects (suppressed V_{oc} and photocurrent) in the GRAPE panels and is one of the major factors in the degradation of the panels.

In the first scenario, panels **1,2,4,7,8,9** are classified and in the second, panels **3,5,6**. Accordingly, the behavior of the voltage change in the panels of the second scenario is presented in the panels that show the largest decrease in their PCE, which could be due to degradation caused by parameters other than solar irradiation, such as manufacturing defects or oxygen and moisture ingress due to lamination defects.

Between the two experiments, there is also a decrease in the maximum voltage values for all panels, which was expected due to the general decrease in the electrical characteristics of photovoltaics of this technology, analyzed in an earlier chapter.

9. Temperature coefficients for GRAPEs

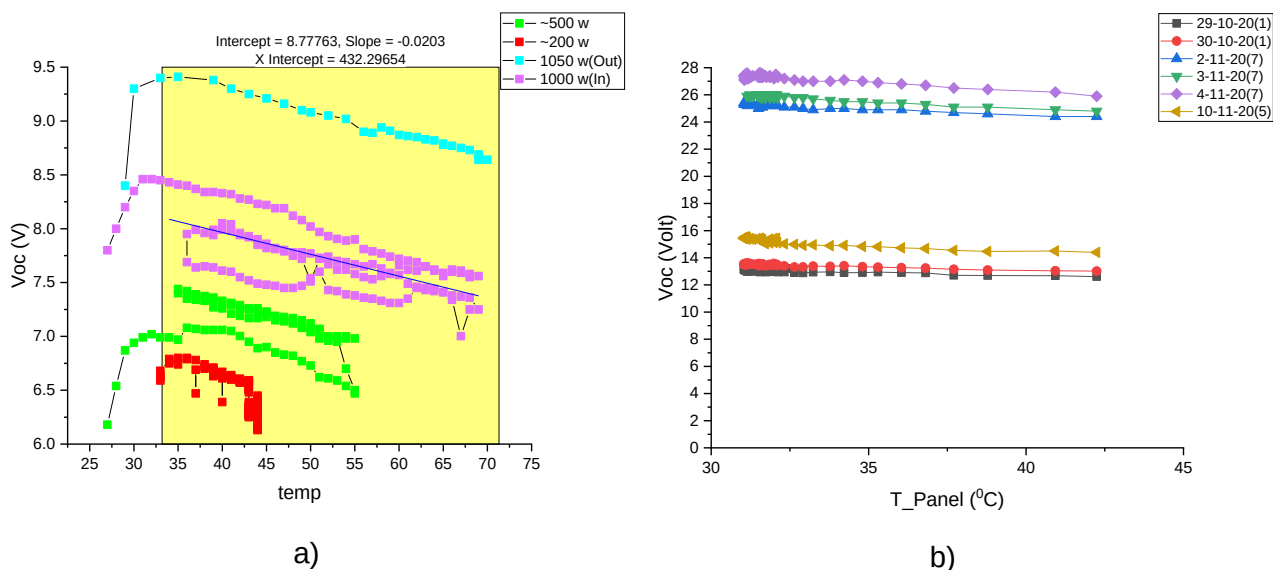
As it was earlier mentioned temperature is a major factor in the efficiency of solar cells and especially perovskite cells. it is thus necessary to study the rate at which these changes occur in this photovoltaic technology.

The methodology followed to investigate this behavior was as follows: the panel was placed opposite of the lamp setup ,so that the irradiance remains constant, in the dark room and a temperature sensor was placed on the back side of it. I-V characterization measurements were performed for each temperature change by 1 °C with the PV-blocks system. Afterwards data

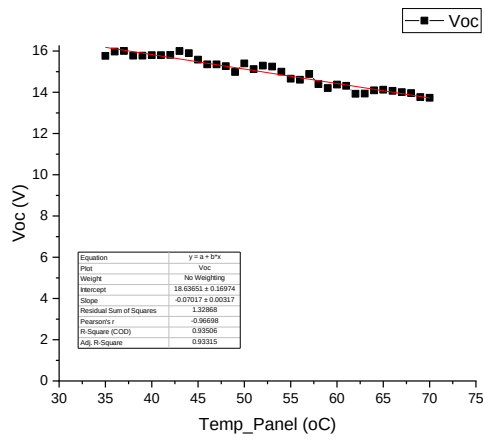
analysis was performed and each electrical characteristic was plotted with respect to the temperature change in Celsius degrees in a graph so that it can be fitted and determine its temperature coefficient. The irradiance that occur in the panel surface was determined with the 5 points system of non uniformity described in previous chapter. Finally the values were fitted with a linear fit so that the equation of the rate of change can be determined.

In the next sections are presented the results of these experiments and their temperature coefficients of all electrical characteristics of GRAPEs of different scale (panel #6 & #9, single & double module).

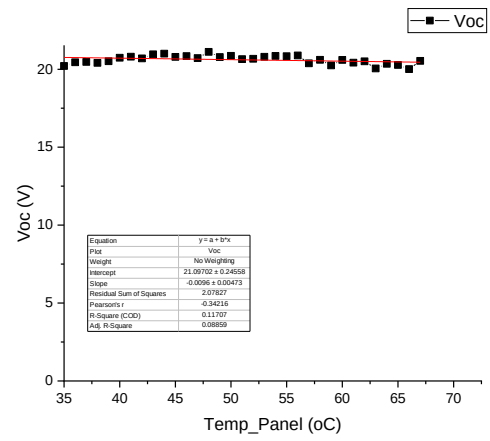
9.1 Voc



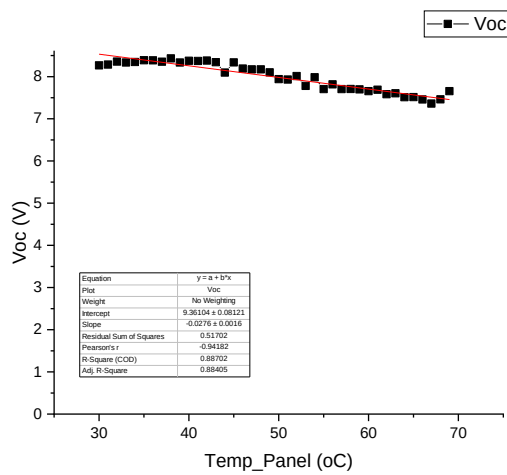
Εικόνα 39 a) The change of the open circuit voltage for the single module in radiations 200,500,1000 watts/m² for indoors and 1000 watts/m² outdoors conditions & b) The change of the open circuit voltage for the panels 1,5,7 in radiations 500 indoors



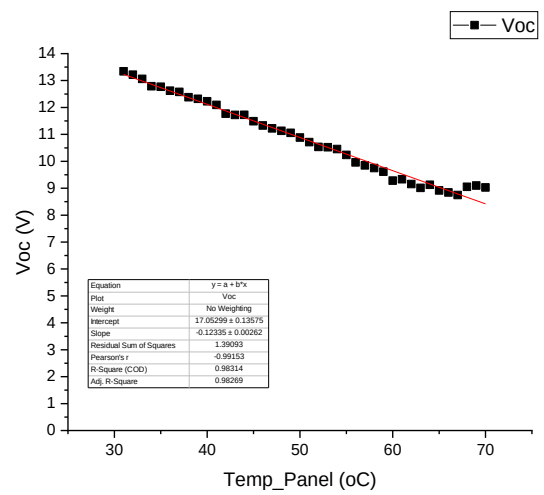
a)



b)



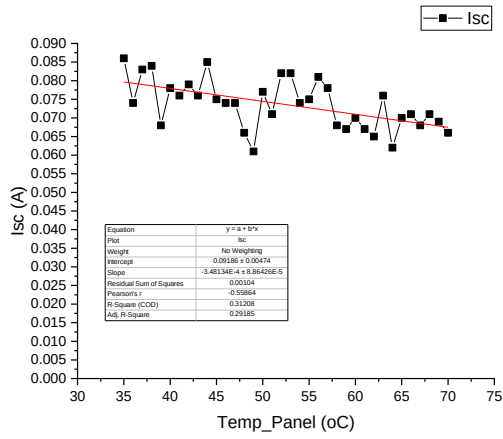
c)



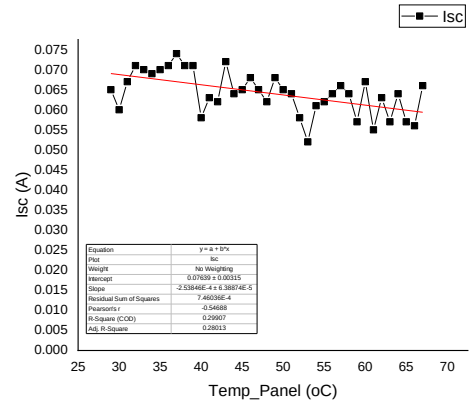
d)

Εικόνα 40 Temperature coefficient of Voc at ~540 Watt/m² irradiance for a) panel 6, b) panel 9 & at ~1000 Watt/m² irradiance for c) single module ,d) double module

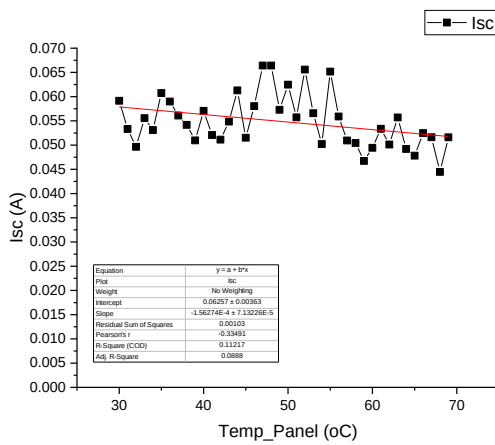
9.2 Isc



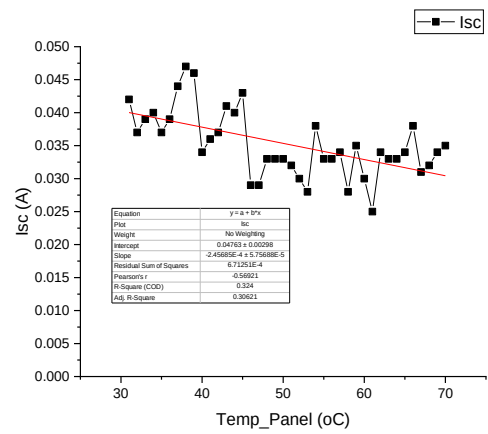
a)



b)



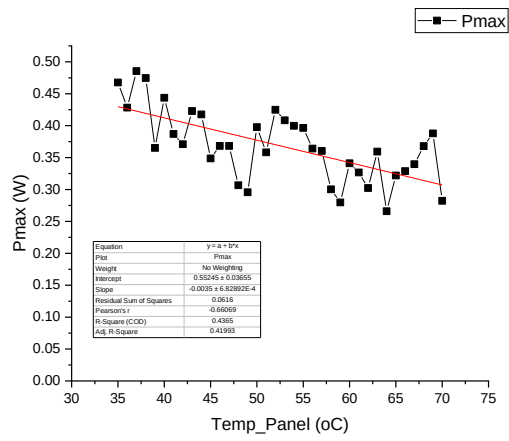
c)



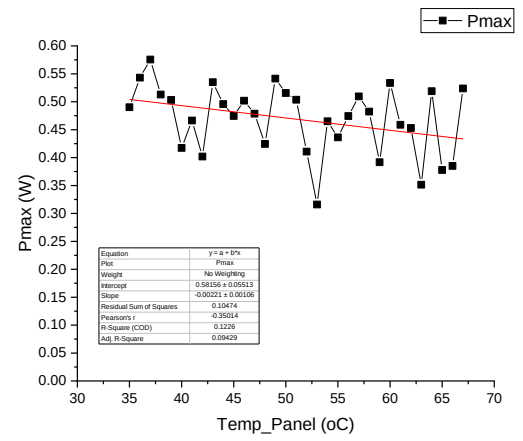
d)

Εικόνα 41 Temperature coefficient of Isc at ~540 Watt/m² irradiance for a) panel 6, b) panel 9 & at ~1000 Watt/m² irradiance for c) single module ,d) double module

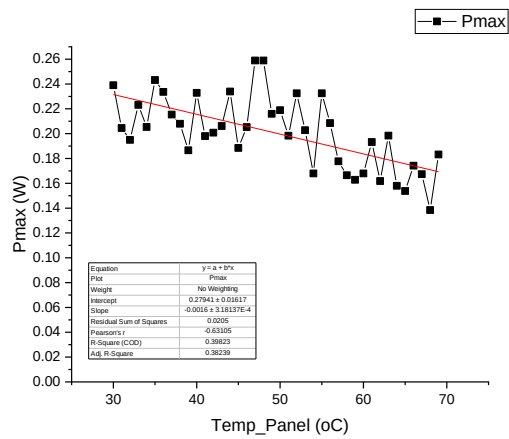
9.3 Pmax



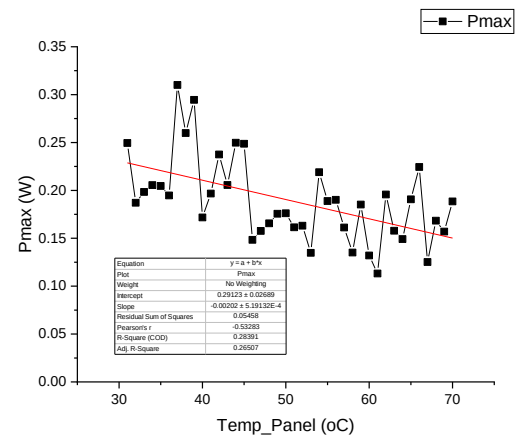
a)



b)



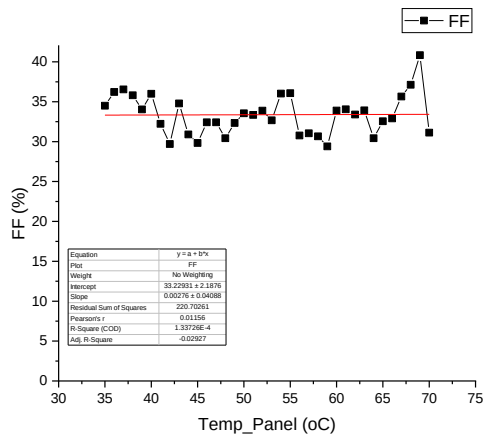
c)



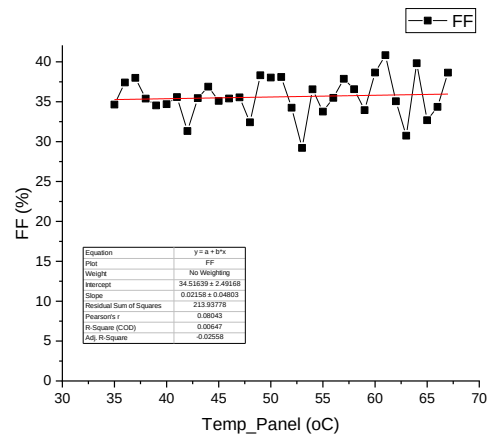
d)

Εικόνα 42 Temperature coefficient of Pmax at ~540 Watt/m2 irradiance for a) panel 6, b) panel 9 & at ~1000 Watt/m2 irradiance for c) single module ,d) double module

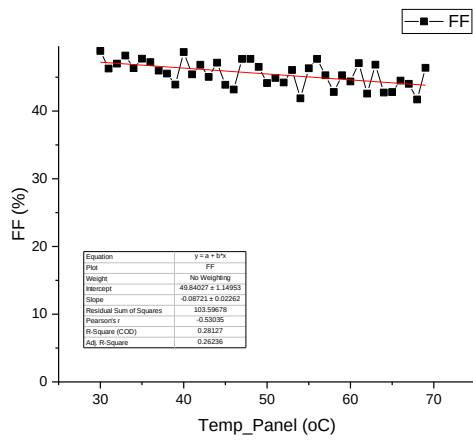
9.4 FF



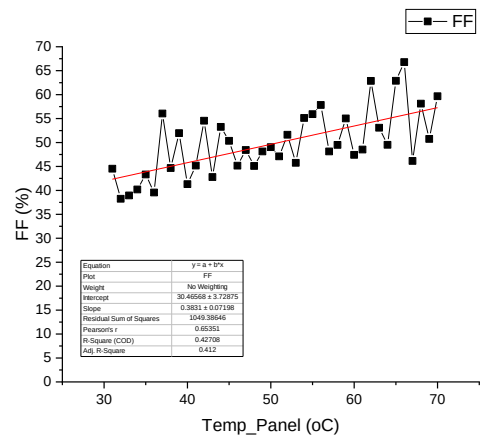
a)



b)



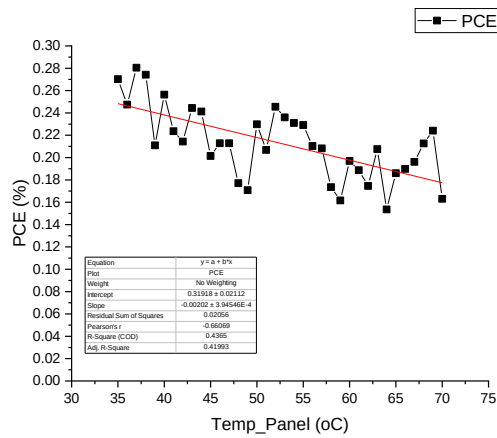
c)



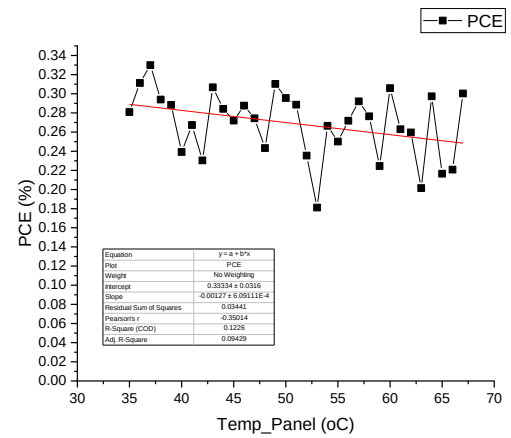
d)

Εικόνα 43 Temperature coefficient of FF at ~540 Watt/m2 irradiance for a) panel 6, b) panel 9 & at ~1000 Watt/m2 irradiance for c) single module ,d) double module

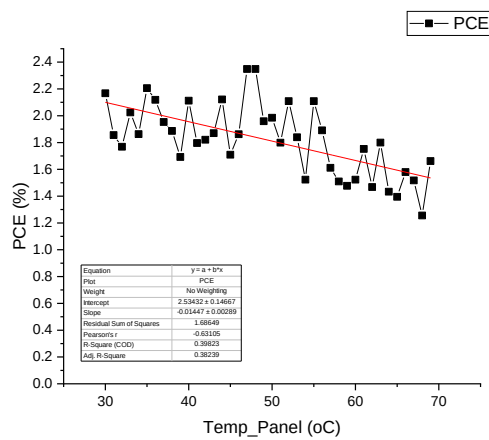
9.5 PCE



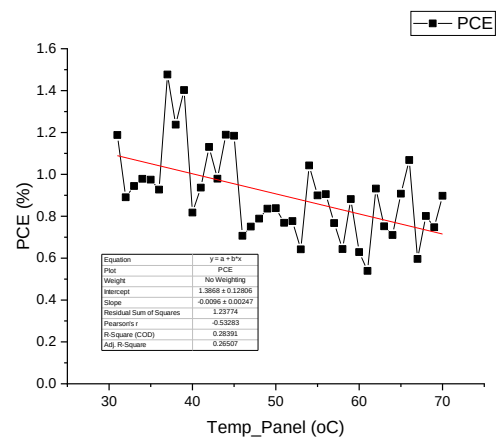
a)



b)



c)



d)

Εικόνα 44 Temperature coefficient of PCE at ~540 Watt/m2 irradiance for a) panel 6, b) panel 9 & at ~1000 Watt/m2 irradiance for c) single module ,d) double module

Analyzing the data of the experimental results, we find that, as expected, the open-circuit voltage (V_{oc}) decreases with increasing temperature for both panels and modules.

In contrast, the short-circuit current (I_{sc}) shows a different behavior than photovoltaic panels of other technologies. A slightly decreasing trend is observed that leads to a further decrease in the other electrical characteristics.

The FF remains constant throughout the experiments with a slightly increasing behavior. This is due to the limited time of irradiation of the panels

as well as to the absence of ultraviolet radiation, since lamps that do not emit at this wavelength were used as a source.

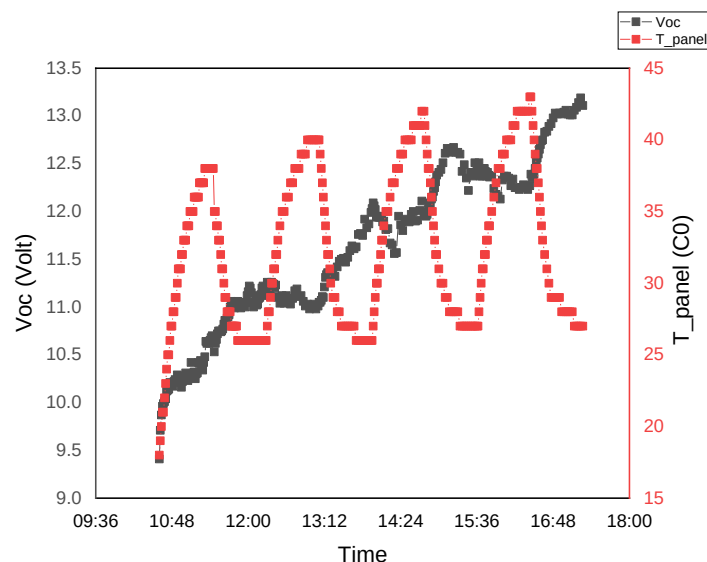
In conclusion, as expected, the reduction of all the electrical characteristics of the grapes was directly related to the reduction and their overall performance and efficiency.

The following table shows the concentrated changes in the electrical properties of the grapes per degree Celsius for each size category.

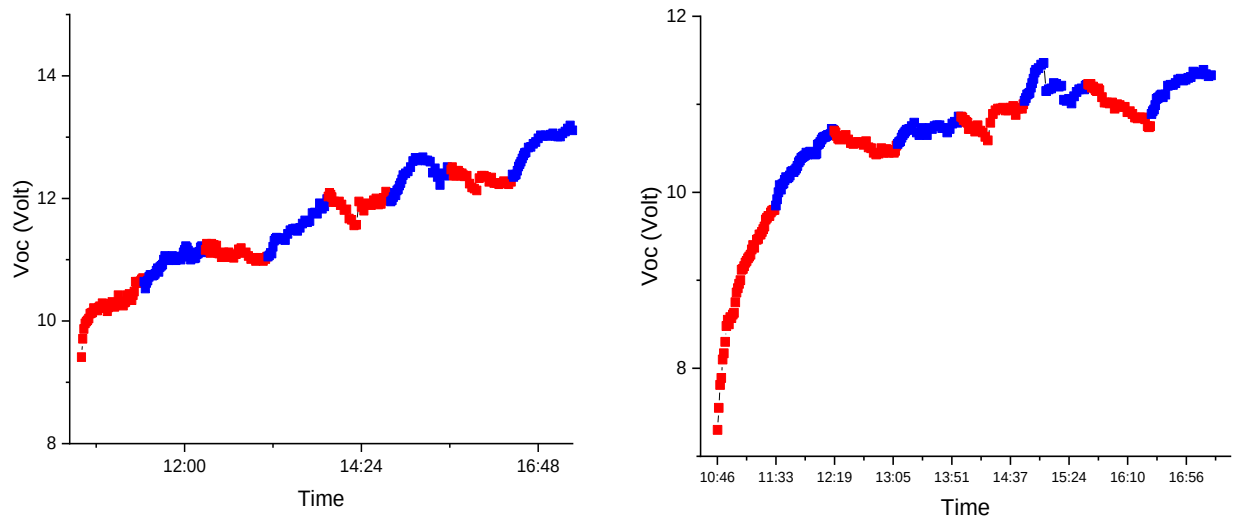
GRAPEs Type	Voc	Isc	Pmax	FF	PCE
	V/ ⁰ C	A/ ⁰ C	W/ ⁰ C	%/ ⁰ C	%/ ⁰ C
Panel 6	-0.07017	-0.00035	-0.0035	0.00276	-0.00202
Panel 9	-0.0096	-0.00025	-0.00221	0.02158	-0.00127
Single module	-0.0276	-0.00016	-0.0016	-0.08721	-0.01447
Double module	-1.2335	-0.00025	-0.00202	0.3831	-0.0096

9.6 Heating and cooling experiments

In order to better understand the behavior of open circuit voltage, since it is the factor that is mostly affected from natural factors such as irradiance and temperature, an extra set of experiments were carried out. In this scenario the panel was constantly heated by the lamps until the temperature of its back surface was stabilized in a peak value. Then a fan was used to cool the panel down to its initial temperature value. These heating-cooling alternation were performed several times in each set of this experiment so that the change of the Voc in terms of temperature is obvious and exhibit a repetitive behavior.



Εικόνα 45 The change in the voltage of the panel in contrast to the fluctuation of the temperature



Εικόνα 46 The change in the voltage of the panel in contrast to the fluctuation of the temperature represented with red color while heated and blue while cooling.

These experiments were performed under controlled conditions in the dark room on two different days in panel 7 with and at $\sim 250 \text{ watt/m}^2$ irradiance, measured using the Non Uniformity Five Point Algorithm.

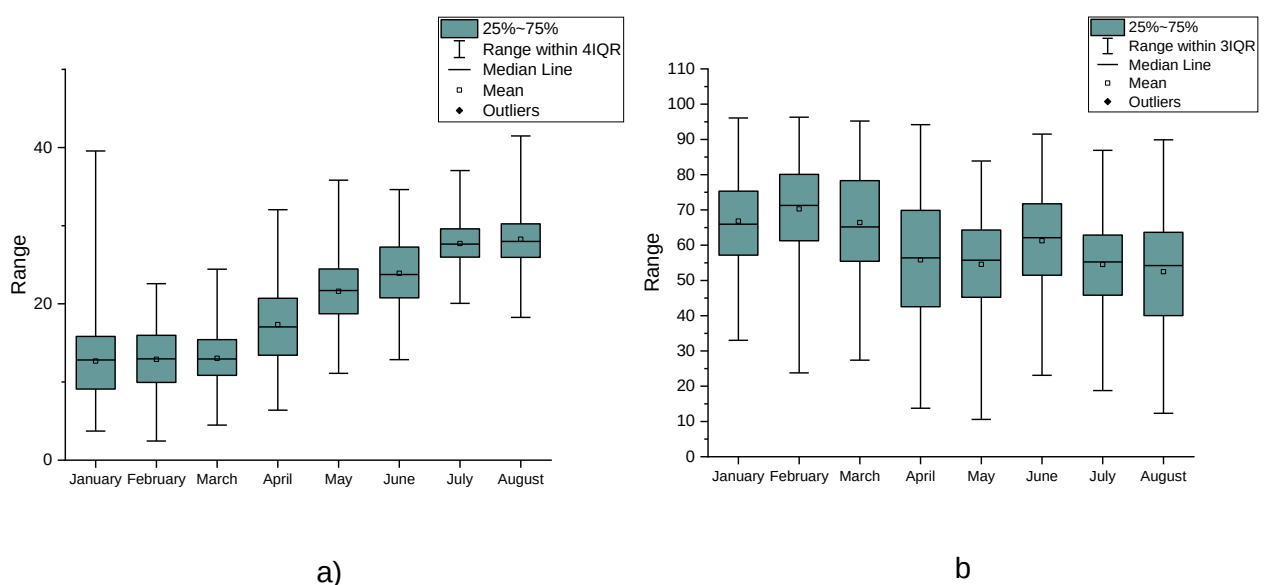
From the graphs of the two days on which the two experiments were performed, it is evident that as the temperature of the panel increased, the open circuit voltage decreased, while as the panel cooled, an increase in the open circuit voltage was observed. So it is obvious that heat has a great influence on the performance of panels of this technology.

10. Energy Yield & Solar Farm Meteorological Data

As it was mentioned in chapter 3.1.1 the meteorological data of the solar park were collected for the measurement period that the experiments took place.

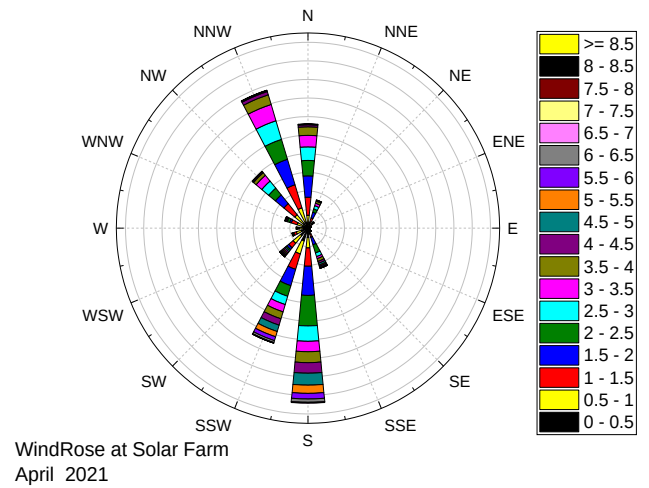
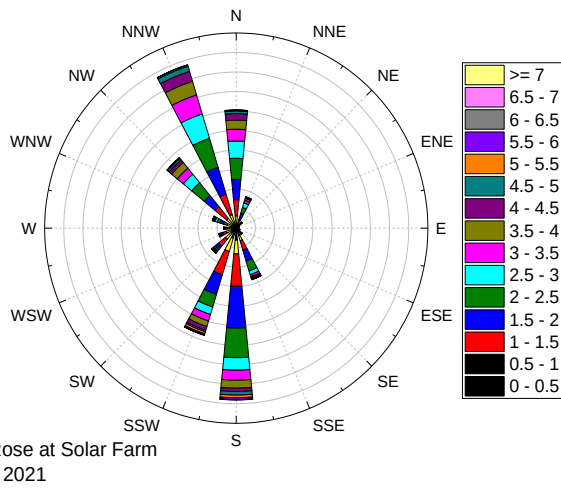
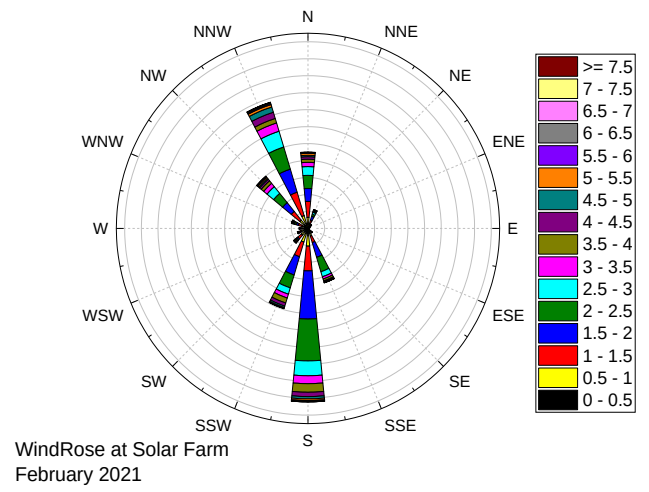
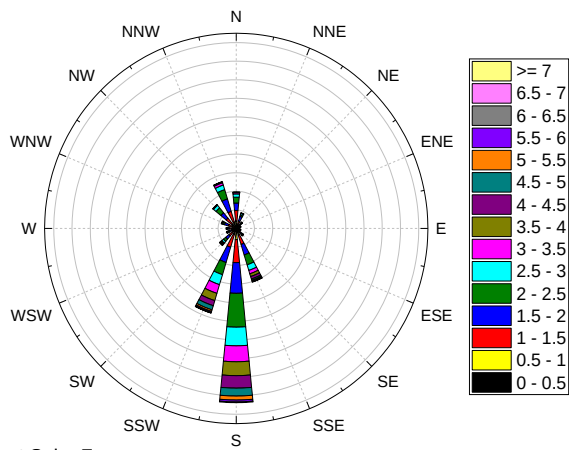
In this chapter these data are presented in order to have an overview of the meteorological data of the area, of the solar farm ,per month of the year 2021.

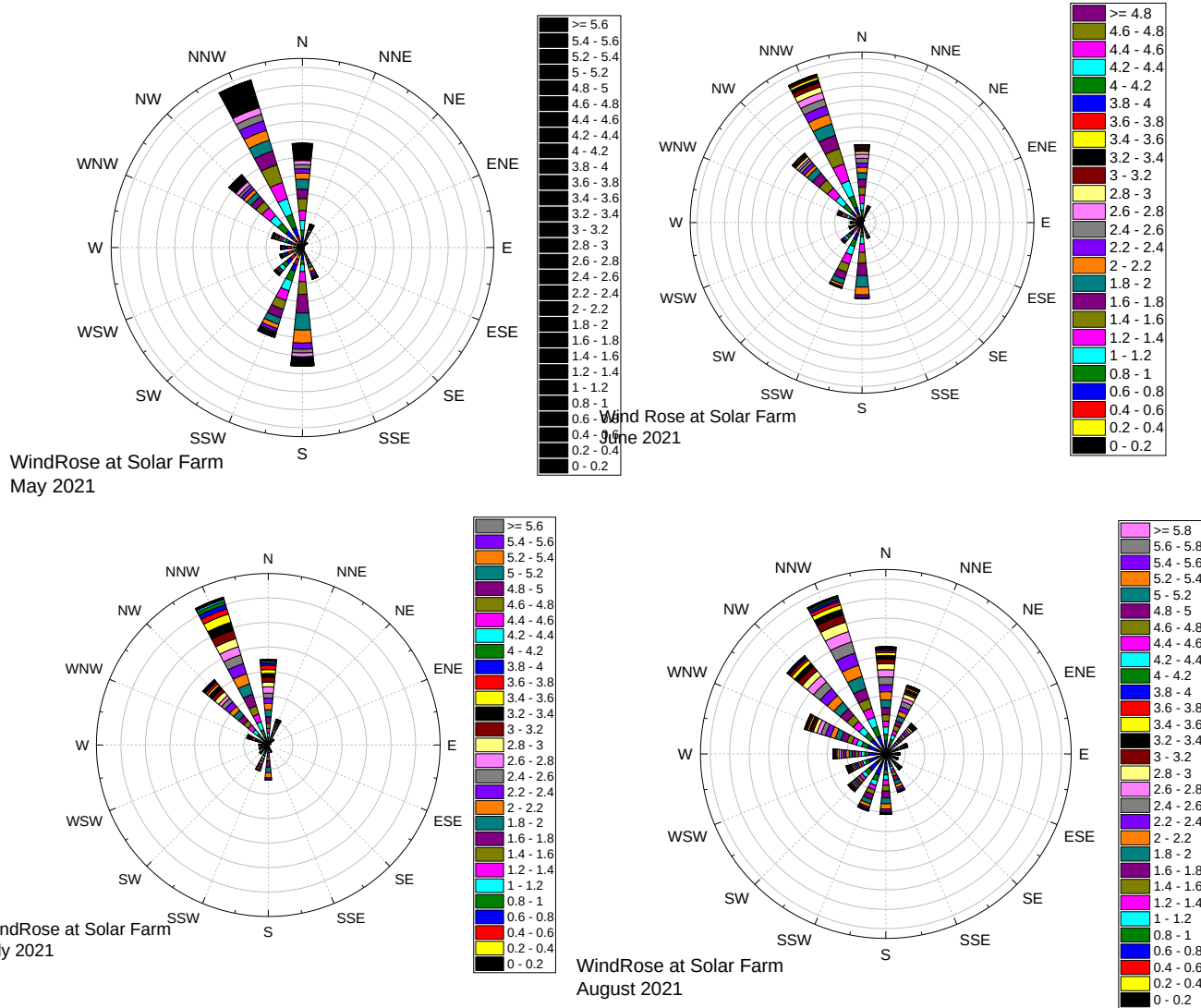
Air Temperature and Relative Humidity at solar farm for 2021



Εικόνα 47 Monthly range of a) Air temperature b) Relative Humidity at solar farm for the period the experiments were performed

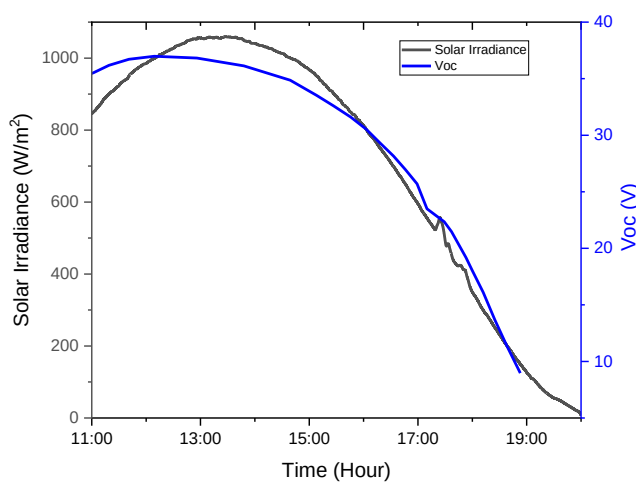
Wind Data at solar farm for 2021



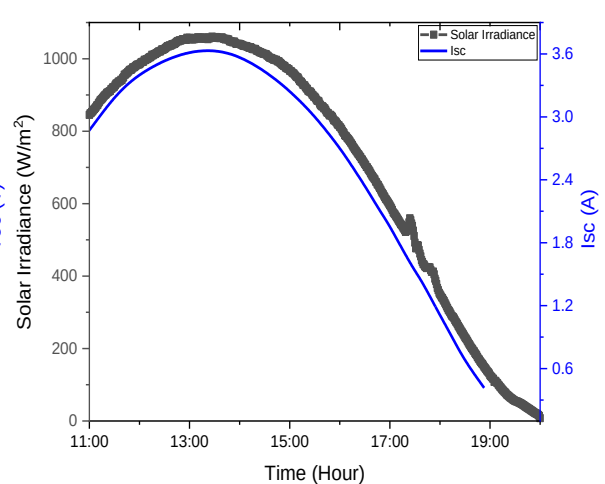


Εικόνα 48 Monthly wind rose at solar farm for the period the experiments were performed

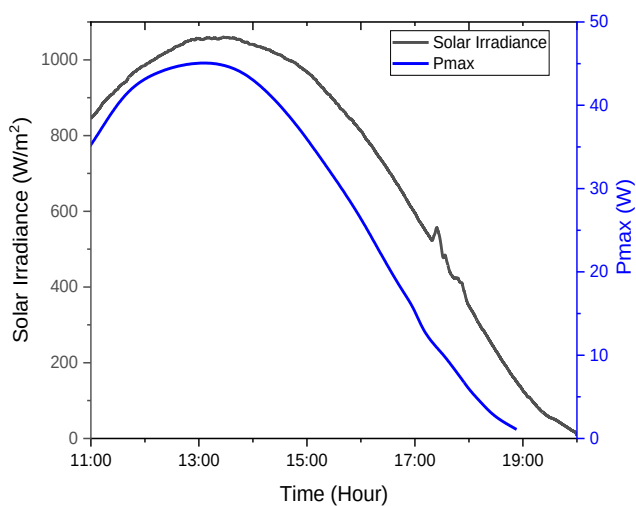
Energy yield from GRAPEs Panels



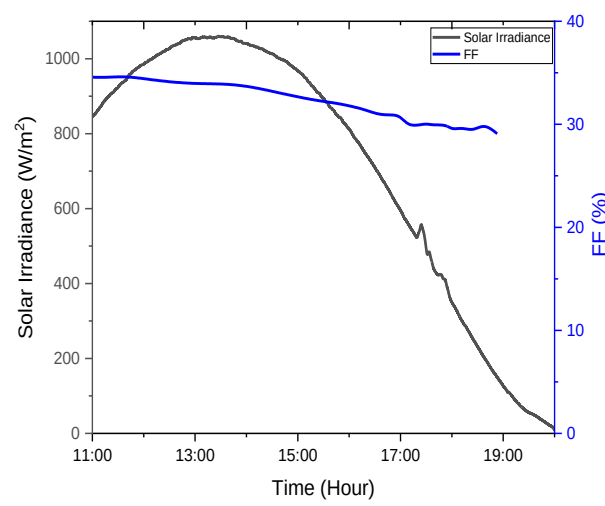
a)



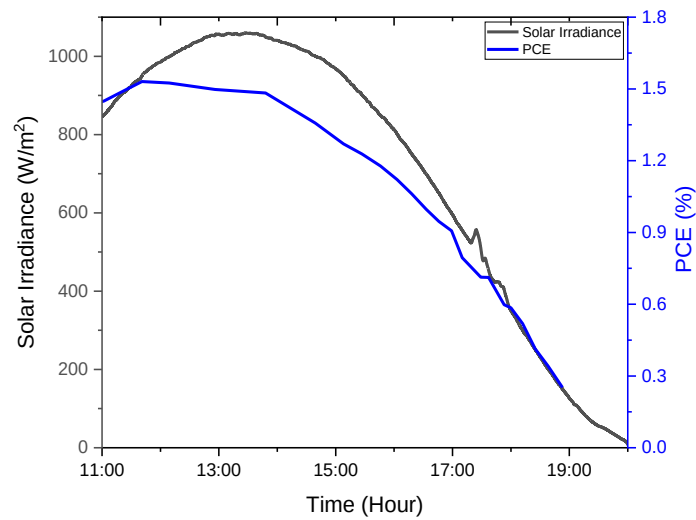
b)



c)



d)

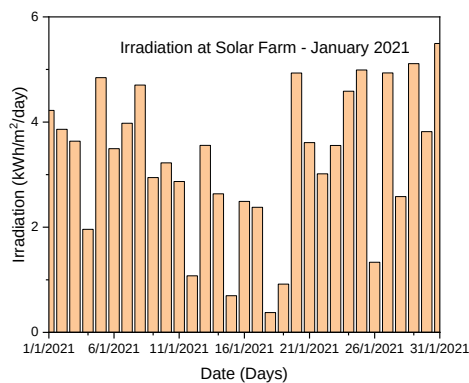


e)

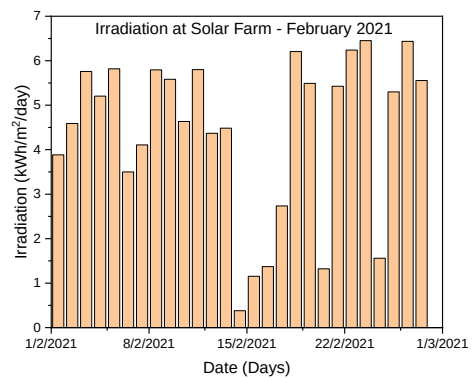
Εικόνα 49 The change in electrical characteristics a)Voc,b)Isc,c)Pmax,d)FF,e)PCE during a day contrastingly to solar radiation

From the above diagrams, it is clear that all the electrical characteristics of photovoltaic panels of GRAPE technology increase and decrease depending on the fluctuations of solar radiation during the day.

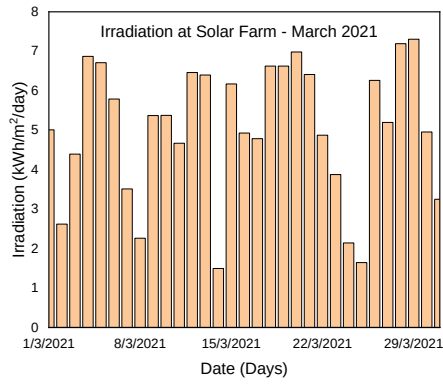
It is important to mention that the parameter FF shows a different behavior, since its progressive decrease during the day is evident, which is due to the decrease of the open circuit voltage due to the degradation caused by the continuous solar radiation, explained in a previous chapter.



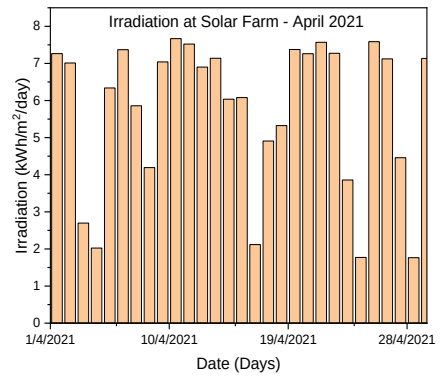
a)



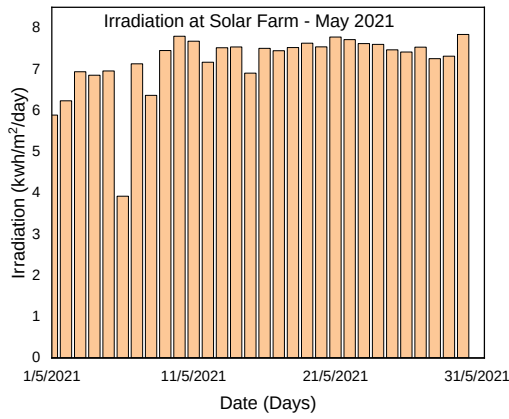
b)



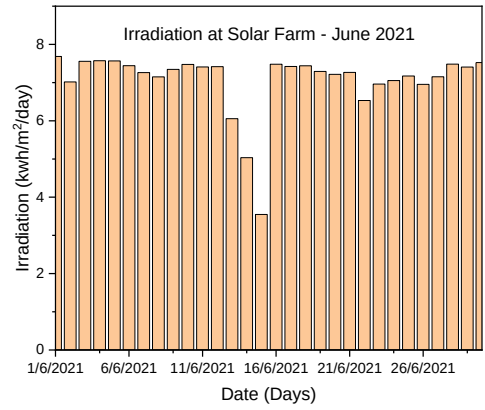
c)



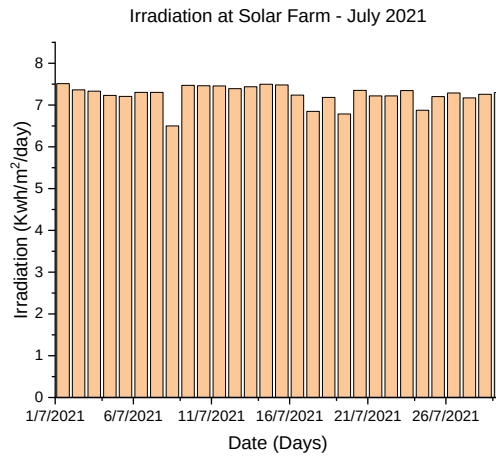
d)



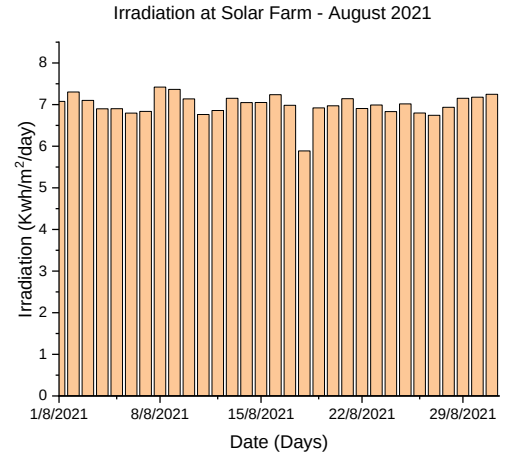
e)



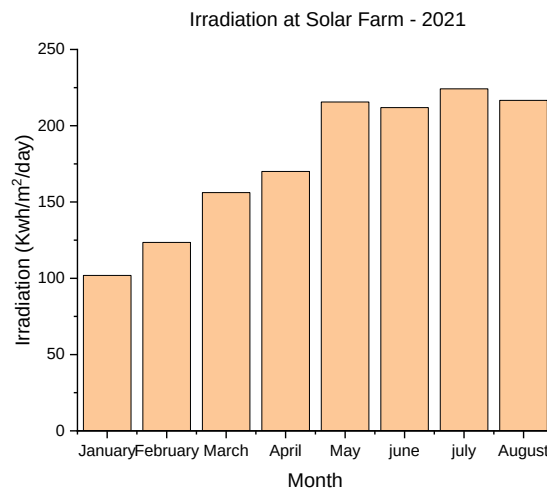
f)



g)



h)



i)

Εικόνα 50 monthly irradiation (KWh/m²/day) occurred during the months that GRAPEs were studied
a)January,b)February,c)March,d)April,e)May,f)June,g)July,g)August,i) irradiation allocation for each month

11. Future research and optimizations

As is evident from the results of the research the photovoltaics of the GRAPE technology while presenting very high efficiencies still have to overcome the long term life span and stability issue.

Furthermore one of the future possible optimizations of this technology, that could increase both their performance and longevity, would be the fabrication of multi junction hybrid solar cells combined with other technologies that have sublime PCEs as well as exhibit stability over time such as silicon PVs. The efficiencies of the two technologies, their different absorption spectrum as well as the voltage generation capacity at low radiation values, that the GRAPE photovoltaics exhibit, could be combined and create a photovoltaic panel taking advantage of the advantages of both.

Additionally another future optimization of this technology would be their use indoors to power low-power electronic devices, such as sensors, with a view to integrating them into the continuously evolving IOT.

The phenomenon of light soaking needs further study to determine if it is a degradation phenomenon or if it is a way to determine degradation. In addition, measurements at frequencies below 1 kHz need to be made to more accurately determine the capacitive response of this photovoltaic technology and to find the **electrical** equivalent circuit.

In conclusion regarding the panels of graphene perovskite technology should be further investigated the regeneration rate as well as the factors that accelerate it which can lead to higher life expectancy.

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