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Topic :

Dynamic Modeling of a Photovoltaic Panel

Publicly defended on **01 / 07 / 2024** , in front of the jury composed of:

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I would like to express my deepest gratitude to Allah, the Most Gracious,

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Abstract:

The heat of photovoltaic (PV) module plates interacts dynamically with changes in solar radiation and is influenced by multiple factors. The dynamic model allows for the inclusion of all electrical, optical, and thermal characteristics by calculating the energy produced and consumed in each layer, enabling the determination of the temperature of PV cells under changing conditions rapidly. The static model for plate temperature is not suitable because the thermal mass of the plate results in a significant response time. Therefore, it is essential to determine the thermal response time of PV plates. Previous studies relied on measurements in controlled indoor environments, such as using fans to control airflow or conducting experiments in the dark to eliminate radiative heat loss. However, these controlled experiments do not replicate the random variations in ambient temperature, wind speeds, and fluctuating directions that occur in actual operating conditions. This study proposes a new thermal model that considers weather conditions, PV panel material composition, and installation structure. Experimental results are presented to verify the thermal behavior of the PV module under a range of wind conditions, from low speeds to high speeds.

Key words: Photovoltaic modules, thermal modelling, module temperature, heat capacity.

Résumé:

La chaleur des plaques de modules photovoltaïques (PV) interagit de manière dynamique avec les variations du rayonnement solaire et est influencée par plusieurs facteurs. Le modèle dynamique permet d'inclure toutes les caractéristiques électriques, optiques et thermiques en calculant l'énergie produite et consommée dans chaque couche, ce qui permet de déterminer rapidement la température des cellules PV dans des conditions changeantes. Le modèle statique de température des plaques n'est pas adapté en raison de la masse thermique importante de la plaque, ce qui entraîne un temps de réponse significatif. Il est donc essentiel de déterminer le temps de réponse thermique des plaques PV. Les études précédentes se sont appuyées sur des mesures réalisées dans des environnements intérieurs contrôlés, tels que l'utilisation de ventilateurs pour contrôler le flux d'air ou la réalisation d'expériences dans l'obscurité pour éliminer les pertes de chaleur radiatives. Cependant, ces expériences contrôlées ne reproduisent pas les variations aléatoires de la température ambiante, des vitesses du vent et des directions fluctuantes qui se produisent dans des conditions de fonctionnement réelles. Cette étude propose un nouveau modèle thermique qui prend en compte les conditions météorologiques, la composition des panneaux PV et la structure d'installation. Des résultats expérimentaux sont présentés pour vérifier le comportement thermique du module PV dans une gamme de conditions de vent, des vitesses faibles aux vitesses élevées.

Mots-clés: Modules photovoltaïques, modélisation thermique, température du module, capacité thermique.

الملخص:

تتفاعل حرارة لوحات الخلايا الشمسية الكهروضوئية (PV) مع التغيرات في الإشعاع الشمسي بشكل ديناميكي وتتأثر بعوامل متعددة. فان نموذج الديناميكي يسمح بادخال جميع الخصائص الكهربائية و البصرية و الحرارية و ذلك بحساب الطاقة المنتجة و المستهلكة في كل طبقة و يسمح بتحديد درجة حرارة الخلايا الشمسية في حالات تغير الظروف بسرعة، لا يعد النموذج الثابت لحرارة اللوحة مناسبًا لأن الكتلة الحرارية للوحة يتسبب في زمن استجابة كبير. لذلك، يتعين تحديد زمن الاستجابة الحرارية لوحات PV بشكل أساسي. اعتمدت الدراسات السابقة على قياسات في الأماكن المغلقة بظروف مضبوطة، مثل استخدام المراوح للتحكم في تدفق الهواء أو إجراء التجارب في الظلام للتخلص من فقدان الحرارة الإشعاعية. ومع ذلك، فإن هذه التجارب المضبوطة لا تقم بتكرار التغيرات العشوائية في درجة حرارة المحيط وسرعات الرياح واتجاهاتها المتقلبة التي تحدث في ظروف التشغيل الفعلية. تقترح هذه الدراسة نموذجًا حراريًا جديدًا يأخذ في الاعتبار الظروف الجوية وتركيبة مواد لوحات PV وهيكل التركيب. يتم تقديم النتائج التجريبية للتحقق من السلوك الحراري للوحة الكهروضوئية تحت مجموعة من ظروف الرياح، من السرعات المنخفضة إلى السرعات العالية.

الكلمات المفتاحية: وحدات توليد الطاقة الشمسية، النمذجة الحرارية، درجة حرارة الوحدة، السعة الحرارية.

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Nomenclature :	**Greek letters :**
T: Temperature (°C)	α : Cell Absorptivity (dimensionless)
t: time (s)	β_0 : Expansion Thermal Coefficient ($°C^{-1}$)
A: Surface Area (m^2)	ε : Emissivity (dimensionless)
w: Wind Speed (m/s)	γ : Coefficient of Solar Radiation
e: Thickness of material (m)	η : Electrical Efficiency
c: Specific heat (J/kg·K)	ϑ : Tilt Angle (°)
C: Heat Capacity (J/K)	λ : Thermal Conductivity (W/m·K)
G: Irradiance (W/m^2)	ρ : Density (kg/m^3)
h: Convective Coefficient	σ: Boltzmann Constant (W/m^2·K^4)
Lc: Characteristic Length (m)	τ: Transmittivity (dimensionless)
p: Perimeter of the PV panel	Φ : heat source (W/m2)
q: Thermal Coefficient (W/m^2·K)	**Abbreviations:**
F: View Factor (dimensionless)	STC (Standard Test Conditions)
Gr: Grashof Number (dimensionless)	NOCT(Normal Operating Cell Temperature)
Ra: Rayleigh Number (dimensionless)	
Re: Reynolds Number (dimensionless)	

Nu:	Nusselt Number (dimensionless)
Pr:	Prandtl Number (dimensionless)
d:	gas layer thickness(m)
C_p	constant pressuer
M	Molecular weight (g/mol)

Subscripts:

a:	Ambient
bg:	Back Surface
fg:	Front Glass Surface
gr:	Ground
pan:	Panel
pv:	Photovoltaic
r:	Radiative
cd:	Conduction
conv:	Convection

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Introduction general

Dynamic modeling of panel photovoltaic (PV) systems plays a crucial role in understanding the behavior and performance of these renewable energy systems. As the demand for clean and sustainable energy sources continues to grow, photovoltaic technology has emerged as a prominent solution for generating electricity from sunlight.

Dynamic modeling involves capturing the time-varying nature of PV system operation, considering various factors such as solar irradiance, temperature, shading, and electrical characteristics. By simulating the dynamic behavior of PV panels, researchers and engineers can assess system performance, optimize design, and develop efficient control strategies.

One key aspect of dynamic modeling is the consideration of solar irradiance, which varies throughout the day and across different seasons. Solar irradiance affects the amount of energy that can be harvested by PV panels and directly influences their electrical output. Additionally, temperature variations impact the performance of PV panels, as excessive heat can reduce their efficiency.

Shading is another important factor to consider in dynamic modeling. Even partial shading on a PV panel can significantly affect its performance, leading to reduced power generation and potential hotspots. Modeling shading effects accurately allows for the assessment of optimal panel placement, shading mitigation techniques, and overall system design improvements.

Electrical characteristics, such as the maximum power point tracking (MPPT) algorithm, the inverter, and the interconnection with the grid, also play a crucial role in dynamic modeling. These components affect the energy conversion efficiency, system stability, and grid integration of the PV system.

Dynamic modeling techniques can range from simple empirical models to more advanced physics-based models, including circuit-level simulations and computational fluid dynamics (CFD) models. These models can provide insights into the behavior of PV systems under different operating conditions and enable the evaluation of system performance over time.

Overall, dynamic modeling of panel photovoltaic systems is essential for understanding their behavior, optimizing their performance, and developing efficient control strategies. It allows researchers, engineers, and system operators to assess the impact of various factors on system performance, enhance energy generation, and contribute to the widespread adoption of clean and sustainable solar energy.

Chapter I

Generality on renewable energy and photovoltaic modules

I.1. Introduction:

One of the most widespread technologies of renewable energy generation is the use of photovoltaic (PV) systems, which convert sunlight to into usable electrical energy [1, 2]. This type of renewable energy technology which is pollutant free during operation, diminishes global warming issues, lowers operational cost, and offers minimal maintenance and highest power density compared to the other renewable energy technologies, highlights the advantages of solar photovoltaic (PV) energy [3,4].

Apart from the several advantages displayed by the PV technology, this conversion system does have some general problems, such as hail, dust and surface operating temperature which can negatively affect the efficiency of the conversion system [5].

Exogenous climatic parameters such as wind speed, ambient temperature, relative humidity, accumulated dust and solar radiation are the most common natural factors, which influence the surface temperature of a PV module.

Every 1 °C surface temperature rise of the PV module causes a reduction in efficiency of 0.5% [6]. Therefore, due to the temperature rise, not all of the solar energy absorbed by the photovoltaic cells is converted into electrical energy.

To satisfy the law of conservation of energy, the remaining solar energy is converted into heat.

I.2. Renewable Energy:

Sunlight and wind, for example, are such sources that are constantly being replenished. Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed. Renewable energy sources are plentiful and all around us.

Fossil fuels - coal, oil and gas - on the other hand, are non-renewable resources that take hundreds of millions of years to form. Fossil fuels, when burned to produce energy, cause harmful greenhouse gas emissions, such as carbon dioxide.

Generating renewable energy creates far lower emissions than burning fossil fuels. Transitioning from fossil fuels, which currently account for the lion’s share of emissions, to renewable energy is key to addressing the climate crisis.

Renewables are now cheaper in most countries, and generate three times more jobs than fossil fuels [7].

I.2.1. Importance of energy renewable:

Renewable energy is a vital and growing sector, primarily characterized by its plentiful and infinite supply. Compared to conventional fossil energy technologies, renewables have significantly less environmental impact, making them more hygienic sources of energy.

Investments in renewable energy projects mainly focus on materials and personnel for building and maintaining facilities, thereby diverting funds from costly energy imports.

Technological advancements and improved mass communication have raised public awareness about the drawbacks of burning fossil fuels, leading to a shift towards cleaner and more sustainable energy alternatives. Renewable energy sources, such as solar, wind, biomass, geothermal, hydropower, and tidal energy, are not only dependable and abundant but also have the potential to become very cheap as technology and infrastructure improve [8].

I.2.2. Characteristics of renewable energies:

Among the main features of renewable energies, we find:

- **Unlimited power source**: Unlike fossil fuels, such as coal, natural gas, or oil, whose reserves are finite and dwindling, renewable energy sources are virtually unlimited and do not deplete as they are consumed
- **Derived from natual resources**: Renewable energies are fueled by natural elements, such as sunlight, water, and wind, which are abundant and constantly replenished
- **Zero greenhouse gas emissions**: A significant advantage over fossil fuels, renewable energies do not produce greenhouse gas emissions, thereby mitigating climate change and environmental harm.
- **No waste generation**: Renewable energies have a minimal environmental impact, as they do not generate hazardous waste or pollutants [9].

I.2.3. Types energy renewable:

I.2.3.1. Solar energy:

Solar energy is the primary source of nearly all energy on Earth. Humans, like all other living organisms, rely on the sun for warmth and sustenance. However, people also harness the sun's energy in various ways. For instance, fossil fuels, which are remnants of plant matter from a past geological era, are used for transportation and electricity generation.

In essence, fossil fuels are stored solar energy from millions of years ago. Similarly, biomass converts the sun's energy into a fuel, which can then be used for heat, transportation, or electricity. Wind energy, utilized for centuries to provide mechanical energy or for transportation, relies on air currents created by solar-heated air and the Earth's rotation [10].

Figure I.1. Renewable solar energy [10].

I.2.3.2. Wind:

Wind energy is an abundant and environmentally friendly source of power, wind farms have become a common feature, significantly contributing to the National Grid's energy supply.

These farms utilize turbines to convert wind energy into electricity, which is then integrated into the grid. While there are options for domestic or 'off-grid' wind energy generation, not all properties are suitable for installing a domestic wind turbine.

Explore the potential of wind energy today! Our renewables website offers valuable insights into how wind power plays a rucial role in the UK's energy landscape [11].

Figure I.2. Renewable wind energy.

I.2.3.3. Hydro energy:

Hydropower, as a renewable energy resource, is one of the most commercially developed options available. By constructing a dam or barrier, a large reservoir can be created, allowing for the controlled release of water to drive turbines and generate electricity.

This form of energy production often boasts greater reliability compared to solar or wind power, particularly if it has derived from tidal forces rather than river flow. Additionally, hydroelectricity offers the advantage of energy storage, enabling electricity to be stored during times of low demand and utilized when demand peaks.

Figure I.3. Renewable hydro energy [11]

I.2.3.4. Geothermal energy:

Utilizing the natural heat beneath the Earth's surface, geothermal energy has the capacity to directly heat homes or generate electricity. Despite tapping into power sources directly beneath us, geothermal energy holds minimal significance in the UK when compared to countries like Iceland, where geothermal heat is more abundant and readily accessible [11].

Figure I.4. Renewable Geothermal energy [11].

I.2.3.5. Biomass Energy:

This process involves converting solid fuel derived from plant materials into electricity. While traditionally biomass entails burning organic materials to generate electricity, advancements have led to a cleaner and more energy-efficient process. By transforming agricultural, industrial, and domestic waste into solid, liquid, and gas fuels, biomass power generation occurs at significantly lower economic and environmental costs [11].

Figure I.5. Renewable biomass energy [11].

I.2.3.6. Tidal energy:

Tidal energy is a form of hydro energy that harnesses the power of twice-daily tidal currents to generate electricity. Unlike some other hydro energy sources, tidal flow is not constant but it is highly predictable. This predictability allows tidal energy systems to compensate for periods when the tide current is low, ensuring a consistent and reliable energy supply.

Tidal energy is generated by using turbine generators that are driven by the kinetic energy of tidal currents. As the tides ebb and flow, the movement of water turns the turbines, converting the mechanical energy into electrical energy. Tidal energy has the advantage of being a renewable energy source since it relies on the gravitational pull of the moon and the sun, which will continue to occur indefinitely [11].

Figure I.6. Renewable Tidal energy.

I.3. Solar irradiation:

Solar irradiance is the power per unit area (surface power density) received from the sun in the form of electromagnetic radiation. In simpler terms, its how much solar power is shining down on a specific area at a given time?

Understanding solar irradiance is crucial because it directly affects how much solar energy a solar panel can convert into electricity [12].

I.3.1. Types of Solar irradiation:

There are three types of solar irradiance: direct, diffuse, and reflected. Direct irradiance is sunlight that travels straight from the sun to the earth, unobstructed by clouds or the atmosphere. Diffuse irradiance refers to sunlight scattered by the atmosphere.

Reflected irradiance is sunlight that has reached the earth and bounced back off the surface. All three types contribute to the total solar irradiance that reaches a solar panel [12].

I.3.2. Measurement of solar irraddiation:

Solar irradiance is generally measured in watts per square meter (W/m²). This unit of measurement allows for a clear understanding of how much solar power is being received per square meter of a given surface area.

The higher the irradiance level, the solar power available to be converted into electricity [12].

I.3.3. Distrubution of solar irradiation:

The spectral distribution of solar radiation refers to the distribution of solar energy across different wavelengths or colors of light. The spectral distribution of solar radiation varies depending on the position of the sun, the atmospheric conditions, and the altitude of the observer.

At the Earth's surface, the spectral distribution of solar radiation is affected by the atmosphere, which absorbs, scatters, and transmits different wavelengths of light differently. The amount of atmospheric absorption, scattering, and transmission depends on the amount of atmospheric pollution or turbidity, as well as the air mass value, which is a measure of the amount of atmosphere that the solar radiation must pass through [13].

I.4. photovoltaic:

Photovoltaic solar energy (PV) is indeed one of the fastest-growing industries globally.

To sustain this rapid growth, continuous advancements are being made in various areas, including material usage, energy consumption during manufacturing, device design, production technologies, and innovative concepts aimed at enhancing the overall efficiency of solar cells [14].

I.4.1. Advantage photovoltaic:

- Clean and Silent: Solar cells produce electricity without emitting harmful pollutants into the environment. They do not release air or water pollution, deplete natural resources, or pose health risks to humans and animals. Additionally, solar systems operate silently.
- Visual Appeal: Photovoltaic systems are quiet and visually unobtrusive. They can be installed on rooftops, utilizing unused space on existing buildings without disrupting the landscape.
- Reliability and Low Maintenance: PV cells were initially developed for space applications, where repair is extremely costly or impossible. The durability and reliability of solar panels make them suitable for long-term operation with minimal maintenance. This is why solar power is extensively used in satellites.
- Locally Available Renewable Resource: Solar energy is a locally available resource that does not require transportation from distant regions. This reduces environmental impacts associated with fuel transportation and decreases dependence on imported oil. Unlike mined or harvested fuels, solar energy does not deplete or alter the resource when used for electricity production.
- Scalability and Flexibility: PV systems can be designed and constructed to meet specific energy requirements. Owners can easily expand or relocate the system based on changing energy needs. For example, homeowners can add modules as their energy usage grows, and ranchers can use mobile trailer-mounted systems for flexible water pumping.[15]

I.4.2. Disadvantages of photovoltaic :

- Use of Toxic Chemicals: Some PV production processes involve the use of toxic chemicals such as cadmium and arsenic. However, these environmental impacts can be minimized through proper recycling and disposal practices.
- Initial Cost: Solar energy production can be more expensive compared to conventional energy sources due to the manufacturing cost of PV devices and the efficiency of the equipment. However, as technology advances and manufacturing costs decrease, solar power becomes increasingly cost-competitive with conventional fuels.
- Variable Energy Source: Solar power is reliant on sunlight, making it a variable energy source. Energy production may fluctuate depending on weather conditions and time of day. Over-reliance on solar power without sufficient energy storage or backup systems could lead to energy shortages during periods of low sunlight [16].

I.5. Pv cells:

Solar cells, also known as photovoltaic cells, are devices that utilize the field of technology called photovoltaics to convert solar energy into electrical energy. These cells are typically constructed using semiconductor materials like silicon.

Semiconductors have the property of releasing electrons when they absorb energy, which in the case of solar cells, is solar energy.

PV cells incorporate one or more electric fields with the purpose of directing the released electrons in a specific direction.

This process is similar to the functioning of a diode, which allows current flow in only one direction. As a result, an electric current is generated in the solar cell. Metal contacts are positioned at the top and bottom of the PV cell to facilitate the extraction and utilization of this current [17].

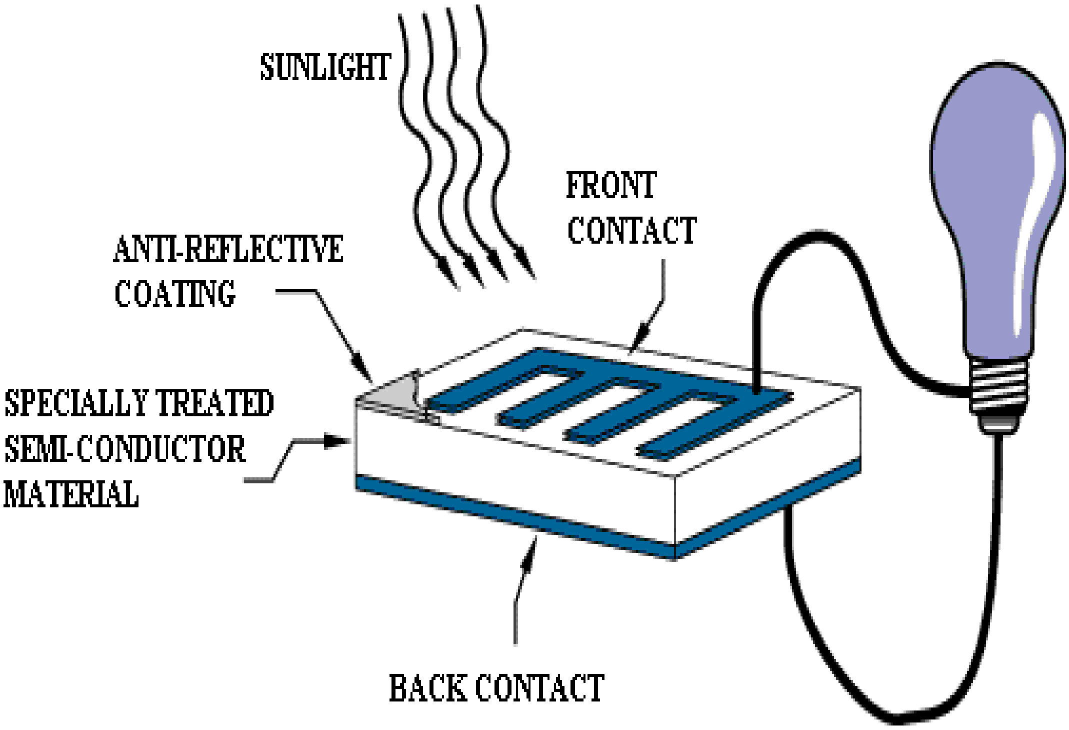

Figure I.7. The basic operation of a PV cell [18].

I.5.1.Layers of photovoltaic cell:

A photovoltaic cell consists of multiple layers of materials, each serving a specific purpose. The most crucial layer is the specially treated semiconductor layer, which is responsible for converting sunlight into usable electricity through the photovoltaic effect.

This layer is composed of two distinct regions: p-type and n-type (as shown in Figure 8). On either side of the semiconductor layer are layers of conductive material that collect the generated electricity. Note that the backside of the cell, which is not exposed to sunlight, can be fully covered with a conductor, whereas the front side, which is illuminated, requires a more sparse application of conductors to avoid blocking too much sunlight from reaching the semiconductor.

The final layer, applied only to the illuminated side, is the anti-reflection coating. Since semiconductors are naturally reflective, reflection loss can be significant. To mitigate this, one or multiple layers of anti-reflection coating (similar to those used in eyeglasses and cameras) are applied to reduce the amount of solar radiation reflected off the cell's surface [19].

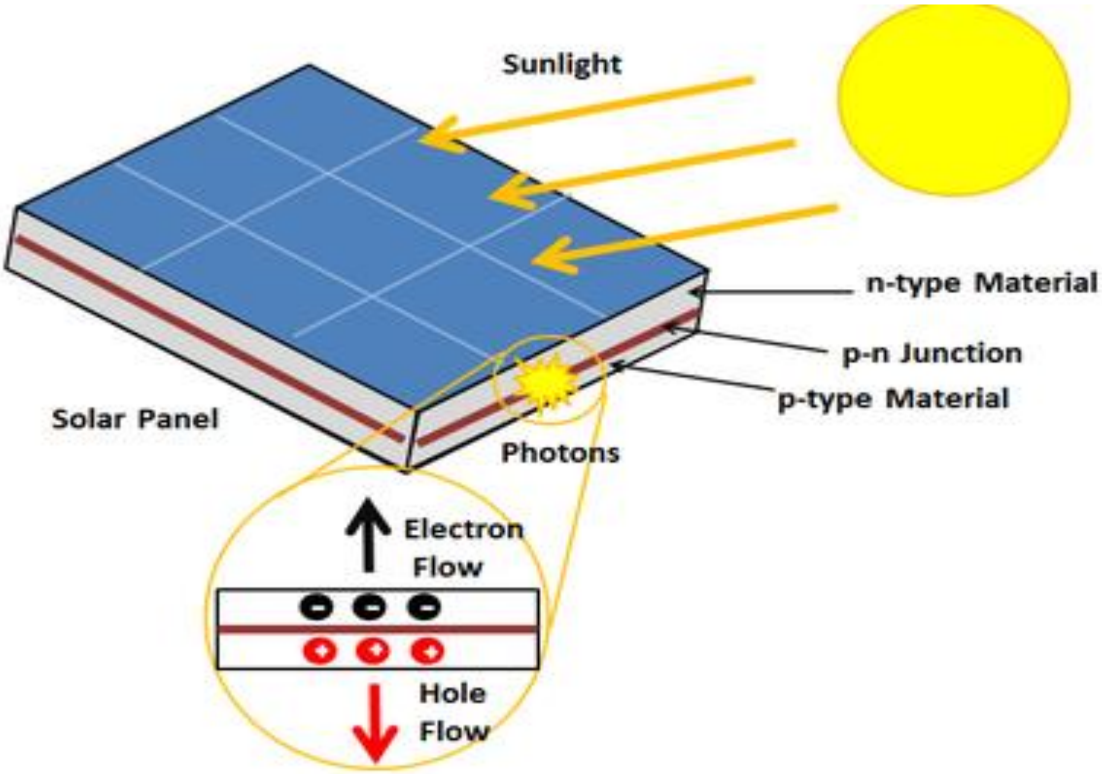

Figure I.8. A diagram showing the photovoltaic effect [20].

I.5.2. Quantum efficiency:

The quantum efficiency of a solar cell refers to the percentage of photons that are converted into electric current when the cell is operated under short circuit conditions. There are two types of quantum efficiency: external and internal.

External quantum efficiency (EQE) relates to the measurable properties of the solar cell. It takes into account optical losses such as transmission and reflection. Reflection losses, which can contribute up to 10% of the incident energy, can be reduced through techniques like texturization, which modifies the average light path to trap more light. [21]

Internal quantum efficiency (IQE) provides insights into the internal material parameters of the solar cell, such as the absorption coefficient or internal luminescence quantum efficiency. [22] IQE is primarily used to understand the potential of a specific material rather than a full device.

Quantum efficiency is often measured spectrally, meaning it is expressed as a function of photon wavelength or energy. Since different wavelengths are absorbed with varying effectiveness, spectral measurements of quantum efficiency can provide valuable information about the quality of the semiconductor bulk and surfaces.

I.5.2. Spectral response:

The spectral response of a silicon solar cell under glass. At short wavelengths below 400 nm, the glass absorbs most of the light and the cell response is very low. At intermediate wavelengths, the cell approaches the ideal. At long wavelengths, the response falls back to zero. Silicon is an indirect band gap semiconductor so there is not a sharp cut off at the wavelength corresponding to the band gap (E_g = 1.12 eV).

The ideal spectral response is limited at long wavelengths by the inability of the semiconductor to absorb photons with energies below the band gap. This limit is the same as that encountered in quantum efficiency curves. However, unlike the square shape of QE curves, the spectral response decreases at small photon wavelengths. At these wavelengths, each photon has a large energy, and hence the ratio of photons to power is reduced. Any energy above the band gap energy is not utilized by the solar cell and instead goes to heating the solar cell. The inability to fully utilize the incident energy at high energies and the inability to absorb low energies of light represents a significant power loss in solar cells consisting of a single p-n junction. [23]

I.6. photovoltaic technology:

Photovoltaic (PV) technology plays a crucial role in mitigating climate change due to its significantly lower carbon dioxide emissions compared to fossil fuels. When it comes to solar PV as an energy source, it offers distinct advantages. Once installed, PV systems operate without generating pollution or greenhouse gas emissions. This characteristic makes PV a clean and environmentally friendly energy option.

Furthermore, solar PV exhibits scalability, allowing it to meet various power needs. The availability of silicon, a key material used in PV cell manufacturing, is abundant in the Earth's crust.

However, there are certain constraints and disadvantages associated with PV technology. One major constraint is the competition for land use [24].

As large-scale PV, installations require significant land area. Additionally, for PV to serve as a primary energy source, energy storage systems or global distribution through high-voltage direct current power lines are necessary, resulting in additional costs.

Moreover, PV systems have specific disadvantages that need to be addressed. One such disadvantage is the variable nature of solar power generation, which requires balancing mechanisms to ensure a steady and reliable energy supply. Furthermore, the production and installation of PV systems do cause some pollution and greenhouse gas emissions, although these emissions are only a fraction of those produced by fossil fuels [25].

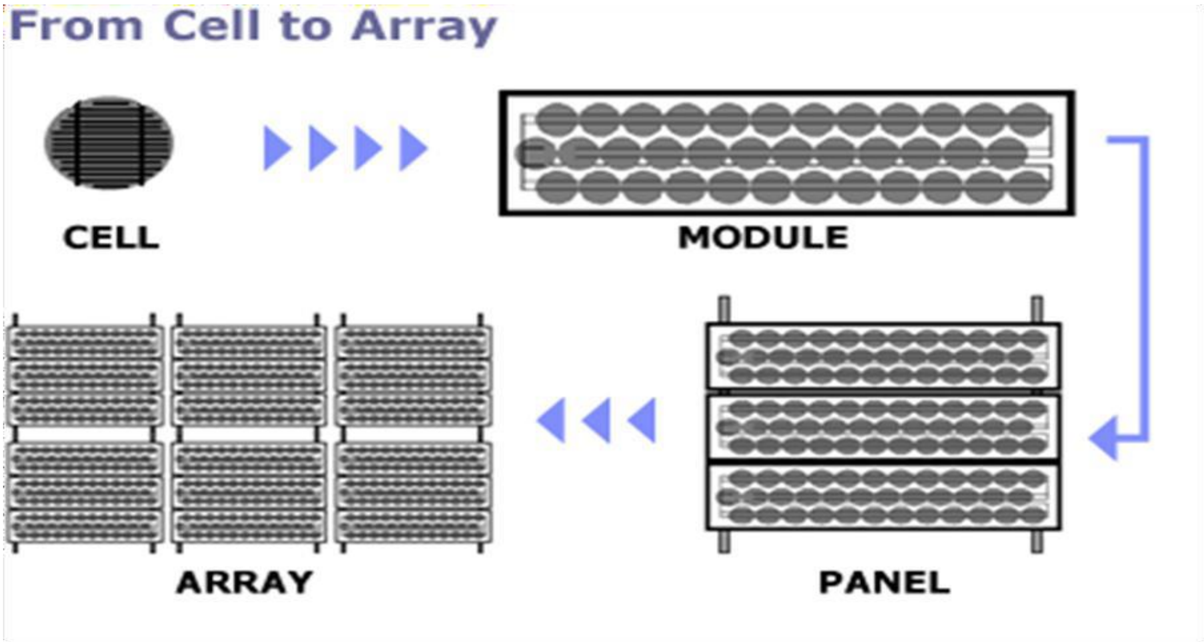

Figure I.9. Structure from PV cell to Array [26].

I.6.1.Types of PV modules:

There are three types of PV cell technologies that dominate the world market: monocrystalline silicon, polycrystalline silicon, and thin film.

I.6.1.1. Monocrystalline Silicon Cell:

The first commercially available solar cells were made from monocrystalline silicon, which is an extremely pure form of silicon. To produce these cells, a seed crystal is pulled out of a mass of molten silicon, creating a cylindrical ingot with a single, continuous crystal lattice structure. This ingot is then mechanically sawn into thin wafers, polished, and doped to create the required p-n junction. After applying an anti-reflective coating and adding front and rear metal contacts, the cell is finally wired and packaged alongside many other cells into a full solar panel [27].

I.6.1.2. Polycrystalline Silicon Cell:

Instead of having a single uniform crystal structure, polycrystalline (or multicrystalline) cells consist of many small grains of crystals (see Figure 10). They can be manufactured by simply casting a cube-shaped ingot from molten silicon, which is then sawn and packaged similarly to monocrystalline cells. Another method, known as edge-defined film-fed growth (EFG), involves drawing a thin ribbon of polycrystalline silicon from a mass of molten silicon.

Although less efficient, polycrystalline silicon PV cells are a cheaper alternative and dominate the global market, representing approximately 70% of global PV production in 2015 [27].

I.6.1.3. Thin Film Cells:

Although crystalline PV cells dominate the market, thin-film cells offer a more flexible and durable alternative. One type of thin-film PV cell is amorphous silicon (a-Si), which is produced by depositing thin layers of silicon onto a glass substrate. This results in a very thin and flexible cell that uses less than 1% of the silicon required for a crystalline cell.

The reduced raw material usage and less energy-intensive manufacturing process make amorphous silicon cells significantly cheaper to produce. However, their efficiency is greatly reduced due to the disordered arrangement of silicon atoms, which leaves "dangling bonds" that combine with other elements, rendering them electrically inactive. Furthermore, these cells experience a 20% drop in efficiency within the first few months of operation before stabilizing, and are therefore sold with power ratings based on their degraded output [27].

Other types of thin-film cells include copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe). While these cell technologies offer higher efficiencies than amorphous silicon, they contain rare and toxic elements, such as cadmium, which require special precautions during manufacture and eventual recycling.

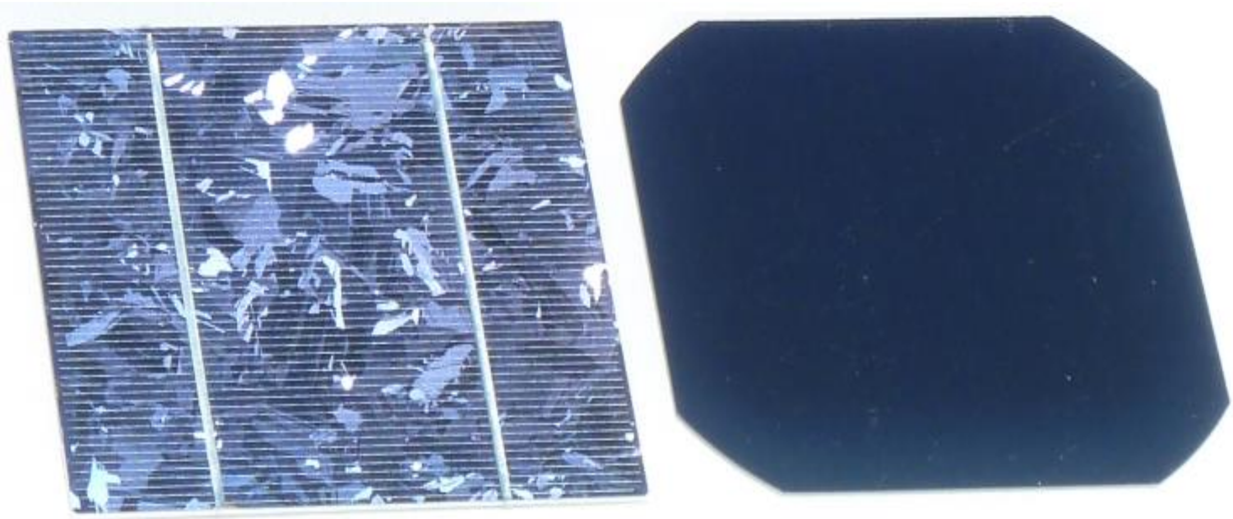

Figure I.1O. An image comparing a polycrystalline silicon cell (left) and a monocrystalline silicon cell (Right) [28].

I.6.1.3.1. Cadmium telluride:

Cadmium telluride (CdTe) is currently the only thin film material that can compete with crystalline silicon in terms of cost per watt. However, it is important to note that cadmium is highly toxic, and the availability of tellurium (which forms the "telluride" anion in CdTe) is limited.

While the presence of cadmium in CdTe cells raises concerns about potential toxicity if released, it is essential to understand that under normal operation of the cells, the release of cadmium is impossible. Additionally, the likelihood of cadmium release during fires on residential roofs is low.

It is worth noting that a square meter of CdTe contains approximately the same amount of cadmium as a single C-cell nickel-cadmium battery. However, the cadmium in CdTe is in a more stable and less soluble form [29]

I.6.1.3.2. Copper indium gallium selenide:

Copper indium gallium selenide (CIGS)-based solar cells have garnered significant global attention for solar power generation. These thin-film solar cells have demonstrated high efficiency, surpassing 23% on a laboratory scale, which is comparable to crystalline silicon (c-Si) wafer-based solar cells. Additionally, CIGS solar cells have achieved over 20% efficiency on flexible polyimide substrates, making them well suited for thin-film applications.

However, one of the major challenges in producing CIGS solar cells on a small scale is the precise control of stoichiometry and efficiency across the CIGS film. Achieving uniform composition and high efficiency throughout the film is crucial for optimal performance. This challenge becomes even more critical when scaling up for industrial production.

In addition to stoichiometry and efficiency, other factors play a vital role in commercializing CIGS technology for large-scale production. High-throughput manufacturing processes are necessary to meet the demands of mass production. Reproducibility ensures consistent performance across a large number of devices. Low-cost manufacturing techniques are essential to make CIGS solar cells competitive with other solar technologies. Lastly, process tolerance, or the ability to withstand variations and deviations during manufacturing, is crucial to ensure reliable and robust production [30].

I.7. Conclusion:

Renewable energy, particularly photovoltaic (PV) modules, has emerged as a crucial solution for sustainable and clean energy generation. This paper aimed to provide a general overview of renewable energy and photovoltaic modules. The study highlighted the significance of dynamic modeling in understanding the performance of PV panels under various operational conditions. By accurately capturing the electrical behavior of PV panels in response to changing solar irradiance and temperature conditions, dynamic models enable better prediction of performance and facilitate the development of advanced control strategies for maximizing energy conversion efficiency.

The research emphasized the importance of incorporating factors like the panel's electrical characteristics, solar radiation levels, temperature effects, and environmental impacts in dynamic modeling. Advanced simulation techniques, such as numerical integration methods, were highlighted as effective tools for simulating the transient response of PV panels.

The findings underscored that dynamic modeling contributes to improving the design, operation, and control of PV panel systems. By providing valuable insights into the dynamic behavior of PV panels, these models enable more informed decision-making and optimization of energy generation. Furthermore, dynamic modeling plays a vital role in advancing the utilization of solar energy, promoting sustainable practices, and reducing reliance on fossil fuels.

Chapter II

Dynamic thermal model

II. Introduction:

The operating temperature of a PV panel is influenced by multiple factors, including solar radiation, ambient temperature, wind speed and direction, panel material composition, and mounting structure. Typically, a commercial PV panel converts 13-20% of the incident solar radiation into electricity, with the remaining energy being converted into heat [31]. Additionally, the PV panel generates its own heat due to the photovoltaic effect, and further heating occurs due to the energy radiated at infrared wavelengths in the solar spectrum. The impact of operating temperature on PV panel output efficiency has been well documented [32, 33], with increasing temperatures resulting in decreased power output. When evaluating PV system efficiency, temperature variations are often assumed instantaneous or modeled using hourly steady-state conditions. However, temperature changes in response to varying solar radiation levels do not occur instantaneously. Instead, the PV panel heats up and cools down gradually in response to step changes in solar radiation, with the temperature lagging behind the solar radiation changes in an exponential manner. When modeling PV panel power output over short time periods, such as minute-by-minute, the temperature response becomes significantly more important relative to the time of interest.

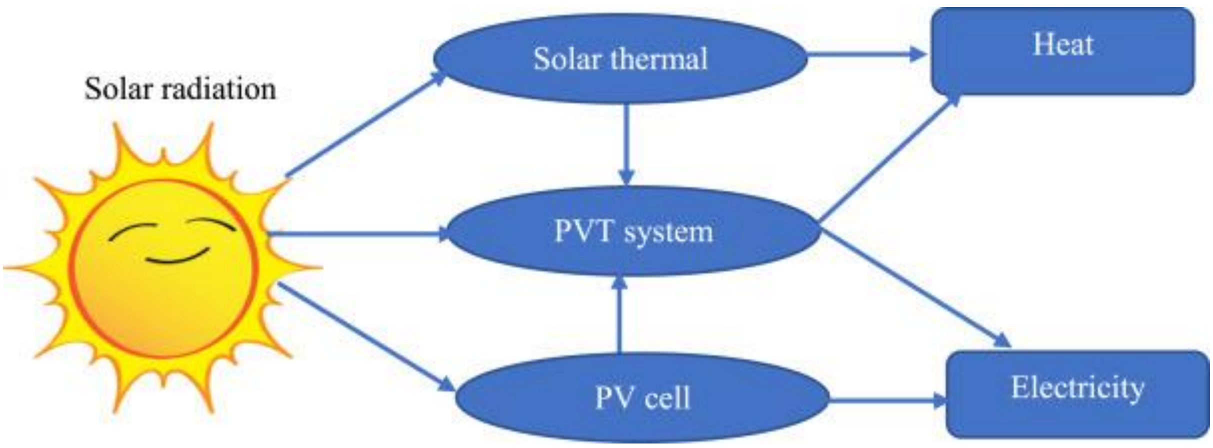

Figure II.1. Components of PV system [34].

II.1. Thermal modelling:

Thermal modelling the basic principle in thermal modelling is the first law of thermodynamics, which is energy conservation. The PV module without the mounting frame is considered as control volume, and lumped transient analysis is adopted for this study. In the case of lumped transient thermal modelling, the governing equation derived from the first law of thermodynamics for a PV [35].

II.2. Modeling:

Modeling has been a valuable tool for engineering design and analysis, encompassing various definitions depending on the specific application. However, the fundamental concept remains consistent; modeling involves solving physical problems by simplifying reality through the use of assumptions. In engineering, modeling is typically categorized into two main types: physical/empirical modeling and theoretical/analytical modeling.

Physical modeling involves conducting laboratory or in situ tests to gather relevant data and information. Engineers and scientists utilize this data to develop empirical or semi-empirical algorithms that can be applied practically. These algorithms are derived from observed relationships and patterns in the collected data. They provide a useful framework for understanding and predicting real-world phenomena.

On the other hand, theoretical or analytical modeling focuses on developing mathematical or computational models based on fundamental principles and theories. These models rely on mathematical equations and logical deductions to describe and analyze the behavior of complex systems. Theoretical models are often used to gain insights into the underlying mechanisms and processes, allowing engineers to make informed decisions and optimize designs [36].

II.2.1. Mathematical modelling:

The mathematical modelling developed in this research was based on the concept of an energy balance. The notion of the energy balance equation states that in any given area, or location in a system, the heat in that area is equal to the heat leaving the area plus any heat that is stored in the material. One may say that

Thermal energy balance:

Thermal energy in = Thermal energy out + Thermal energy stored [37].

II.3. Heat Transmission Mechanisms in PV Panels:

In the thermal modeling of photovoltaic (PV) panels, understanding and accurately representing the mechanisms of heat transmission is crucial for predicting performance and optimizing design. The primary mechanisms of heat transmission are heat conduction, heat convection, and heat radiation. Each of these mechanisms operates according to distinct physical principles and affects the thermal behavior of PV panels differently [38].

II.3.1. Heat Conduction:

Equation for Heat Conduction: The rate of heat conduction (Qcond) through a material is :

$$Q_{cond} = A_1 . \frac{1}{r_1+r_2} . (T_1\text{-}T_2) \qquad \text{(II.1)}$$

In addition, the equation for conductive resistance is given by:

$$r_{cd} = \frac{S}{\lambda} \qquad \text{(II.2)}$$

II. 3.2.Heat Convection:

Convective heat transfer, also known as convection, is the process of transferring heat from one location to another through the movement of fluids. It involves the combined effects of heat conduction within the fluid (diffusion) and heat transfer by bulk fluid flow (advection). Convection is the dominant mode of heat transfer in liquids and gases [39].

In the context of convection, the term "advection" refers to the transport of heat by fluid streaming, [40], which is accompanied by, heat diffusion (conduction) within the fluid. The overall process of heat transfer by convection encompasses both advection and diffusion.

Free convection occurs when the fluid motion is driven by buoyancy forces resulting from temperature variations within the fluid. This type of convection occurs naturally without any external forcing. On the other hand, forced convection refers to situations where external means, such as fans, stirrers, or pumps, induce fluid motion and create an artificially induced convection current [41].

m

$$Q_{conv,fg,forcd} = A_{fg} . h_{conv_f} . \left(T_{fg}\text{-}T_a\right) \qquad \text{(II.3)}$$

In this work the convective coefficients have been calculated by means of the following correlations

$$h_{conv,fg,forced} = 5{,}7 . W + 11{,}4 \qquad \text{(II.4)}$$

Where W represents the speed of the wind (m/s).

II.3.2.2. Free (Natural) Convection:

Occurs due to the buoyancy effects induced by temperature differences within the fluid, causing fluid motion without any external mechanical force. This type of convection is prevalent when the fluid surrounding the PV panel heats up, becomes less dense, and rises, while cooler, denser fluid moves downward to replace it [38].

Equation for Free Convection: Newton's law of cooling also gives the heat transfer rate (Qconv) due to free convection:

$$h_{conv,fg,free} = \frac{NU_{free,fg} \cdot L_C}{\lambda} \qquad \text{(II.5)}$$

Back glass

$$h_{conv,bg,free} = \frac{NU_{free,bg} \cdot L_C}{\lambda} \qquad \text{(II.6)}$$

Where the Nusselt number is a dimensionless number that describes the ratio of convective to conductive heat transfer across a boundary (such as a surface). It indicates the efficiency of convective heat transfer. A higher Nusselt number signifies more efficient convective heat transfer compared to conduction [37].

Otherwise, the convection is mixed, a combination of forced and free convections, and the coefficient of convection is calculated as follows [37].

$$h_{conv,mix} = ({h^3}_{conv,fg,forced} + {h^3}_{conv,fg})^{\frac{1}{3}} \qquad \text{(II.7)}$$

II. 3.2.3 Convective Heat Transfer Coefficient:

The coefficient $h_{conv,free}$ is influenced by factors such as fluid properties, temperature difference, and surface orientation. It can be determined using empirical correlations based on dimensionless numbers such as the Grashof number (Gr) and the Nusselt number (Nu) [38].

$$h_{conv,fg} = \frac{\lambda_{fg} \cdot NU}{L_C} \qquad \text{(II.8)}$$

Function of the Nusselt number

$$Nu = [0.825 + (0.387 * Ra^{1/6})/\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}]\text{^}2 \qquad \text{(II.9)}$$

$$Ra = Gr{*}Pr \qquad \text{(II.10)}$$

$$Pr = \frac{c_\mu}{k} \qquad \text{(II.11)}$$

The Rayleigh number (Ra) is the product of the Grashof (Gr) and Prandtl (Pr) [43]. numbers. It is a measure In fluid dynamics and heat transfer, the Rayleigh number (Ra), Prandtl number (Pr), and Grashof number (Gr) are dimensionless numbers that characterize the behavior of fluid flow and thermal convection. The Rayleigh number combines the effects of thermal buoyancy and thermal diffusivity, indicating the likelihood of convective motion in a fluid. The Prandtl number describes the ratio of momentum diffusivity (viscosity) to thermal diffusivity, providing insight into the relative thickness of the velocity and thermal boundary layers. The Grashof number quantifies the relative importance of buoyancy forces compared to viscous forces in natural convection scenarios. Together, these numbers help predict and analyze the onset and intensity of convective heat transfer in fluids [37].

II. 3. 4Heat Radiation in PV Panels:

Radiation is the transfer of heat in the form of electromagnetic waves, primarily in the infrared spectrum. Unlike conduction and convection, radiation does not require a medium and can occur in a vacuum. In the context of photovoltaic (PV) panels, radiative heat transfer is a significant mechanism for energy loss, particularly at high operating temperatures

Radiative heat transfer is defined as the heat transferred by the emission of electromagnetic waves from a surface. Stefan-Boltzmann's law of blackbody radiation governs this process. In the case of PV modules mounted on a roof, radiation exchange occurs with the sky, earth, and roof. The critical step in calculating radiative heat loss is the accurate estimation of the temperature of these surfaces [38].

heat sink in layers:

$$\emptyset_1 = A_{fg} * \alpha_{fg} * G \qquad (II.12)$$

Where G is the irradiation emitting from the sun, Afg is the surface of the glass, and a is the absorptivity of it .

II. 3.4.1 Fundamentals of Heat Radiation:

Heat radiation from a PV panel involves the emission of thermal energy from the panel's surface to the surrounding environment. This process is governed by the Stefan-Boltzmann law, which states that the power radiated per unit area of a surface is proportional to the fourth power of its absolute temperature. In real-world applications, the net radiative heat transfer from a PV panel also considers the radiation absorbed from the surroundings. [38]. the net radiative heat transfer rate (Qrad) from a PV panel to its surroundings can be expressed as:

$$Q_{rad} = A_{fg} . h_{r,fg \to sky} . (T_{sky} - T_{fg}) \qquad (II.13)$$

The radiative heat transfer coefficient (h_r) is a useful parameter that simplifies the calculation of radiative heat transfer, allowing it to be treated similarly to convective heat transfer in some thermal analyses. This coefficient essentially quantifies the rate of radiative heat transfer per unit area per unit temperature difference between the surface and its surroundings:

$$h_{r,fg\rightarrow sky} = \sigma.\varepsilon_{fg}.F_{fg\rightarrow sky}.(T_{sky} + T_{fg}).(T_{sky}^{\ 2} + T_{fg}^{\ 2}) \qquad \text{(II.14)}$$

In the equation, delta represents Boltzman constant, which relates the average kinetic energy of particles in a gas to temperature. The symbol epsilon denotes the emissivity of the glass, determining how well it radiates energy compared to a perfect black body. The term F represents the view factor, which accounts for the geometric configuration and inclination of the panel, affecting how much radiation emitted from one surface is received by another

The sky temperature can be calculated using a correlation given in Refs. [35]. However, estimating the earth and roof temperatures is more complicated, as they depend on the state of the land surrounding the PV module and the materials used in the roof covering, respectively. In this study, both earth and roof temperatures are assumed equal to the ambient temperature

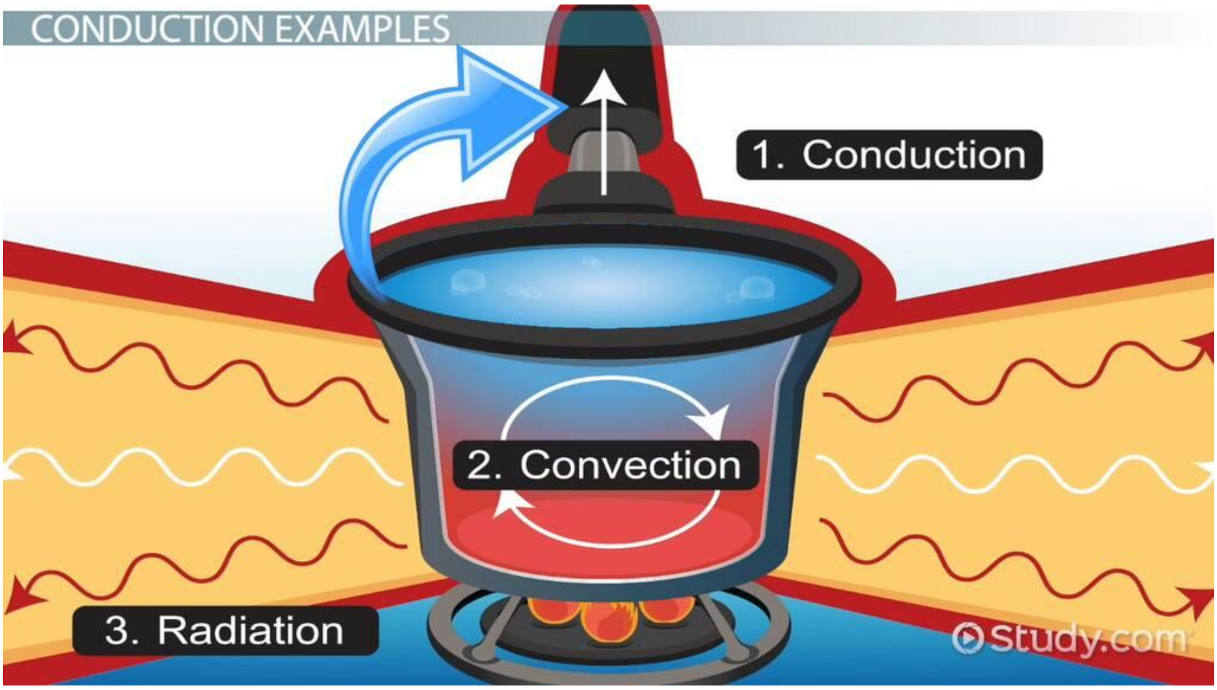

Figure II.2. Heat transfer methods [44].

II.3.5. Heat capacity:

Heat capacity is a crucial parameter of PV modules and a necessary component of transient thermal analyses. However, surprisingly, there is a lack of studies in the literature on measuring the heat capacity of PV modules. Most transient thermal models developed for PV modules assume a fixed value for heat capacity [43-45].

In a study by Torres Lobera [37], the impact of heat capacity value selection on a dynamic thermal model was investigated using measurements taken at 1-second intervals from a research plant in Finland, where cold and rainy weather prevails for most of the year. The authors parameterized the heat capacity value in the model and evaluated the resulting deviation of the module temperature from the measured value as a performance indicator. They concluded that the assumed value of heat capacity in the model significantly influences the model's performance during the summer months when ambient temperatures are relatively higher.

$$C_{fg} = \rho_{fg}.A_{fg}.S_{fg}.c_{fg} \qquad \text{(II.15)}$$

Where P (Kg/m^3) represents the density of the material, S its height (m), and c its specific heat (J/kg*K).

II.4. Theoretical Models:

The description of most engineering problems involves identifying key variables and defining how these variables interact. The study of theoretical modeling involves two important steps.

In the first step, all the variables that affect the phenomena under consideration are identified. This includes factors such as physical properties, boundary conditions, external forces, and any other relevant parameters [47].

Reasonable assumptions and approximations are then made to simplify the problem and make it more tractable. These assumptions help to narrow down the scope of the problem and focus on the most significant variables.

The interdependence of these variables is studied to understand how they influence each other and contribute to the overall behavior of the system. This involves analyzing the cause-and-effect relationships between the variables and identifying any feedback loops or dependencies that exist.

In the second step, the relevant physical laws and principles that govern the phenomena are invoked. These laws can come from various branches of science and engineering, such as mechanics, thermodynamics, electromagnetism, or fluid dynamics. By applying these laws, the behavior of the system can be described and predicted.

The problem is then formulated mathematically, typically with equations and mathematical models. These equations represent the relationships between the variables and describe how they change over time or in response to different conditions. Numerical methods or analytical techniques may be employed to solve these equations and obtain solutions that provide insights into the system's behavior.

Overall, theoretical modeling involves a systematic approach to understanding and describing engineering problems. It requires identifying relevant variables, making appropriate assumptions, applying physical laws, and formulating the problem mathematically to gain insights and predictions about the system's behavior [36].

II.4.1. Thermal resistances (K/W):

A thermal resistance network is composed of interconnected thermal resistances placed between nodes. These thermal resistances symbolize the resistance to heat flow across different points within the analyzed model. The thermal resistances in the network are modeled to account for conduction, convection, and radiation, which are the three primary mechanisms of heat transfer.

Conduction refers to the transfer of heat through direct contact between materials or within a solid medium. It is modeled by assigning appropriate thermal resistances to represent the resistance to heat flow through different components or layers.

Convection involves the transfer of heat through the movement of a fluid (liquid or gas). It is accounted for in the thermal resistance network by including convective thermal resistances that represent the resistance to heat transfer between a solid surface and the surrounding fluid.

Radiation is the transmission of heat through electromagnetic waves. In the thermal resistance network, radiation is considered by incorporating radiative thermal resistances to represent the resistance to heat transfer between surfaces due to thermal radiation [48].

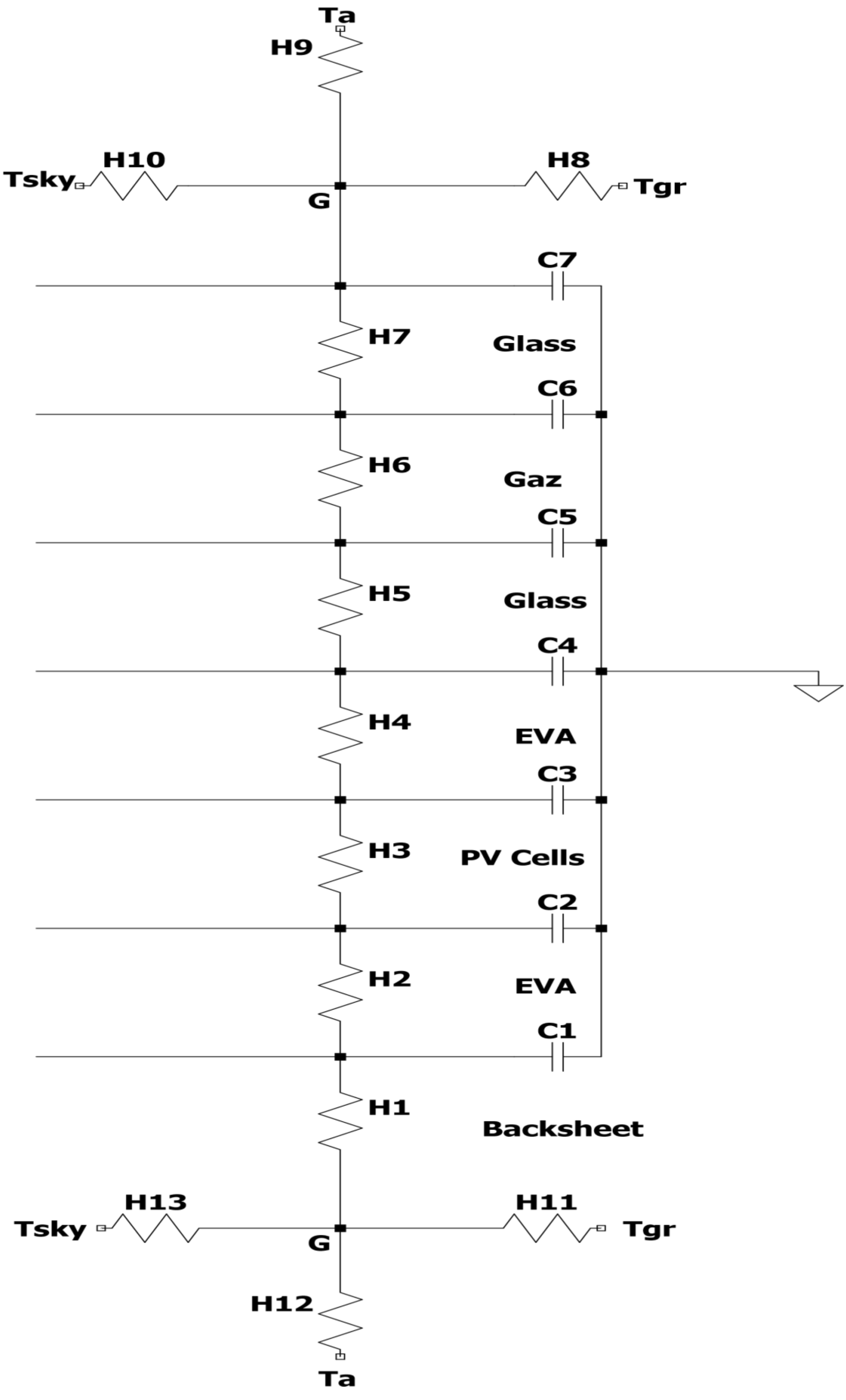

Figure II.3. Layer network system.

II.5. Model desing:

With thermal equivalent electrical circuit we can modeling each layer by a resistance and a capacitance this help to solve the energy balance equations between layers and also between the PV panel and surrounding environments, the Front, back side and ambient temperatures, irradiation, wind speed can be measured during the operation of the PV panel those variables can be used to calculate the inner layers temperature.

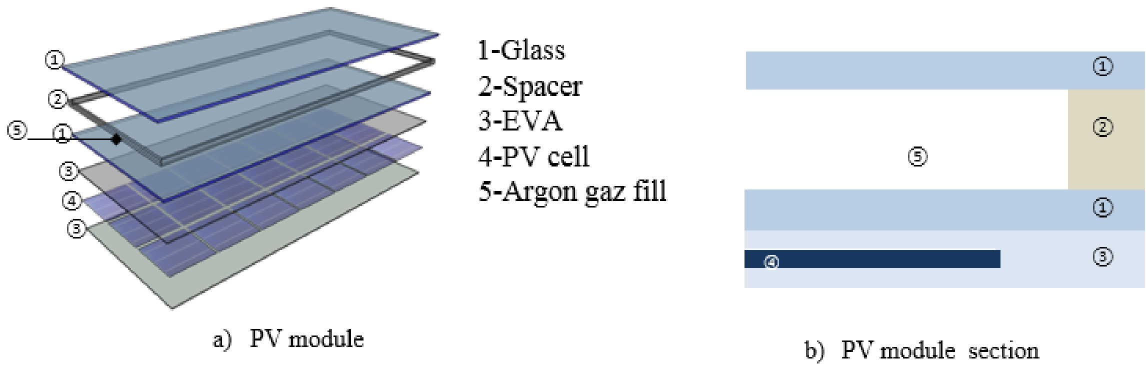

Figure II.4. The section schematic (b) and tested glass gas glass (3G) module sample (a).

II.5.1. Static Layer description:

First, we write the energy balance equation for each panel layer taking into account all energy exchanges between the layer and its environment.

Second, we solve this series of differential equations by a numerical method in order to obtain the temperature of each layer as a function of the time.

Crystalline silicon PV panel with a standard configuration is chosen for the simulation .It is composed of five layers as presented in Fig In general, the structure of PV panels depends on the PV supplier.

- **Energy balance equations:**
- **The front side (glass):**

The temperature in the front glass is the temperature in the node 1, presented the surface temperature (T_{fs}).

The node 1 (glass1):

$$Q_1 = (\dot{q}_{r,fg\to sky} + \dot{q}_{r,fg\to gr} + \emptyset_1 - \dot{q}_{conv,fg,mix} - \dot{q}_{cd,fg})*dt-(C1*(T_{fg}-T_{initial})) \qquad (II.16)$$

In this equation, the terms of the second member are respectively the thermal power exchanged by convection (K_c) between the front glass and the ambient air, by radiation (K_{sky}), (K_{gr}) between respectively the glass and the sky on the one hand and between the glass and the ground on the other hand, the thermal power exchanged by conduction (K_{fs}) between the glass and the first layer of EVA, Q1 is the thermal power absorbed by the glass.

Pfs is the density f the front glass (kg/m^3), c_{fs} specific heat (J/kg.K), d_{fs} thickness of the front glass (m).

The thermal power exchanged by conduction in the front glass is calculated as:

$$K_{fg} = \frac{\lambda_{fg}.A_{fg}}{d_{fg}} \qquad (II.17)$$

Several expressions allows us to calculate the sky temperature, the first expression is

The formula of Schott [49].

$$T_{sky} = T_{am}\text{-}\delta t \qquad (II.18)$$

δT = 20 K for the clear sky conditions, δT=0 for the cloudy sky conditions

$$T_{gr} = T_{am} \qquad (II.19)$$

The node 2 (gas):

$$Q_2 = (\dot{q}_{cd,fg} + \dot{q}_{r,gas\rightarrow fg} + \emptyset_2 \text{-} \dot{q}_{conv,gas})\text{*}dt\text{-}(C2\text{*}(T_{gaz}\text{-}T_{initial})) \qquad (II.20)$$

The node 3 (glass 2):

$$Q_3 = (\dot{q}_{conv,gas} + \emptyset_3 + \dot{q}_{r,glass2\rightarrow gas} \text{-} \dot{q}_{cd,glass2})\text{*}dt\text{-}(C1\text{*}(T_{glass}\text{-}T_{initial})) \qquad (II.21)$$

The node 4 (EVA1):

$$Q_4 = (\dot{q}_{cd,glass2} + \dot{q}_{r,eva1\rightarrow glass2} + \emptyset_4 \text{-} \dot{q}_{cd,eva1})\text{*}dt\text{-}(C3\text{*}(T_{eva}\text{-}T_{initial})) \qquad (II.22)$$

The node 5 (PV):

$$Q_5 = (\dot{q}_{cd,eva1} + \dot{q}_{r,pv\rightarrow eva1} + \emptyset_5 \text{-} \dot{q}_{cd,pv})\text{*}dt\text{-}(C4\text{*}(T_{pv}\text{-}T_{initial})) \qquad (II.23)$$

The node 6 (EVA 2):

$$Q_6 = (\dot{q}_{cd,pv} \text{-} \dot{q}_{cd,eva2})\text{*}dt\text{-}(C3\text{*}(T_{eva2}\text{-}T_{initial})) \qquad (II.24)$$

The node 7(backglass):

$$Q_7 = (\dot{q}_{cd,eva2} \text{-} \dot{q}_{r,bg\rightarrow sky} \text{-} \dot{q}_{r,bg\rightarrow gr} \text{-} \dot{q}_{conv,bg})\text{*}dt\text{-}(C5\text{*}(T_{bg}\text{-}T_{initial})) \qquad (II.25)$$

The electrical efficiency of the panel has been calculated as:

$$\eta = \eta_{ref}\left[1 - \beta_0\left(T_{pv} - T_a\right) + \gamma . log(G)\right] \qquad (II.26)$$

Table II.1. Characteristics of the layers [51].

	Front layer	Central layer	Back layer
λ (W/mK)	1.4	168	1.4
e (m)	0.003	0.003	0.005
ρ (kg/m^3)	3000	2330	1200
E	0.9	-	0.9
A	0.6	0.6	0.6
τ	0.84	-	-
c (J/kgK)	500	757	500

Table II.2. Characteristics of the PV module [51].

Characteristic	Value
ϑ (°)	90
Front glass surface (m^2)	1
Pv surface (m^2)	0.4
Back glass surface (m^2)	1

II.6.Buildings photovoltaic:

The integration of photovoltaic energy in buildings (BIPV) has proven to be an efficient and aesthetically pleasing way to combine local renewable electricity generation with various functions of the building envelope Whether in existing buildings or new constructions, BIPV solutions offer diverse possibilities and can significantly contribute to energy savings In urban settings, façades have a tremendous potential for BIPV implementation, often surpassing that of roofs Ventilated façades (rainscreens) and curtain walls are commonly used building-envelope systems in commercial buildings, and to a lesser extent, residential buildings. These types of façades are particularly suitable for BIPV integration as demonstrated by numerous international examples in recent years the market currently offers a variety of products and solutions for the successful development of BIPV rainscreens and curtain walls. Additionally, recent research has explored the technological advancements and design possibilities for BIPV materials

As BIPV continues to grow, it becomes increasingly important to enhance the available tools for optimal electrical design and simulation of BIPV systems. This entails accurately modeling the performance of BIPV systems, including the modeling of PV module temperature. Over the years, various modeling approaches have addressed the operating temperature of freestanding PV modules, as summarized in However, in building-integrated systems, the modules are not typically mounted in open racks, and they are often not optimally tilted or ventilated like PV plants. Consequently, the operating temperatures of PV modules in buildings are generally higher than those in PV plants. Since determining, the module temperature is crucial for accurately simulating and predicting the performance of PV systems, testing procedures, modeling techniques, and standards have historically focused on module temperature. However, most of these efforts have been directed towards PV plants rather than PV integration in buildings [50].

II.7. Conclusion:

Dynamic thermal modeling plays a crucial role in understanding and predicting the thermal behavior of various systems and components. In the context of solar panels, dynamic thermal modeling allows for the assessment of temperature variations and their impact on the performance and efficiency of the panels.

By considering factors such as solar radiation, ambient temperature, airflow, and heat transfer mechanisms, dynamic thermal models can simulate and predict the temperature distribution within solar panels over time. This knowledge is essential for optimizing the design, efficiency, and reliability of solar energy systems.

Dynamic thermal modeling enables researchers and engineers to identify potential hotspots, evaluate the effectiveness of cooling strategies, and assess the long-term thermal performance of solar panels. It also helps in the development of thermal management techniques, such as active cooling or passive heat dissipation, to mitigate temperature-related issues and enhance the overall performance of solar energy systems.

Furthermore, dynamic thermal modeling can be integrated with electrical models to provide a comprehensive understanding of the combined electrical and thermal behavior of solar panels.

Chapter III

Validation test and discussion

III. Introduction:

The dynamic modelization of solar panels involves understanding and simulating their thermal behavior under various environmental conditions. Solar panels are complex devices composed of multiple layers that interact with each other and the environment, influencing their performance and efficiency. This chapter focuses on developing a dynamic model to simulate the temperature distribution across different layers of a solar panel, thereby helping to predict its performance and optimize its design. By accurately modeling the thermal dynamics, we can better understand how external factors such as irradiance, ambient temperature, and wind speed affect the solar panel's operation. This knowledge is crucial for improving the design and efficiency of solar panels, ultimately contributing to the advancement of renewable energy technologies.

III.1. Methadology:

Our PV module is attached to a wall and consists of seven distinct layers: glass1, argon gas, glass2, EVA (ethylene-vinyl acetate), PV cell, EVA, and backsheet. The argon gas is sandwiched between the two glass layers using a spacer, similar to glazing techniques used in windows. The entire PV module is covered with polystyrene for additional insulation. This setup helps in understanding the impact of each layer and the insulating effect of argon gas on the overall thermal performance of the solar panel.

To measure the meteorological parameters, an illumination device (lux meter) was placed on top of the PV module. This device measures the amount of solar irradiance incident on the panel, which is a critical factor influencing its thermal behavior. A portable thermocouple was used to measure the ambient temperature and the temperature on the left side of the backsheet. This provides a reference for the environmental conditions during the test.

A data logger was employed to collect voltage, current, the temperature of the front glass (T glass), and the temperature on the right side of the backsheet (T backsheet). The data logger ensures continuous and accurate recording of these parameters, allowing for detailed analysis.

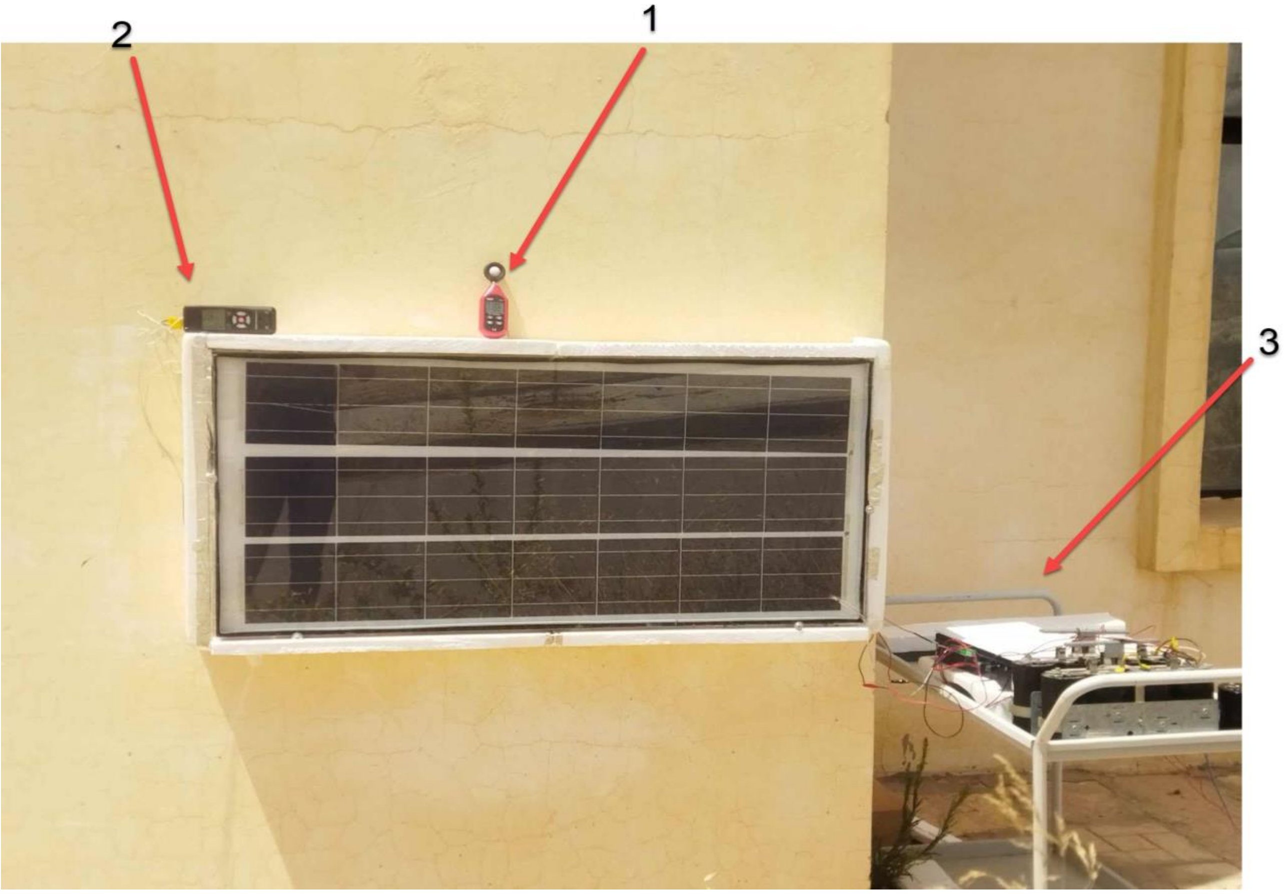

Figure III.1. Panel photovoltaic.

1-Irradiance Measuring Device

2-portable thermocouple device

3-DataLogger

The experimental procedures began with a preliminary testing phase on the first day, dedicated to ensuring the proper functioning and calibration of all equipment. This involved setting up the instruments, verifying their readings, and making necessary adjustments. The actual data collection took place on the second day over a six-hour period, from 10:00 AM to 3:00 PM. Measurements were taken every 15 minutes to ensure accuracy,. The environmental conditions were monitored carefully; the day was mostly sunny with occasional partial cloud cover, which intermittently blocked the sun. And the wind was stable for the most part.

III.2. Thermal Network:

By modeling the solar panel using an equivalent circuit composed of capacitors and resistors, we can effectively simulate the dynamic thermal and electrical interactions within the panel. This method allows us to capture the transient thermal responses and steady-state conditions of the solar panel layers. The capacitors represent the thermal capacitance of each layer, indicating their ability to store heat, while the resistors represent the thermal resistance, indicating the layers' resistance to heat flow.

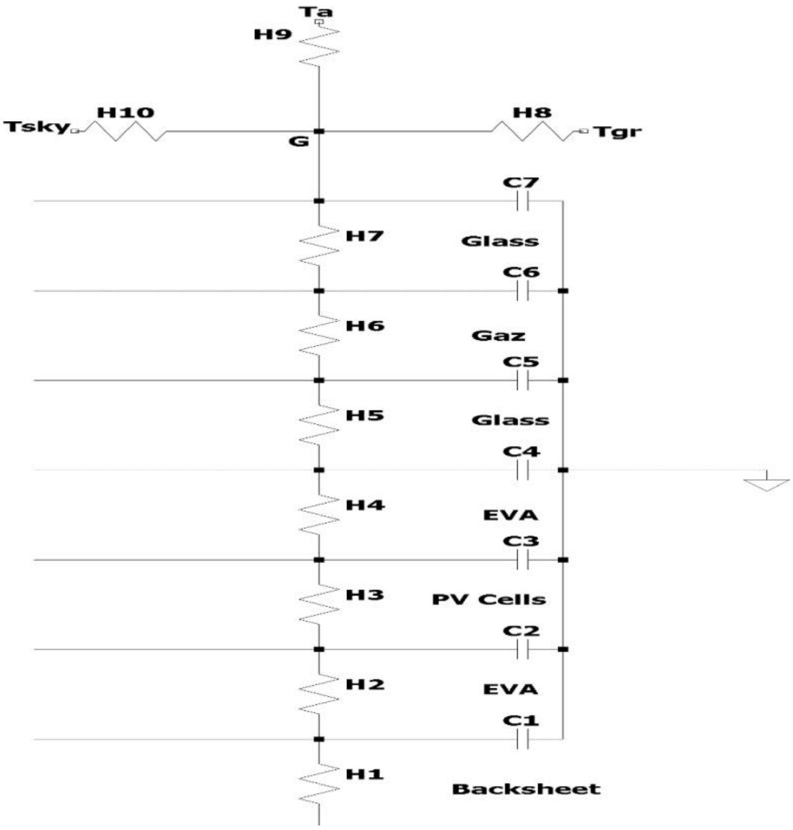

Figure III.2. Thermel network.

III.2.1 Boundary conditions:

Variable ambient temperature and variable irradiance based on actual measurements, as well as convective heat transfer coefficients that account for the natural convection around the panel. The wind is taken as a fixed value for simplification.

III.3. Argon Gas Characteristics:

Argon gas is a noble gas known for its excellent insulation properties. It is commonly used in double-glazing windows to improve thermal insulation by reducing heat transfer through conduction and convection. Argon gas is heavier than air, which makes it an effective insulator because it reduces the movement of heat through the gas space. Additionally, argon gas is nonreactive, non-toxic, and does not contribute to environmental pollution, making it an ideal choice for enhancing the thermal performance of various systems.

In the context of solar panels, argon gas can be utilized to improve insulation between the glass layers, thereby reducing the thermal conductivity of the panel. This reduced heat transfer can lower the operating temperature of the photovoltaic (PV) cells, which is beneficial for their efficiency and lifespan. The lower temperature reduces thermal stress on the PV cells, minimizing the risk of overheating and potential damage. Moreover, argon gas provides sound insulation, which can be advantageous in residential and commercial installations where noise reduction is a concern. Theoretically, the inclusion of argon gas in the PV module can help maintain a more stable and cooler operating environment for the PV cells, enhancing overall performance [52].

III.4. Fsolve Method:

Fsolve is a MATLAB function used for solving systems of nonlinear equations. It is particularly useful in engineering and scientific computations where such equations are common. In this study, FSolve is employed to calculate the temperatures of various layers in the PV module by solving the differential equations governing heat transfer. The heat transfer equations account for conduction, convection, and radiation effects within the layers of the solar panel.

The differential equations describe how heat flows through each layer of the panel, considering the thermal properties and boundary conditions. By inputting these equations into FSolve, along with the known parameters such as ambient temperature, irradiance, and material properties, we can obtain the temperature distribution across the layers. This allows for an accurate simulation of the panel's thermal behavior under different environmental conditions.

The ability to solve these equations iteratively helps in refining the model to better match experimental data, ensuring that the simulated temperatures closely align with the measured values [53].

III.5. Simulation and teste results:

The tests were conducted over two days. The first day was dedicated to testing and calibrating the equipment to ensure accurate measurements. On the second day, the actual data collection was carried out over approximately six hours, from 10 AM to 3 PM, on a mostly sunny day with occasional partial cloud cover. Measurements were taken every 15 minutes to capture the dynamic changes in temperature and other parameters, resulting in a total of 18 measurements.

III.5.1. Simulation Meteorological Parameters:

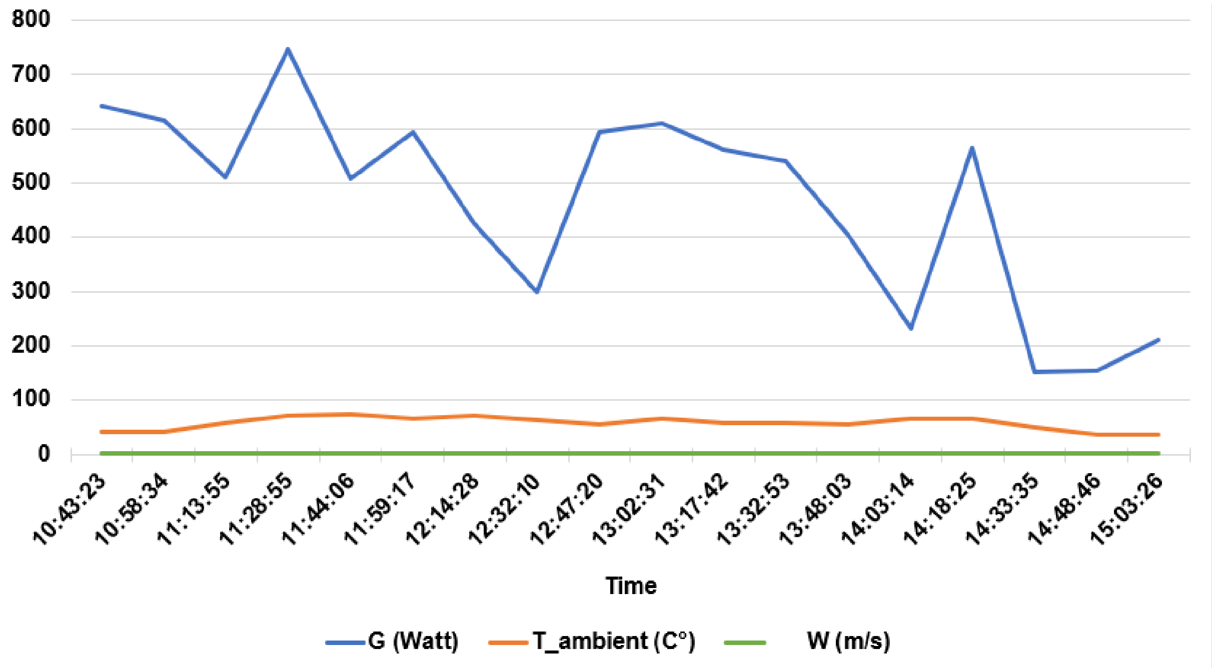

Figure III.3. Meteorological Parameters.

In this section, we present the results from our simulations and the subsequent analysis. We conducted two simulations: one using the parameters of argon gas sandwiched between the glass layers, and another with an air gap. The objective was to compare the thermal behavior and effectiveness of argon gas as an insulating material against an air gap.

III.5.2.Simulation air gap module:

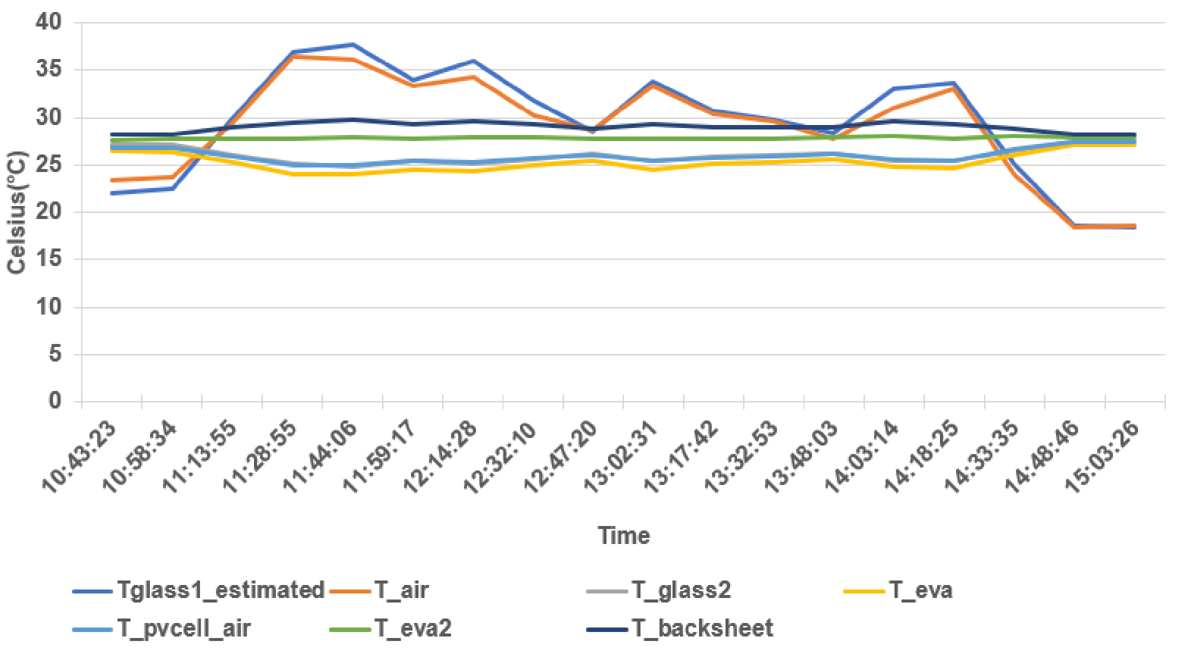

Figure III.3. air gap module.

III.5.3. Simulation argon module:

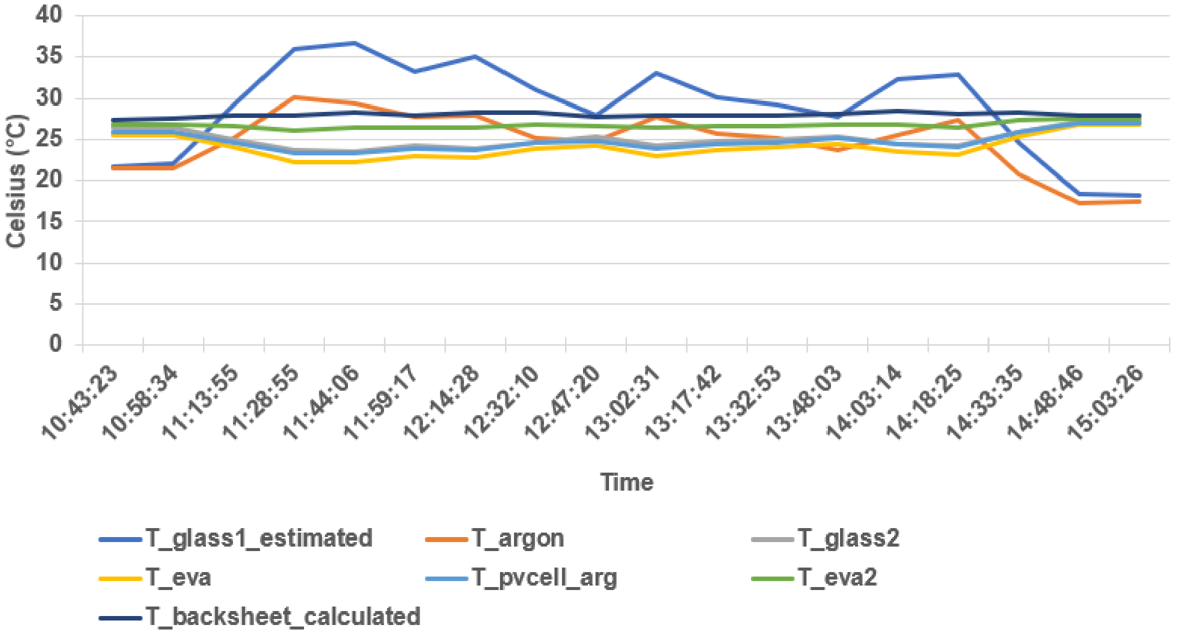

Figure III.4. Argon module tempreatures.

III.5.4. Simulation glass temperature

analysis compares the measured glass temperature with the estimated temperatures from our simulation. The measured glass temperatures (°C) are as follows:

There is a significant difference between the measured and estimated temperatures at the start. The model underestimates the temperature, which suggests potential adjustments or additional factors to consider in the thermal model. Although they're close during midday

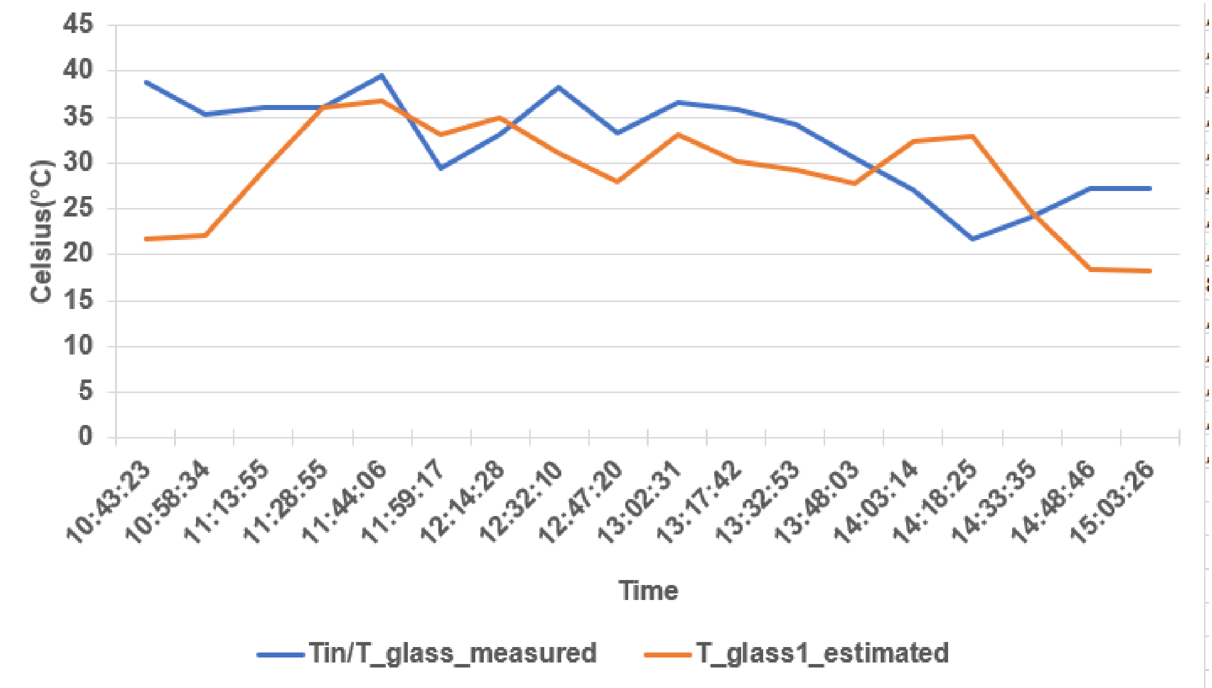

Figure III.5. Glass Temperature.

III.5.5.Simulation Backsheet Temperature.

analysis compares the measured backsheet temperatures with the calculated values. The measured backsheet temperatures (°C) are:

The calculated values are closer to the measured values but still show discrepancies, indicating that the model needs refinement

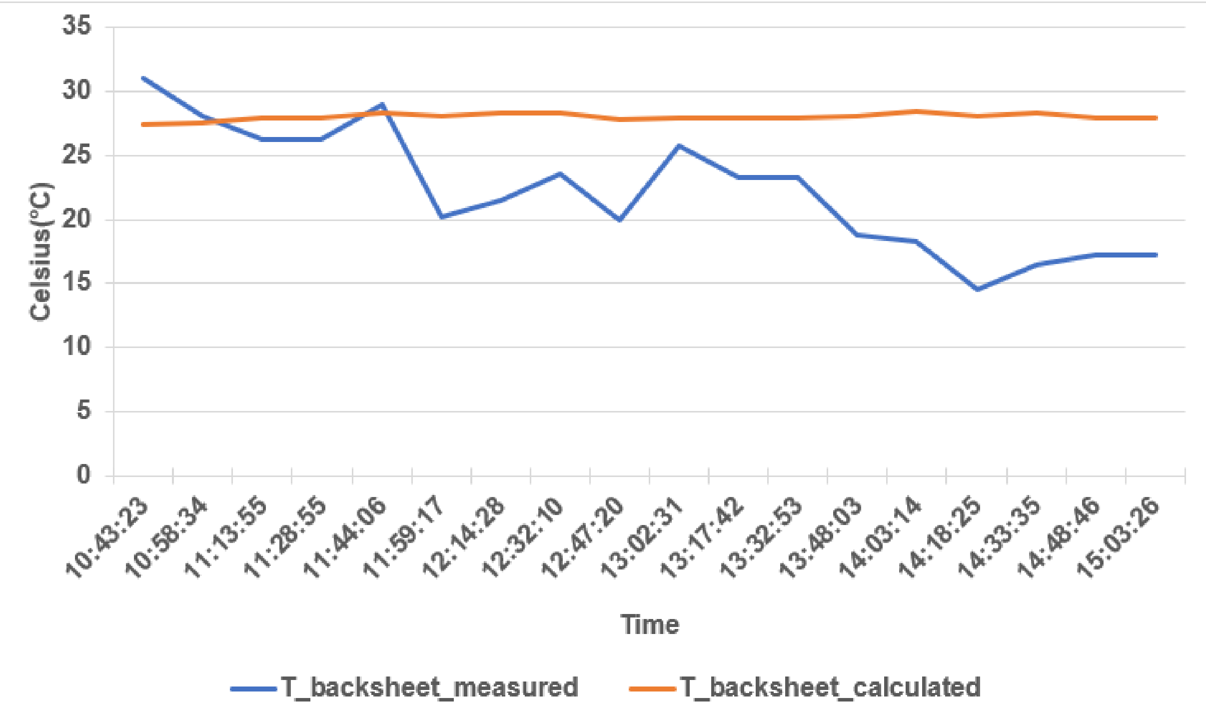

Figure III.6. Backsheet Temperature.

III.5.6. Simulation Glass and Backsheet temperature analysis:

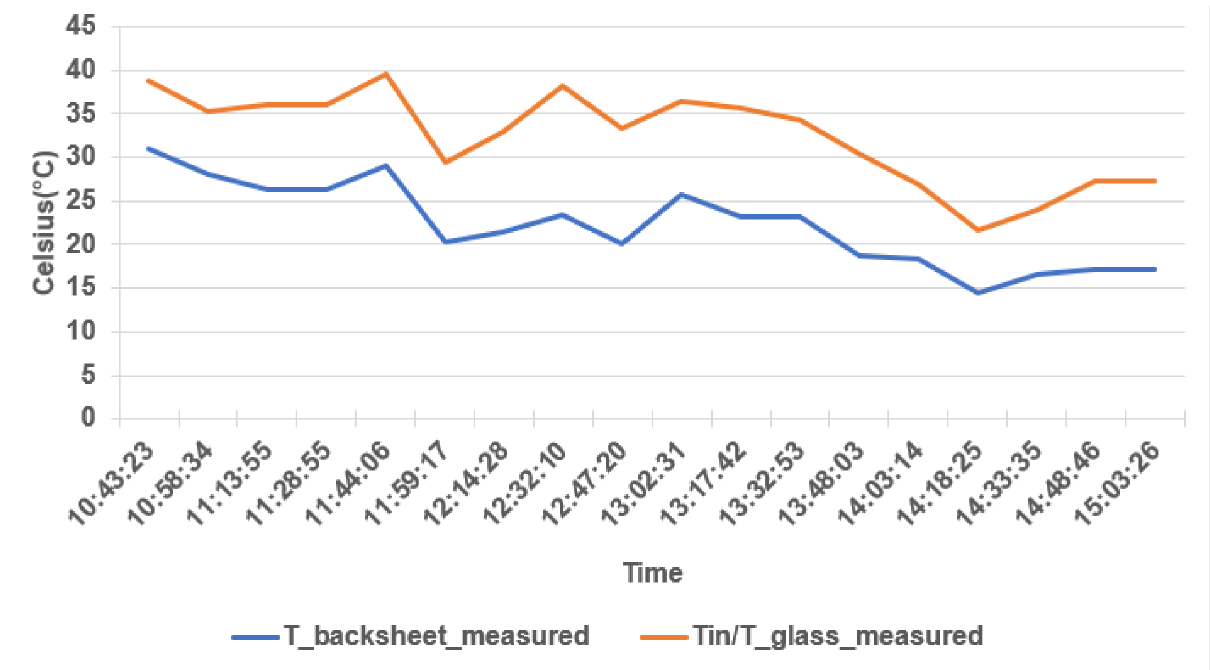

Figure III.7. Glass Backsheet Temperature.

From the measured data, it is evident that the glass temperature is consistently higher than the backsheet temperature. This difference can be attributed to the location of the glass at the front, directly exposed to solar irradiance, which heats it up more compared to the backsheet that is positioned at the rear and has lesser exposure to direct sunlight. The backsheet also benefits from better heat dissipation due to its position being attached to the wall and polystel on the panels' edges

III.5.7. Simulation PV Cell Temperature Analysis:

We also compared the PV cell temperatures from the argon module and the air gap module. As to analyse which one provides better insulation to the module theoretically

The temperatures are slightly higher for the air gap module, which is consistent with the insulating properties of argon gas

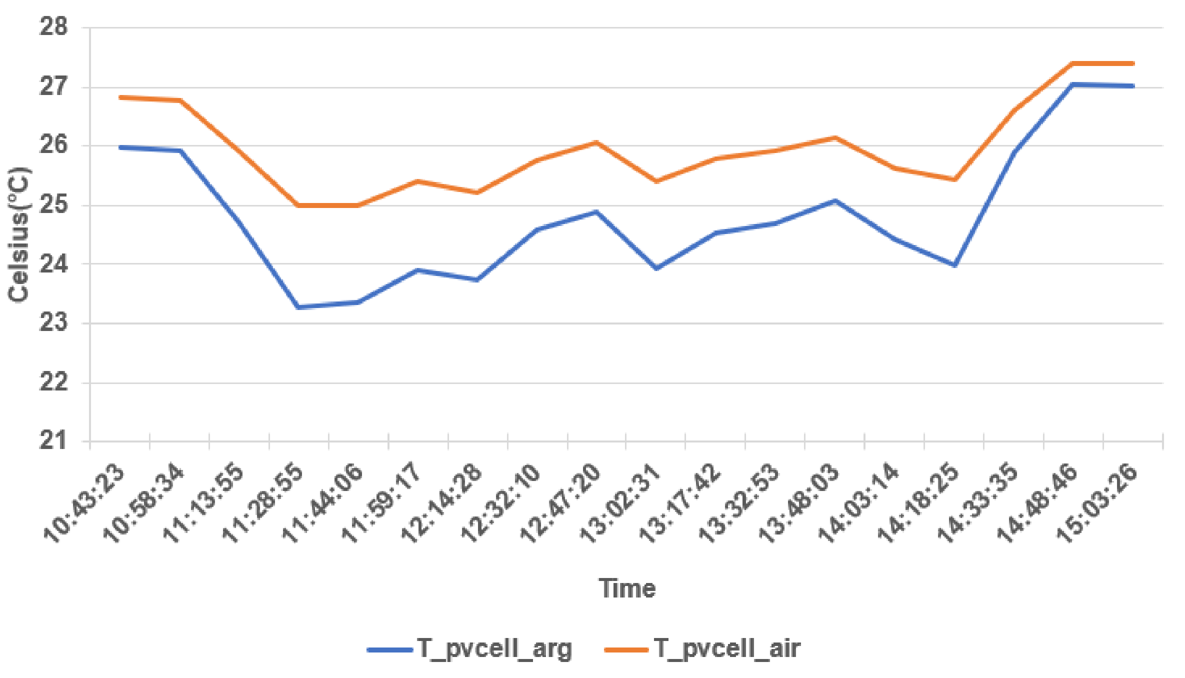

Figure III.8. PV Cell Temperature.

III.5.8. Simulation Power generated Analysis:

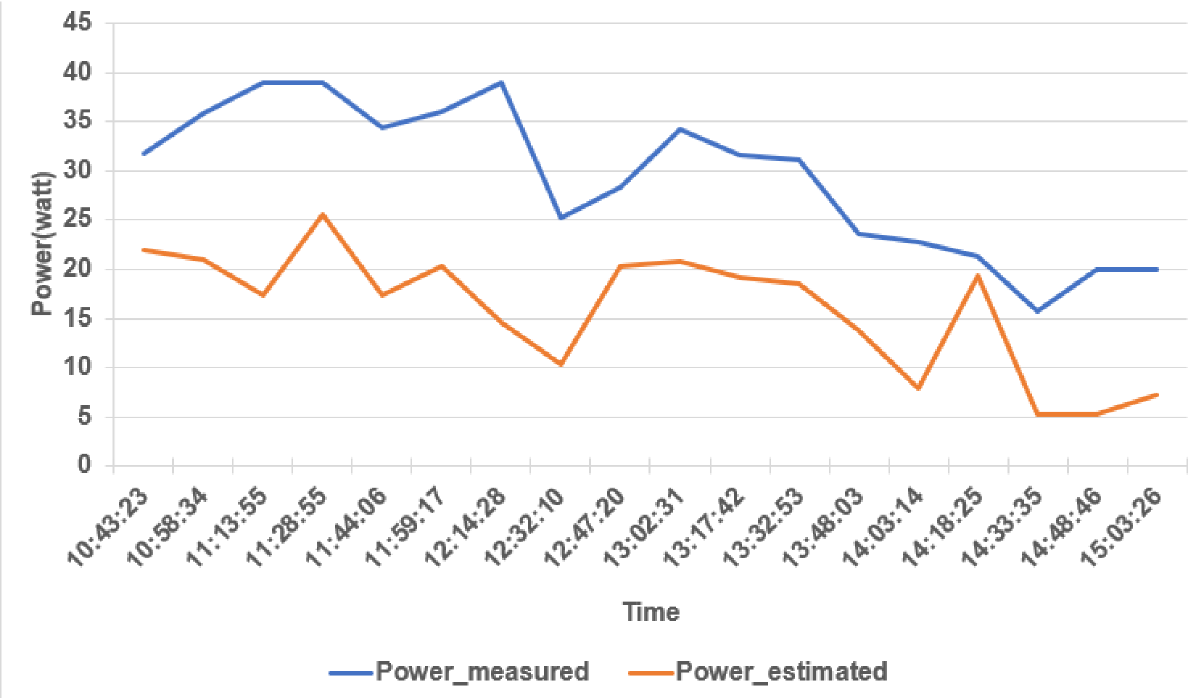

Figure III.9. Power generated.

The significant differences between the measured and calculated power generation suggest that our model needs refinement to better capture the complex interactions and efficiencies within the PV module.

III.6. Conclusion:

The comparison between the argon and air gap modules shows that argon gas offers better insulation properties, leading to lower temperatures in the PV cell. The use of argon gas in the PV module can reduce the temperature more effectively than an air gap, potentially enhancing the efficiency and longevity of the solar panel. However, the differences between measured and estimated temperatures and power generation indicate the need for further refinement in the thermal model to accurately capture the heat transfer dynamics in the PV module.

The two-day testing period, with the first day for equipment calibration and the second day for data collection, provided valuable insights. Conducting measurements every 15 minutes from 10 AM to 3 PM, we collected 18 data points, which were crucial for validating our model. The data logger, thermocouple, and illumination device played key roles in capturing the necessary data for our analysis.

The argon-filled module demonstrated lower PV cell temperatures compared to the air gap module, confirming the insulating properties of argon gas. This reduction in temperature can lead to improved efficiency and longevity of the solar panels. Despite the promising results, further refinement and validation of the thermal model are required to ensure accurate predictions and optimal design of PV modules with argon insulation.

Conclusion general

his research aimed to enhance the efficiency and performance of solar photovoltaic (PV) modules through advanced thermal management techniques. We began with an exploration of solar panel technology and renewable energy sources, delving into their composition, functionality, and the critical role they play in sustainable energy systems. Understanding the basic components and working principles of solar panels set the foundation for our detailed study.

Next, we focused on the thermal network of solar panels, developing a comprehensive model that incorporates heat transfer equations to simulate the thermal behavior of different layers within the module. This model allowed us to predict the temperature distribution across various components of the PV module, including glass layers, EVA, PV cells, and backsheet. The inclusion of argon gas as an insulating layer was a key innovation aimed at reducing thermal losses and improving overall efficiency.

The practical aspect of the research involved simulating the thermal model using MATLAB and validating the results with experimental data. We conducted tests on two separate days, ensuring the accuracy of our equipment and measurements. The experiments provided valuable data on temperatures and power generation under real-world conditions.

Our findings indicated that the front glass temperature (T_glass) and backsheet temperature (T_backsheet) showed notable differences between the simulated and measured values. The argon gas insulation was effective in lowering the PV cell temperature, as evidenced by the lower temperatures observed in the simulations compared to those with an air gap. However, there were discrepancies between the simulated and measured temperatures, particularly for the glass layers, highlighting the need for further refinement of the model.

Additionally, the comparison between the measured power generation and the calculated values revealed variations that underscored the complexity of accurately modeling all influencing factors. Despite these challenges, the use of argon gas demonstrated potential benefits in thermal management and efficiency enhancement.

In conclusion, the integration of argon gas insulation within PV modules shows promise in improving thermal performance and efficiency. The dynamic thermal model provided valuable insights, although further refinement is necessary to achieve more accurate predictions. This research contributes to the ongoing efforts to optimize solar panel technology, paving the way for more efficient and sustainable renewable energy solutions.

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