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Temperature Effects and Degradation of Building Integrated Photovoltaics

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This master's thesis investigates the temperature effects and degradation of building integrated photovoltaics (BIPV). The purpose of the thesis is to understand how the integration of photovoltaic modules into building's structure influences their performance and longevity, compared to traditional photovoltaic systems. Crystalline silicon photovoltaic technology is the primary focus, due to its prevalent use in both conventional and building integrated solar applications.

The thesis employs a combination of literature review and numerical calculation using the Sandia model temperature to explore the thermal behaviour of BIPV under various configurations and environmental conditions. Key factors such as module mounting configuration, airflow, coloured modules, and backsheet materials are examined to assess their impact on operating temperature and degradation.

The findings indicate that BIPV systems typically operate at higher temperatures than traditional PV due to restricted ventilation and aesthetic-driven design modifications, such as black coloured modules, leading to higher operating temperatures and accelerated degradation. The temperature difference was calculated to be up to 29°C, between typical PV and BIPV under normal operating conditions. Phenomena such as delamination, discolouration, hotspots, cell cracking and corrosion were identified as common thermal degradation mechanisms. Additionally, challenges such as solar curtailment and clipping were shown to contribute to increased thermal stress and heat accumulation in PV systems.

The thesis concludes that while BIPV presents aesthetic and space-saving advantages, careful design considerations and material choices are essential to mitigate temperature-related losses and to enhance the system's performance and durability over its lifecycle.

Key words: building integrated photovoltaics, BIPV

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Tässä diplomityössä tutkitaan rakennuksiin integroitavaan aurinkosähköön (BIPV) liittyviä lämpötilavaikutuksia ja ikääntymismekanismia. Työn tarkoituksena on selvittää, kuinka aurinkokennojen integrointi rakennuksiin vaikuttaa niiden suorituskykyyn ja käyttöikänsä verrattuna perinteisiin aurinkosähköjärjestelmiin. Työn painopisteenä on kiteinen piipohjainen aurinkosähköteknologia, koska sitä käytetään laajalti sekä tavallisissa aurinkopaneeleissa että rakennuksiin integroiduissa aurinkosähkösovelluksissa.

Diplomityössä hyödynnetään kirjallisuuskatsausta sekä numeerista laskentaa Sandia-mallia hyödyntäen BIPV-järjestelmien lämpökäyttäytymisen tutkimiseksi erilaisissa asennus- ja ympäristöolosuhteissa. Keskeisiä tarkasteltavia tekijöitä ovat moduulien asennuskonfiguraatiot, ilmanvaihto, värilliset aurinkopaneelit, sekä taustalevyjen materiaalit, joiden vaikutusta aurinkokennon lämpötilaan ja ikääntymiseen arvioidaan.

Tulokset osoittavat, että BIPV-järjestelmät toimivat tyypillisesti korkeammissa lämpötiloissa kuin perinteiset aurinkopaneelit, mikä johtuu rajoitetusta ilmanvaihdosta sekä esteettisistä suunnitteluratkaisuista, kuten mustista aurinkopaneeleista. Nämä tekijät aiheuttavat korkeamman käyttölämpötilan ja nopeamman ikääntymisen rakennuksiin integroiduissa aurinkopaneeleissa. Lämpötilaeron laskettiin olevan jopa 29°C tyypillisen aurinkopaneelin ja rakennukseen integroidun paneelin välillä normaalissa käyttöolosuhteissa. Yleisimpiä korkean lämpötilan aikaansaamia vaurioita ovat delaminaatio, värimuutokset, kuumapisteet, kennojen halkeaminen ja korrosio. Lisäksi ilmiöt, kuten aurinkosähkön käytön rajoitus (curtailment) ja invertterin tehorojoitukset (clipping), osoittautuivat lisäävän järjestelmän lämpörasitusta ja lämmön kertymistä.

Johtopäätöksenä todetaan, että BIPV-järjestelmät tarjoavat esteettisiä ja tilansäästöön liittyviä etuja, mutta järjestelmien huolellinen suunnittelu ja materiaalivalinnat ovat keskeisessä osassa lämpötilasta johtuvien tehohäviöiden minimoimiseksi sekä järjestelmän suorituskyvyn ja käyttöikänsä parantamiseksi.

Avainsanat: rakennuksiin integroitavat aurinkopaneelit, BIPV

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Introduction

The increasing global demand for renewable energy solutions has been driven largely by concerns over climate change and global warming. Human activities, such as burning fossil fuels, traffic and cutting down forests have led to significant increases in greenhouse gas emissions. This has resulted in rising global temperatures and extreme weather conditions, such as heatwaves, storms and wildfires. Without serious action these changes can have devastating and irreversible consequences for human societies and ecosystems. In response to these challenges governments, industries, and individuals have turned to clean energy alternatives to reduce carbon footprints and prevent climate change. Like other renewable energy sources, solar energy has gained widespread adoption due to its abundance, sustainability, and cost-effectiveness. In theory, the sun provides a limitless amount of energy, making solar energy one of the most promising solutions for global warming. Advances in photovoltaic (PV) technology, along with decreasing manufacturing costs, have made solar panels a viable energy source for residential, commercial, and industrial applications. As a result, traditional PV installations have expanded rapidly, and large-scale solar farms and rooftop PV systems are becoming common sight in the landscape. Many countries are investing heavily in solar technologies, implementing policies that encourage solar energy adoption. [1,2]

As cities' need for sustainable energy solutions has grown, installation of solar panels into the built environment has become a priority. However, conventional PV systems, typically rack mounted on rooftops or in open fields, often present aesthetic challenges in urban settings. Traditional solar panels are not designed to blend seamlessly with architectural elements, leading to concerns about visual appeal, especially in historical and urban areas. To address these challenges, building integrated photovoltaics (BIPV) have become an innovative solution. Unlike traditional PV systems, BIPV modules are designed to be part of a building's structure, replacing conventional materials such as facades, roofs, skylights, and windows. This approach allows buildings to generate renewable energy while maintaining aesthetic harmony and optimizing space usage. BIPV often use same technology as traditional rack mounted PV, but the main difference is that BIPV modules use different colours and transparent structures to make integration of the modules smoother and to make PV modules inseparable from the structure of the building. BIPV has gained popularity as an effective way to produce solar power without too much compromising the architectural design. [3–5]

Despite the advantages of BIPV, there are several challenges associated with its performance and longevity. Compared to traditional PV systems, BIPV modules experience different operational conditions that can impact their efficiency and degradation rate. Three key issues that arise with BIPV compared to standard PV modules are: elevated operating temperatures, decrease in performance, and accelerated degradation rate. When integrating a PV module into a building, and trying to make it blend with the structure, non-optimal mounting configurations are often used. Mounting directions and angles are determined by the existing building and surroundings. As BIPV modules are integrated into a building, rear side ventilation becomes ineffective and causes a rise in operating temperature. Coloured BIPV modules are also a common trend. Different techniques such as optical filters, anti-reflective coatings or coloured backsheets are used to make BIPV visually more pleasing. However, this causes changes in optical properties such as absorption and reflection, affecting the performance of the module. Elevated temperatures eventually lead to lower power production and faster degradation compared to traditional PV systems, and they should be taken into account when designing solar systems. [5–7]

As solar power has become more common, PV systems have faced new kinds of challenges. Solar clipping and solar curtailment have become increasingly common issues as solar power has become more affordable and overproduction occurs more frequently. Solar clipping means that solar panels have higher power output than the inverter's power capacity. The decreasing cost of photovoltaic modules has led to a trend where solar systems are often oversized in comparison to their inverters' capacity. This mismatch leads to wasted energy as excess energy compared to inverter's capacity is curtailed and converted into heat, and places additional stress on PV systems, affecting their efficiency and longevity. [8,9]

Solar curtailment has also become more common problem. The popularity of solar energy has resulted in curtailment, where excess solar power production is deliberately reduced, sometimes forcing PV systems to shut down. However, even when a PV system is open-circuited and not actively supplying power, it continues to generate voltage. Since this energy is not utilized, it places stress on the system, causing increased temperatures and accelerating degradation over time. [10]

When estimating solar system lifetime, it is important to understand how temperature affects PV module's performance and degradation. There are many factors that affect PV module operating temperature such as ambient temperature, geographical location, mounting

configuration, mounting direction and angle, ventilation, technology used, coatings, filters and so on. In this master's thesis temperature effects and degradation of building integrated photovoltaics are evaluated. The thesis focuses on crystalline silicon PV technology and goes through different kind of degradation mechanisms, as well as a comparison of operating temperature of different building integrated photovoltaic technologies versus typical photovoltaic modules. Finally, the operating temperature difference between different PV technologies and mounting configurations is calculated using the Sandia model. The main purpose of the thesis is to estimate what kind of compromises must be made in performance and longevity, when a photovoltaic module is integrated into a building. To reach the set objectives, the thesis aims to provide answers to the following research questions:

- What affects the operating temperature of a PV module?
- Does BIPV have higher operating temperature than typical PV modules?
- What kinds of degradation do high temperatures cause in PV modules?

1 PV module

1.1 Crystalline silicon PV module

Silicon is the most used material in solar cells. It is abundantly available and suitable material for solar cells. Silicon solar cells are reliable, with good efficiency, making them number one in the price-quality ratio. Monocrystalline and polycrystalline are the two most common types of crystalline-silicon solar cells. Monocrystalline cells are made of a single silicon crystal. It is more efficient than polycrystalline. Most commercially sold monocrystalline solar panels have an efficiency of 15% - 20%, while polycrystalline have an efficiency of 13% - 16%. Monocrystalline silicon cells are more expensive than polycrystalline due to the manufacturing process, but due to their higher purity and single crystal structure, they have higher efficiency. Monocrystalline solar panels are preferred for their better electricity production and their higher efficiency allows greater power output in smaller area and fewer PV modules. [2]

1.1.1 Components

A PV module consists of several key components, each having its own role to ensure high efficiency, longevity and durability of the PV module. The solar cell is the most important component, where sunlight is converted into electricity through the photovoltaic effect. Other components, like the glass cover, encapsulant, backsheet, frame, junction box, silver fingers, and bypass diodes are designed to protect the solar cells or to collect and transport electricity [11]. They are designed so that they have a minimum negative impact on the solar cells performance but still ensure durability and longevity of the cells and the whole module. The structure of typical PV module is shown in Figure 1.

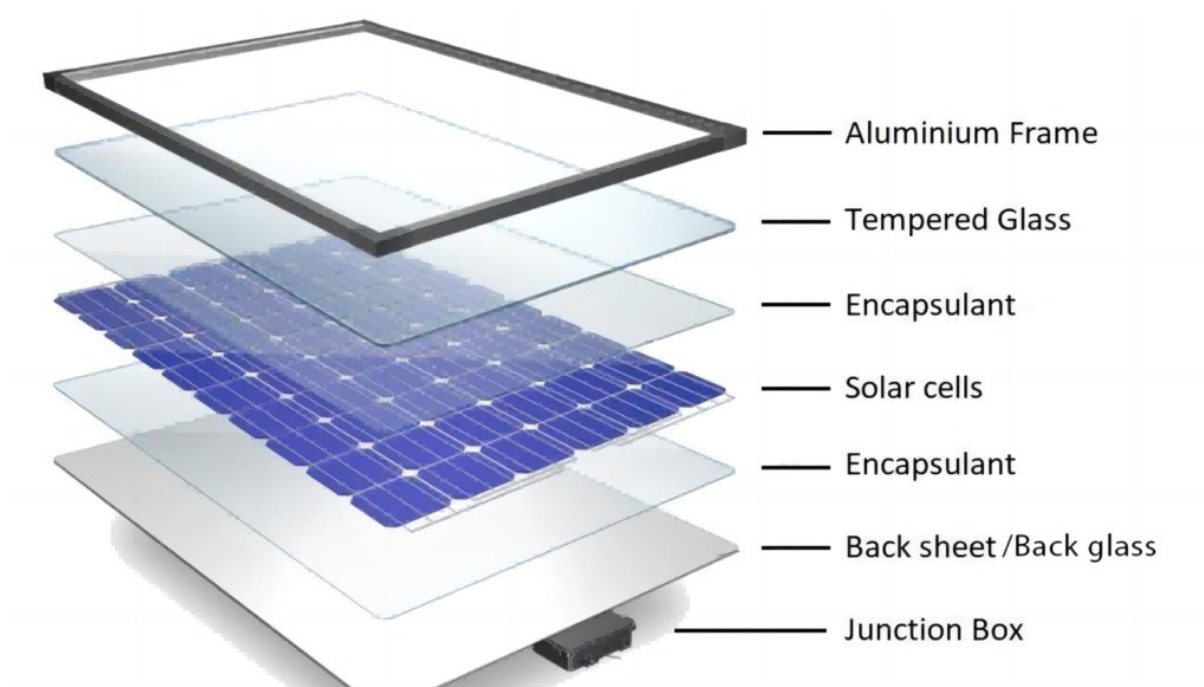


Figure 1. Structure of PV module with components. [11]

The solar cell is the most important component of the PV module. It is made of a semiconductor material that converts sunlight into electricity through the photovoltaic effect. Solar cells consist of p-type and n-type regions, a depletion region, back and front contacts. The n-type region is a material enriched with extra electrons. Negatively charged electrons are donated by impurity atoms added to the material. These impurity or dopant atoms have one extra electron compared to silicon's four valence electrons. For example, phosphorus has five valence electrons and is often used as a dopant in silicon to make n-type material [12]. In the n-type region the conduction band has free electrons, and the valence band is full of electrons. The p-type region is enriched with positively charged holes by acceptor atoms, which are also impurity atoms added to the material. [13] Acceptor atoms added to the material have fewer electrons than silicon. Boron is often used as a dopant in silicon to make p-type material, because it has three valence electrons [12]. In the p-type region the conduction band has only few electrons, and the valence band is full of electrons but has significant number of holes, which are the majority charge carriers. The depletion region separates p-type and n-type regions. It is a layer that is free of charge carriers due to the electric field that keeps it empty of charge carriers. The solar cells are connected in series and parallel to achieve desired voltage and current outputs. Silver fingers or strings are placed on top of the solar cell for current collection. Figure 2 shows an illustrated picture of a p-n junction of a solar cell. [13]

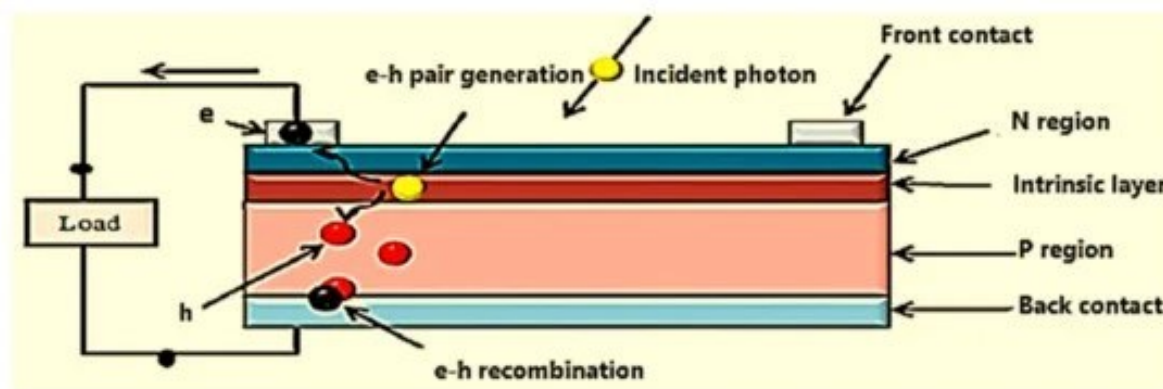


Figure 2. A p-n junction of solar cell. [13]

The glass cover is the outermost component of the PV module and protects the solar cells from weather and debris. Mechanical rigidity, impact resistance, electrical resistance, and weather resistance are the most important properties. The glass is clear and thermally toughened, meaning the glass is heated to high temperatures and rapidly cooled which creates compressive stress on the surface and tensile stress inside, resulting in stronger structure than normal glass. The glass is typically about 3.2 mm thick. Sometimes textured glass surfaces are also used to improve light capture. [1] Usually tempered glass is used because of its structural strength and clear structure [4]. Low reflectance and absorbance are desired so that the maximum amount of light can reach the solar cells. Sometimes anti-reflective coatings are used to reduce reflectance, and to achieve better transmittance and therefore higher electrical production. [1]

The encapsulant is usually made of ethylene-vinyl acetate (EVA) films or other polymer-based materials. The main purpose of the encapsulant is to provide protection, mechanical support and electrical insulation for the solar cell. The encapsulant material is laminated onto the solar cell. The cell is sandwiched between two layers of encapsulant and laminated in a vacuum using high heat and pressure to bond the layers together. The encapsulant protects the solar cell from moisture and contaminants that could cause corrosion. It also provides mechanical support by holding fragile solar cells in place and preventing mechanical stresses. Encapsulant material is designed to be highly transparent, allowing the maximum amount of sunlight to pass through to the solar cell. [4]

The backsheet provides mechanical support, protection against moisture and UV, and electrical insulation at the rear side of the panel. It is usually non-transparent but transparent backsheets are also used, especially in some BIPV applications, such as windows or glass

roofs. Non-transparent backsheets are typically made of polymeric materials and have multilayer structure usually consisting of a polyester film (PET), which is laminated between polyvinyl fluoride, also known as Tedlar. The multilayer structure allows multiple properties: The outer layer provides UV and weather resistance; the core layer ensures mechanical strength, and the inner layer offers adhesion to the encapsulant. Transparent backsheets that are used in some BIPV applications are usually made of glass, so it provides same kind of properties on both sides of the cell. Next to the cell, it allows all light to pass through, and behind the cell it lets indirect sunlight reach the cell. [1,4]

The aluminium frame provides structural support and mounting points for rack installation. It prevents bending of the PV module and protects the glass and the solar cells from damage, but can also help with heat dissipation [6].

The junction box is located at the rear side of the panel to cover cables and other electrical components. It is weatherproofed to protect against moisture and dust, and it ensures safe transfer of electricity. The main function of the junction box is to provide an electrical connection to an external circuit. Junction boxes are also used to link multiple panels together. Junction boxes provide quick and secure cable connections that make installation and maintenance easy. [14] Bypass diodes are often located inside the junction box. Their main function is to prevent power losses and protect the system from overheating. Bypass diodes are placed in parallel with multiple cells. In normal operating conditions, they do not have any function, but in case of a shaded or damaged cell, bypass diodes reroute the current to maintain the performance of the PV system. When a cell is damaged or shaded, it creates less current than other cells. This leads to current flowing into the cell that is producing less current, which lowers performance of the whole module. However, in this case, the bypass diode conducts electricity around the blocked section ensuring uninterrupted performance of the other cells. [15]

1.1.2 Working principle

The working principle of a solar cell is based on the photovoltaic effect, where a semiconductor material is able to convert photon energy from the sun into electricity. Solar cells consist of a semiconductor material that has p-n junctions. Semiconductors can only absorb photons according to their band gap energy, which is the energy difference between the valence and conduction bands. The band gap determines which wavelengths of light the solar cell can absorb and convert into electrical energy. Correlation between photon energy

and wavelength is shown in Equation 1, where E is energy, h is Planck's constant, c is the speed of light, and λ is wavelength. Photons that have higher energy than the band gap can be absorbed, for example a silicon solar cell has a band gap of 1.1 eV. This correlates roughly to a 1127 nm wavelength, which means that silicon solar cell converts wavelengths shorter than 1127 nm into electricity. Absorption happens at the p-n junction and electron-hole pair is generated. Electrons are minority charge carriers in the p-type region and holes minority charge carries in the n-type region. A high concentration of majority charge carries in each region results in current flow of these charge carriers across the depletion region. Charge carries are separated, electrons diffuse from the n-region to p-region and holes from the p-region to n-region. Moving electrons generate current and flow through the external circuit, finally recombining with the holes. [2,13]

$$E = \frac{hc}{\lambda} \quad (1)$$

A crystalline silicon solar cell is known to have roughly 20% efficiency [2], which means that 80% of the irradiance that reaches the cell is not converted into electricity. Photons that have energy lower than the band gap cannot excite electrons over the band gap and therefore are not absorbed. All the energy from photons, with energy lower than the band gap is converted into heat in the PV module. Additionally, not all the energy from the photons with higher energy than the band gap is converted into electricity. Excess energy above the band gap is converted into heat through the thermalization process, where an electron that has excess energy compared to the band gap rapidly loses its energy and returns to the edge of the conduction band. This excess energy is converted into heat. Energy losses in a silicon solar cell are shown in Figure 3, where thermalization losses happen above the band gap energy levels, and transmission losses occur below the band gap. All these energy losses lead to heat buildup in the PV module and cause faster degradation and lower efficiency.

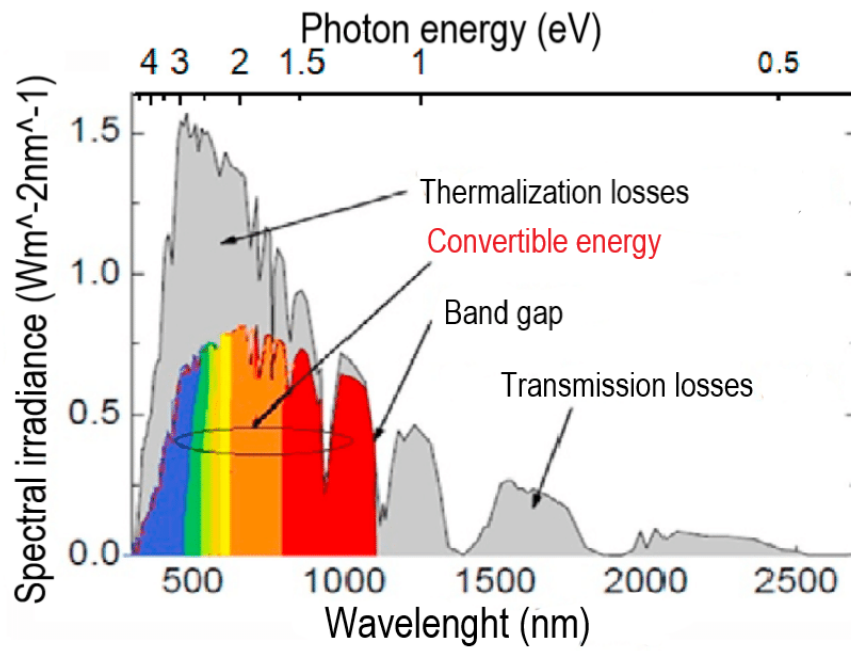


Figure 3. Solar energy conversion of Si solar cell, that shows thermalization losses, transmission losses and convertible energy. Modified from [16]

2 Thermal degradation of solar photovoltaic technologies

Solar photovoltaic modules are designed to generate electricity efficiently for decades, but it is commonly known that solar panels degrade over the years due to various degradation mechanisms. This degradation results in a reduced power output, which lowers the overall performance of a PV system. Manufacturers usually guarantee that the panels still remain at 80% of their nameplate maximum power after 25 years, meaning an average 0.5% efficiency loss per year [1]. Degradation is not limited to manufacturer guarantee, but it's also affected by outdoor and weather conditions. Various external factors influence the degradation rate, including exposure to extreme temperatures, humidity, UV radiation and mechanical stresses. Over time, these factors can cause physical and chemical changes in the solar cells. Understanding the degradation mechanisms of real world PV module applications is crucial for improving the panel's longevity and financial return. [1,2]

2.1 Thermal degradation mechanisms

High temperatures are one of the main reasons for accelerated degradation in PV modules. High temperatures affect to every component of a PV module and cause various types of degradation that reduce efficiency and longevity. Degradation mechanisms that are affected by heat include hotspots, delamination of the encapsulant, broken cells, broken interconnects, encapsulant discoloration, corrosion, glass damage, solder bond failures, bypass diode failures. [1,2]

Encapsulant discoloration is one of the most reported degradation mechanisms in solar panels, but this may be influenced by the fact that discoloration is easily noticeable through visual inspection. High temperatures, UV radiation and humidity play the key roles in the discoloration of encapsulant, but the encapsulant quality and materials also contribute to discoloration. Discoloration appears as yellow or brownish and can also affect grid fingers. Discoloration leads to lower performance, due to a reduced amount of light penetration through encapsulant but usually does not cause failure of the module. However, further developed discoloration can lead to moisture ingress, and therefore cause failures and trigger other degradation mechanisms. [2,17] Uneven discoloration of the PV module can lead to electrical mismatch, as shown in Figure 4. Discoloration of some cells leads to a lower current in those cells, due to increased light reflectivity. This can lead to resistivity losses, increased

heat and current mismatches of connected cells and therefore leading to lower fill factor and decreased power production. [18]

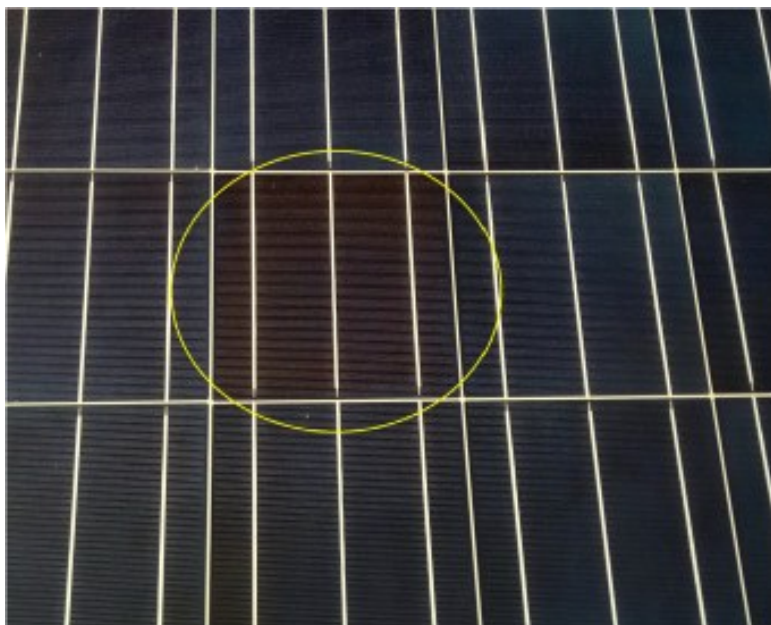


Figure 4. Discoloration of a PV module. [2]

As PV modules are exposed to outdoor conditions, corrosion is commonly observed. An electrolyte, an oxidizing agent, and a metal are required for corrosion to occur in a PV module. Corrosion occurs when moisture penetrates the panel, usually through the laminated edge or backsheet. When the PV module is defective, the laminated EVA can produce acetic acid, which speeds up metal corrosion. Metals with lower oxidation potentials experience higher corrosion rates, since they serve as sacrificial anodes in galvanic couples. Typical and most common metals that are used in PV modules are aluminium, silver, and copper. On the front side of the solar cell, corrosion initiates at the edges of a solder joint when exposed to water and gradually spreads toward the centre. This process reduces the solder contact, leading to an increase in series resistance. On the rear side, corrosion first affects the contacts and solder joints. When the metal with lower oxidation potentials is consumed, other metals become susceptible to corrosion as well. Moisture can also corrode cables and increase leakage current, as shown in Figure 5 on the right, with corroded solar cell on the left. [2,19].



Figure 5. Solar cell corrosion (left) and corroded cables inside junction box (right) [2]

Hotspots are also a common problem in solar cells. Hotspots are localized areas in the cell that heat up excessively, and they are usually formed due to uneven power generation in the panel. This can happen when there is partially shaded, damaged, or electrically mismatched cells. Shaded cells are common reason for formation of hotspots, as shaded cell operates differently compared to other cells, generating less power. Cracked cells can create resistance points and aged or defective cells can lead to electrical miss matches, which lead to uneven power distribution. When the solar cells generate different amounts of current, reverse voltage across other cells connected in series occurs. This causes high resistance points that have higher energy losses, which turn into localized heat points, or so-called hotspots, which are significantly hotter than surrounding areas and cells. Typical hotspots on solar cells are shown in Figure 6, which shows infrared image of PV modules. [2,20]

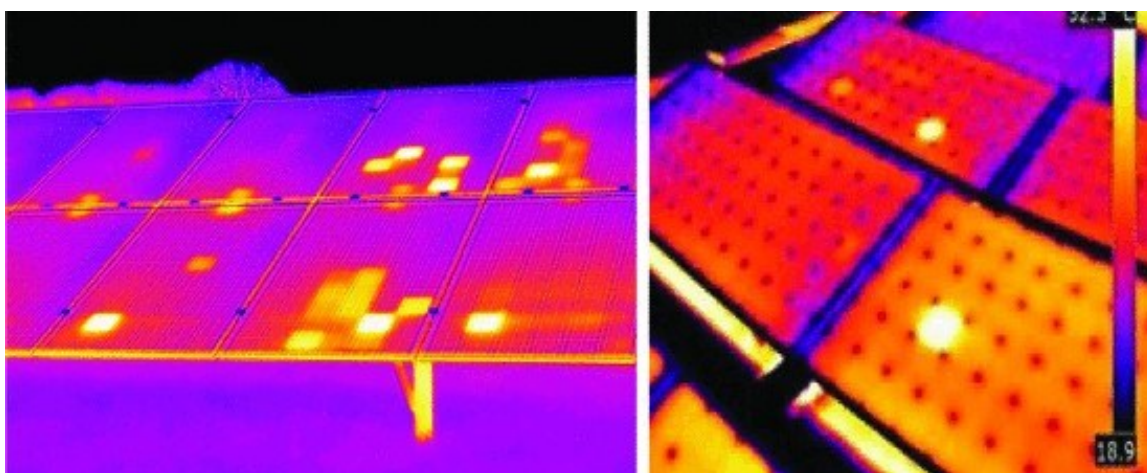


Figure 6. Hotspots on PV modules imaged with IR camera [20]

Delamination of encapsulant means, adhesion loss between encapsulant and solar cell or glass. This causes layers of PV module to separate from each other making the cell vulnerable

to climate conditions [2]. Figure 7 shows typical encapsulation of PV module. It has been found that adhesion shear strength is stronger between glass and EVA than between EVA and cell. Charma et al. studied encapsulant adhesion forces in degraded PV modules. Adhesion shear strength was reported to be only 20% compared to undegraded PV module, after 7 years of outdoor exposure. [1] Delamination causes an increase in light reflectivity and penetration of water into the solar cells that causes decrease in efficiency and accelerated degradation [2]. The presence of other substances like PET can accelerate aging of EVA encapsulant, because chemical bonds can form between the two materials and weaken adhesion between the cell and encapsulant. Delamination can eventually lead to formation of air gaps or bubbles between the cell and encapsulant. The bubbles are usually the result of a chemical reaction that releases the gas that gets stuck inside the PV module. This can lead to moisture ingress and can reduce current flow and therefore lower the performance of the solar cell. Typical formation of bubbles at rear side of PV module can be seen in Figure 8. [18,19]

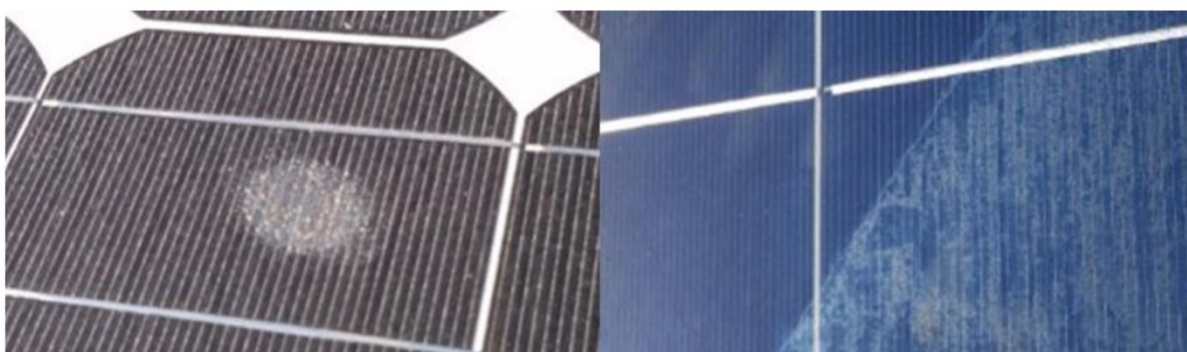


Figure 7. Delamination of encapsulant in PV module. [19]

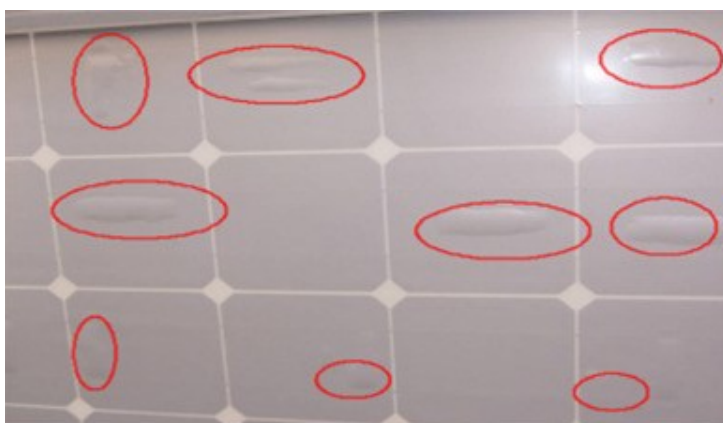


Figure 8. Bubbles at rear side of PV module between encapsulant and backsheet. [2]

Cell cracking can occur when there are extremely high temperatures. When the cells are exposed to temperature changes, materials will expand or contract. If the temperature changes

are high enough, the cells can be under serious stress and cracking may occur. PV modules are designed to tolerate some thermal expansion, but extreme high temperatures, hotspots, or thermal cycling can cause so much stress that cracking can happen. [18]

Major junction box failure means that it significantly disturbs the performance of the PV module. Causes for major junction box failure include moisture ingress, improper wiring, too much stress in the system, poor assembly of the junction box to the backsheet, improperly closed lid, and burned bypass diodes. Bypass diodes protect the cells in case of shadowing or cell problems and are often located in the junction box. In the worst cases, bypass diode failures can lead to fire accidents, as shows in Figure 9. [19]



Figure 9. Burned junction boxes, that was caused by bypass diode failure. [19]

3 Operating temperature and performance of c-Si

PV module's operating temperature has direct impact on its performance. As temperature rises the semiconductor material becomes less efficient affecting power production of the PV module [3,21]. Higher operating temperature also increases resistance of electrical housing, causing further reduction in power production. Over time high operating temperatures cause faster degradation. The operating temperature in crystalline silicon solar modules mainly depends on the ambient temperature, incident sunlight, wind speed, mounting configuration and packaging configuration. [3,22]

3.1 Temperature and band gap

PV modules' operating temperature is known to affect power production. The band gap of the semiconductor in solar cells is dependent on temperature, but temperature also affects other factors such as carrier concentration. The band gap of silicon decreases linearly as the temperature rises, and this is shown in band gap linear approximation Equation 2, where $E_g(T)$ is band gap at specific temperature, $E_g(300\text{ K})$ is band gap at 300 K (1.12 eV for Silicon), dE_g/dT is temperature coefficient (-2.3×10^{-4} eV/K for Silicon). [3,21]

$$E_g(T) = E_g(300\text{ K}) + dE_g/dT(T - 300\text{ K}) \quad (2)$$

The band gap decreases because atomic vibrations in the crystal lattice increase, leading to greater interaction between electrons and the lattice. These interactions reduce the energy required for an electron to jump from the valence band to the conduction band. Smaller band gap means that more electrons are thermally excited from the valence band to the conduction band, increasing the intrinsic carrier concentration. This leads to a slight increase in short-circuit current, as more charge carriers are thermally generated. However, this also leads to higher recombination rates and a reduction in the built-in potential of the p-n junction, which causes a drop in the open-circuit voltage as the temperature rises. The increase in current is not strong enough to compensate for the voltage drop and changes in voltage and current reduce the fill factor and efficiency of solar cells. Due to the more significant voltage drop, the maximum power output of the solar cell declines as temperature rises. The decrease in power output can be up to 0.4% - 0.65% per degree. [3,21]

3.2 Effect of ambient temperature on PV module performance

The power output of a PV module is influenced by the operating temperature of its solar cells. The module temperature is always higher than the surrounding ambient temperature when generating electricity, because of heat absorption and the increase in heat caused by the electrical resistance. Temperature rise also occurs due to the glass cover, which traps infrared radiation. The higher the ambient temperature, the higher the module temperature. As the temperature rises, the band gap of the PV cells narrows, leading to lower efficiency and power production. [1]

Climate and geographical location significantly influence the temperature of the PV module and other degradation-related environmental stressors such as, moisture, UV radiation and irradiance, which affect PV module performance and lifetime. Not only temperature-related degradation but also other mechanisms like photo-degradation or hydrolysis are each affected by specific climate factors. In tropical climates, high humidity and temperature accelerate hydrolysis, leading to delamination and corrosion of PV modules. In desert regions PV modules experience intense UV exposure and large temperature variations, which cause discoloration and backsheet degradation. In colder climates PV modules face lower degradation rates as temperatures are lower but are susceptible to mechanical damage from snow. A study about global analysis of PV module total degradation found that the commonly assumed degradation rate of 0.5% per year varies significantly depending on the climate, with tropical regions experiencing degradation rates as high as 1.5% per year [23]. Different degradation rates are shown in Figure 10, categorizing degradation in Europe based on temperature, UV radiation and humidity. The figure indicates that the hottest areas in Europe, such as Spain and Portugal, can experience degradation rates up to 0.8%. In contrast, in the northernmost parts of Europe such as Finland, degradation can drop below 0.2%. The highest degradation rates globally are observed at locations near the equator. Moreover, climate change and increasing global temperatures could further impact PV module degradation, as there is a direct correlation between ambient temperatures and degradation rates. The importance of climate conditions should be considered when designing and installing PV systems to maximize performance and longevity. [23]

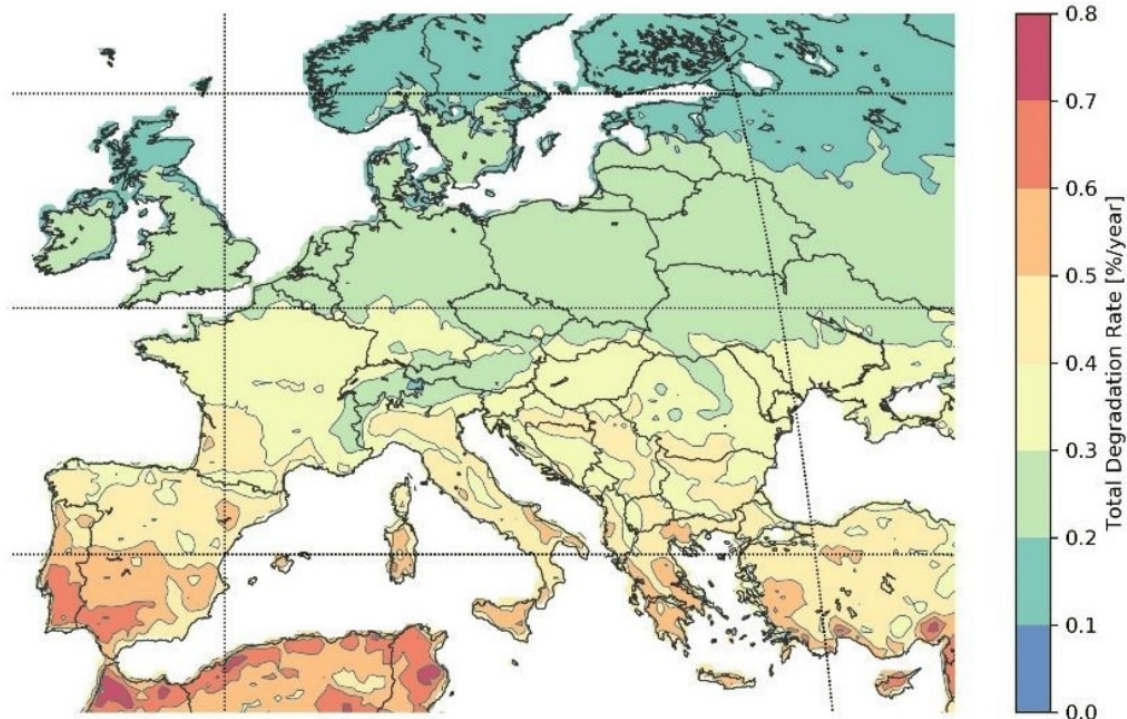


Figure 10. Total degradation rates of silicon PV modules in Europe categorized based on temperature, UV-radiation and humidity. [23]

3.3 Wind and operating temperature.

When wind flows over the surface of a solar panel, it removes excess heat through convection, reducing the operating temperature. Higher wind speeds improve cooling efficiency, leading to lower operating temperatures and improved performance. The temperature-lowering effect of wind strongly depends on the orientation of the PV modules and mounting configurations. Two common mounting configurations for PV modules are open-rack and close-roof mounting, which are shown in Figure 11. The main difference in PV module's operating temperature between these two is ventilation on the rear side of the module.

Open-rack mounted PV systems are commonly preferred when maximizing electricity production is the primary goal. These systems allow for optimal tilt angle adjustments, ensuring they capture the maximum amount of sunlight. Additionally, open-rack mounted PV panels benefit from superior ventilation, as air can flow freely around them on both sides of the panel. This increased airflow plays a crucial role in cooling the panels. The cooling effect provided by wind helps lower the overall operating temperature of the solar panels. Since

higher temperatures can reduce efficiency, better ventilation leads to improved energy output. Furthermore, maintaining lower temperatures not only enhances performance but also slows down panel degradation over time. Excessive heat can accelerate material wear and shorten the lifespan of PV panels, so effective cooling contributes to long-term reliability. [24]

Close-roof mounting is often chosen for its aesthetic appeal, as the panels sit closer to the roof and blend in with the building's design. In addition, in cities and densely built areas, close-roof mounting is sometimes necessary, because of the lack of space. However, compared to open-rack mounted systems, close-roof mounting has significant drawbacks in terms of performance and longevity. One major disadvantage is reduced ventilation. Usually there is only a small gap behind the PV modules, but in some BIPV applications there is no gap at all, and the module is integrated directly into the building. Since there is limited airflow beneath the panels, heat tends to build up, leading to higher operating temperatures. The higher temperatures in close-roof mounting contribute to a faster degradation rate, shortening the lifespan of the panels compared to better ventilated open-rack mounted systems. [24]



Figure 11. Illustrated picture of open-rack (left) and close-roof (right) PV mounting configurations. Generated by AI

3.4 PV temperature increase caused by the restriction of solar power production

3.4.1 Solar curtailment

Solar curtailment means intentionally reducing electricity production from PV systems. This can be due to lack of demand, grid congestion or oversupply which can lead to negative electricity prices and therefore shutdown of PV systems to avoid paying for produced electricity. Solar curtailment is becoming a more widespread problem as the amount of installed solar power is increasing and taking a larger share of the grid capacity. The main problem with solar power is that PV systems tend to produce solar energy depending on the solar radiation, and especially when the irradiation is at the highest, most of the systems produce the maximum amount of energy at the same time, causing overproduction. The typical time for oversupply is midday when solar power production is at the highest and demand is low. Geographical location can also cause oversupply. If a location that has a lot of solar power production is located far away from major load centres and electricity transport capacity is insufficient, then local oversupply is frequent problem. One common reason for solar curtailment nowadays is economic reasons. In some markets, electricity can reach negative values, which means that solar power producers must pay for the electricity that they are selling. Solar curtailment has many consequences. Clean and free electricity is lost as solar energy has no operating cost and is emission-free. It has an economic impact on PV projects, because solar power producers are not able to sell electricity and this needs to be considered when designing solar power projects. Additionally, it can also affect the popularity of the solar power in the future. [10] One consequence that has not been extensively studied yet is how curtailment affects solar panel's aging.

Solar power producers might disconnect the system to avoid paying when electricity prices are negative. When PV system is disconnected from the grid and is under solar irradiance, it still generates voltage (open-circuit voltage) and charge carriers. But when there is no load, current does not flow, and no power is produced. Eventually charge carriers release their energy into heat which can lead to excess heating of the PV module and therefore increase in degradation rate.

Zhen et al. studied temperature effects of BIPV and compared results to open rack mounted PV [25]. They measured solar cell operating temperatures with open rack PV modules and with BIPV modules in two scenarios under outdoor conditions: 1. where solar modules were

connected to grid; 2. where modules were in open-circuit voltage conditions, meaning they were disconnected from the grid and from any load. Scenario 2 has the same effect as solar curtailment, where PV modules are disconnected from the grid. Figure 12 shows IR images of grid-connected open-rack PV module (on the left) and open-circuit open-rack PV module (on the right). Average cell temperature was 2.2°C higher on the open-circuit PV module with irradiance of 600 W/m² compared to the grid connected. Temperature difference was even higher in BIPV modules, compared to open rack PV modules. Open-circuit BIPV modules experience roughly 7°C higher cell temperature than grid connected BIPV. The higher temperature of BIPV modules compared to open-rack modules was due to poor ventilation which resulted in heat build-up. In open-circuit condition, which is consequence of solar curtailment, cell operating temperature was higher because, no electrical power is extracted but instead converted into heat. [25]

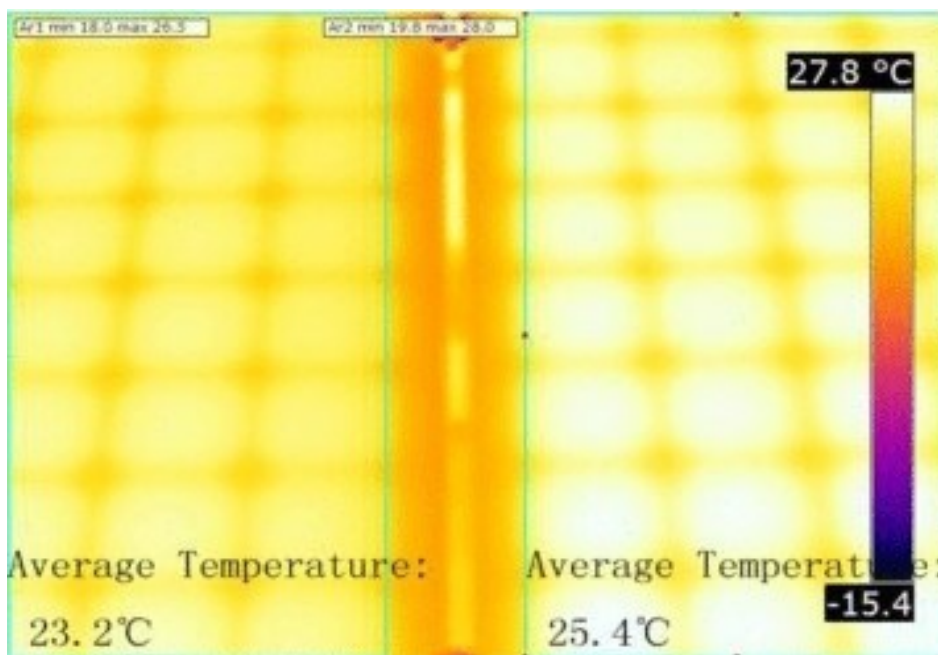


Figure 12. IR images of glass/cell/glass PV module under grid connection (left) and open circuit condition (right) on the open rack mounting.

The study shows that when solar curtailment occurs and systems are disconnected from the grid, PV modules experience higher temperatures than during operating conditions when producing power to the grid. The study showed that elevated temperatures during curtailment can be quite significant. They found roughly 7°C higher temperatures during curtailment, with relatively small levels of irradiation, which means that even more elevated temperatures can be experienced with higher levels of irradiation. If solar curtailment occurs often, higher

temperatures can have an impact on the longevity of the PV systems. Delamination, moisture ingress, corrosion, module failures and other forms of degradation can occur more frequently if solar curtailment increases.

3.4.2 Solar clipping

Inverter's main function is to convert electricity produced by the solar panels into a form that can be utilized in households. Solar panels produce direct current (DC), which the inverter converts into alternating current (AC) that is typically used in the electrical grid, homes, businesses, and industry. The inverter also ensures that the electricity matches the voltage used in households. Nowadays inverters make up a large portion of the entire solar system's price. This can lead to a situation where money is saved when purchasing an inverter and it is undersized compared to solar panels. This means that solar panels can have higher power output than the inverter's power capacity and all the excess electricity is wasted; this is called clipping. [8]

Clipping depends on DC/AC ratio of the system. DC/AC ratio is shown in Equation 3, where P_{DC} is total DC power of solar panels and P_{AC} is inverter's AC power rating. DC/AC ratios higher than one indicate that the inverter is undersized. Solar power producers usually desire DC/AC ratios close to one for optimal LCOE. The maximum amount of energy produced per installed inverter capacity means overall cost per produced kWh is reduced. [8] Oversized systems are sometimes preferred because they can capture more energy on the days when irradiance is low, possibly without clipping if the total power output of the solar modules is still below inverter capacity. But oversized systems usually generate more power than inverter's capacity, especially during the peak power hours, and excess power is compensated for at solar panels operating voltages. Typically, DC/AC ratios close to 1 are preferred for optimal LCOE. [9]

$$\text{DC/AC ratio} = \frac{P_{DC}}{P_{AC}} \quad (3)$$

In solar clipping, PV systems' power output is higher than the inverter can convert electricity from DC to AC. This causes solar modules to operate either below or above maximum power point (MPP), so that the power of the solar modules is curtailed to match the inverter's capacity. This is called power limiting control. When a PV module is operating above MPP, it is called high voltage clipping. When operating below MPP, low voltage clipping occurs.

Figure 13 shows how power is limited in clipping. In red and blue scenarios where irradiance

is so low that PV module is able to operate at MPP and still be under inverter's capacity. In the black scenario, irradiance is high enough so that if PV module would operate at MPP, power would be over inverter's rated power. To compensate this voltage must either drop or rise, so that power matches inverter rated power. In scenario A voltage drops (low voltage clipping) as long as it reaches same power as inverter's capacity and in scenario B voltage rises to match inverter's capacity (high voltage clipping). Power that is lost due to clipping is the difference between MPP and inverter's power capacity. [8,9]

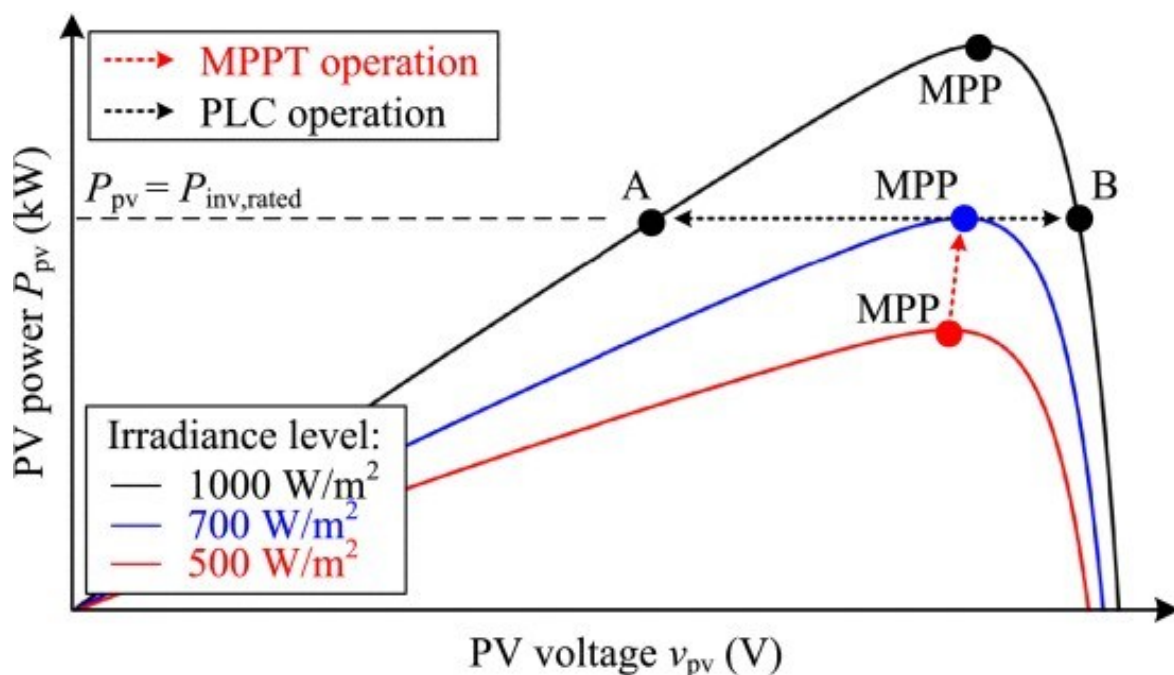


Figure 13. Limiting power control working principle, where A represents low voltage clipping and B represents high voltage clipping. [9]

High voltage clipping causes an increase in solar module temperature due to charge carriers recombining and in resistive losses. In low voltage clipping, the temperature rise is more local and only affects in certain cells, compared to high voltage clipping where the temperature rises uniformly. Low voltage clipping causes resistivity losses and non-uniform current distribution, leading to local hotspots. Solar module temperatures are shown in Figure 14 with high and low voltage clipping. V_{MPP} shows the temperature of the module operating normally at the maximum power point. Below V_{MPP} shows low voltage clipping and uneven heat distribution can be seen. Heat difference between hotspots and normal operating temperature is 15°C . Above V_{MPP} shows high voltage clipping. Heat distribution in PV module is fairly

uniform and average temperature was 5°C higher compared to normal operating temperature.

[8]

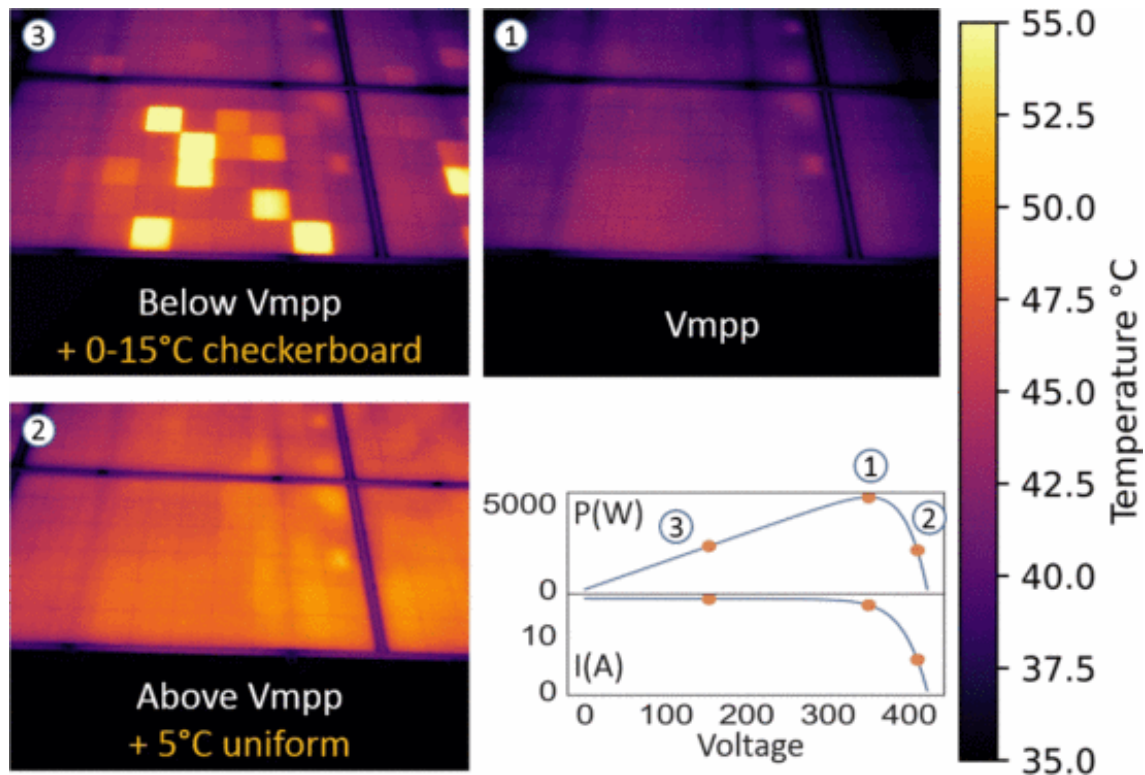


Figure 14. IR image of 3 solar modules operating at: 1. V_{MPP} , 2. above V_{MPP} and 3. below V_{MPP} [5]

Solar clipping and therefore high temperature can cause also damage to the inverter itself when DC/AC ratio is high. High DC/AC ratio means that input power from solar panels (DC) is high compared to inverter output power (AC). This causes inverter to operate near its maximum capacity and leads to rise in temperature. [8]

4 Building integrated photovoltaics

Building integrated photovoltaics (BIPV) are PV modules that are integrated into the structure of the building rather than being separate solar panels that are detached from the structure. They represent an innovative and sustainable solution for harnessing solar energy while maintaining aesthetic appeal. Unlike traditional photovoltaic systems, which are mounted as separate panels, BIPV act as a component of a building, such as roofs, facades, windows or canopies. BIPV differ from typical crystalline silicon PV modules, with different colours, transparency or texture, to make it blend seamlessly with the building's design. For instance, transparent PV module consists of glass/cell/glass structure, which can be used as windows, facades or skylights, enabling the building to capture solar energy while still maintaining natural lighting and visual appeal indoors. Different kinds of BIPV applications are shown in Figure 15. The benefits of BIPV are numerous, making it an attractive option for building owners. They allow efficient use of space, as BIPV modules are integrated into the building structure, so they do not require additional roof space or land, which is often limited in urban areas. Particularly in densely built cities where space is limited or expensive, BIPV offer a great way to harness solar energy. Furthermore, BIPV systems contribute to energy savings by generating renewable energy and reducing building's need for grid power, while helping to lower utility costs. BIPV also supports sustainability goals by producing electricity from solar energy and reducing the carbon footprint of a building. However, despite its many advantages, BIPV have its own challenges compared to traditional PV systems. Integrating PV modules into the building's structure and design can have some negative effects on the performance of the PV modules. Typical disadvantages of BIPV include higher operating temperatures due to poor ventilation, light absorption or reflection when using coloured PV modules, reduced power production due to cell spacing in transparent BIPV roofs, and non-optimal installation angle. [5,6,26].

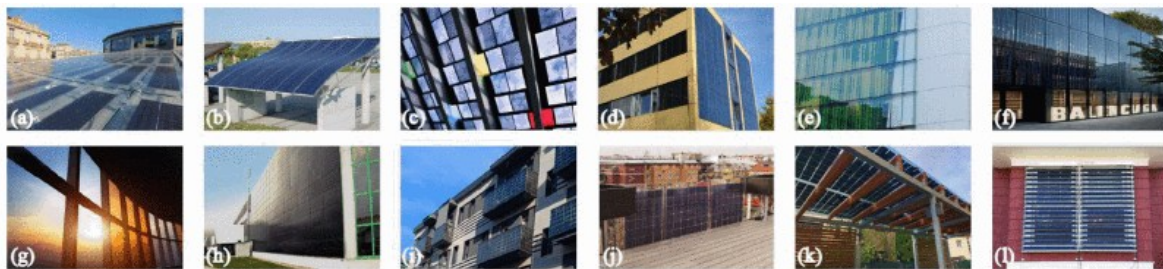


Figure 15. BIPV in different applications. [27]

4.1 Effect of airflow in BIPV

One of the most crucial disadvantages that BIPV have compared to normal PV modules is that they are mounted close to the building or integrated into the building's structure and used as roofs and skylights with restricted airflow. Close-mounted BIPV only have a small gap behind the module to allow airflow cooling at the rear side and indoor BIPV skylights rear side cooling is controlled by the building ventilation system, which is less effective than natural outside ventilation. BIPV can also have restricted airflow due to the PV module positioning and wind direction.

Kalogirou et al. studied the effect of airflow in BIPV modules by changing the gap size behind the panel [28]. In the study they used computational methods to estimate heat flux and airflow around the PV module to calculate the temperature of the PV module. Solar radiation data was based on a typical June day in Cyprus, and it was assumed that PV modules had 15% efficiency and 85% of the radiation would convert to heat. The PV module was vertically installed, and steady air velocity of 0.2 m/s was used in the calculations. In the study they found that a higher gap behind the panel led to a lower temperature in the PV module but when the gap size exceeded 0.05 m, a wider gap had no additional effect on the temperature. A similar finding was observed when they kept the gap size constant and varied the air velocity. The higher the air velocity, the lower the temperature of the PV module. Air velocity of 1.2 m/s was able to lower the PV temperature from 77°C (air velocity of 0.05 m/s) to 31.7°C with gap behind the panel that was constantly 0.02 m. [28] Although the study relied on computational methods and results may vary in real outdoor operating conditions, it still provides valuable insights into how BIPV performance is affected by airflow and wind speed, as well as how cooling efficiency can be improved by adjusting the gap size behind the panel.

4.2 Coloured BIPV

In building integrated photovoltaics, where aesthetics plays a crucial role, users might prefer solar panels with coloured backsheets or coloured optical filters. This is mostly due to design reasons to make panels more visually appealing and fit into the urban environment. Figure 16 shows how black PV modules are used as facade of a building, to make integration of PV look visually pleasing. However, choosing coloured BIPV involves a trade-off between aesthetics and performance. While coloured BIPV technologies improve the visual integration

of PV modules, they can also impact performance by affecting light absorption and overall power output. This efficiency loss depends on the type of colour application, material properties, and filtering techniques used.



Figure 16. Black building integrated photovoltaics. [29]

4.2.1 Coloured filters

Coloured optical filters offer a way to make solar panels more visually appealing by selectively reflecting or transmitting specific wavelengths of light and creating different colours. In some cases, PV module's operating temperature can be lower with coloured optical filters. Lizcano et al studied optical filters in BIPV [30]. In the study they simulated operating temperature of PV modules with different coloured optical filters under NOCT conditions. It was observed that some filters were able to lower the cell temperature. They found that coloured optical filters increased reflectance in some wavelengths, which reduced heat absorption. However, an increase in reflectance also reduces power production. This can be seen in Figures 17 and 18. In Figure 18 a brown coloured filter was able to lower operating temperature of PV module by 3.1°C, compared to solar cell without filter in Figure 17. This reduced temperature was observed because of higher reflectance close to 600 nm wavelengths, which can be seen as a drop in Figure 18, indicating lower absorbance in those

wavelengths and lower power production. However, from a total of 400 colours studied, the use of optical filters resulted loss in absolute efficiency, with maximum absolute decrease of 1.6% at normal incidence compared to standard dark blue solar cells. Annual direct current relative losses were between 5.9% and 13.7% depending on simulated locations and colours. [30]

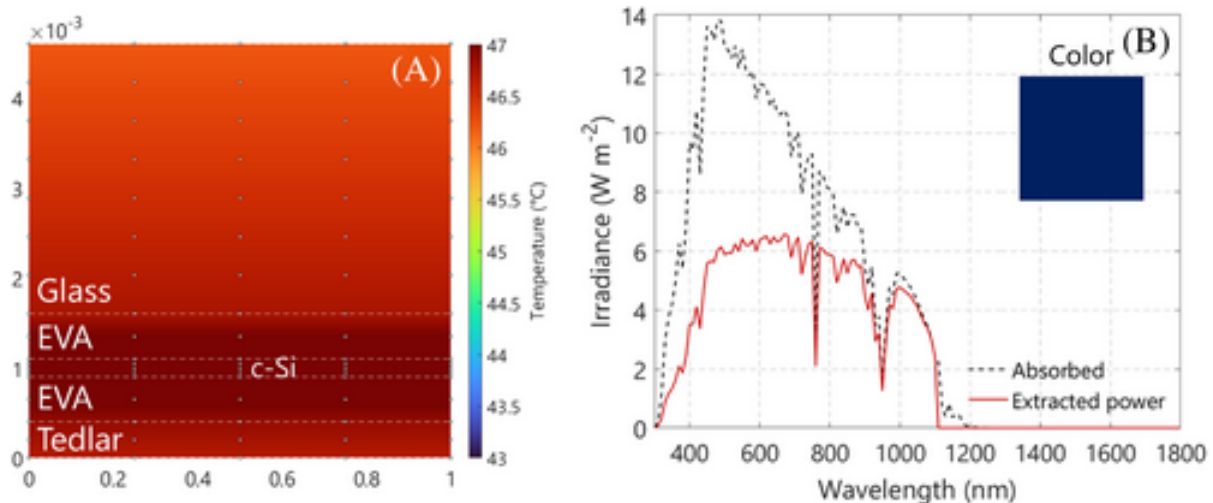


Figure 17. Temperature of the standard solar cell without colour filter (A). Thermalized power of the crystalline silicon cell for a wavelength ranges from 300 to 1800 nm (B). The band gap of the cell was assumed independent from the temperature and equal to 1100 nm. [30]

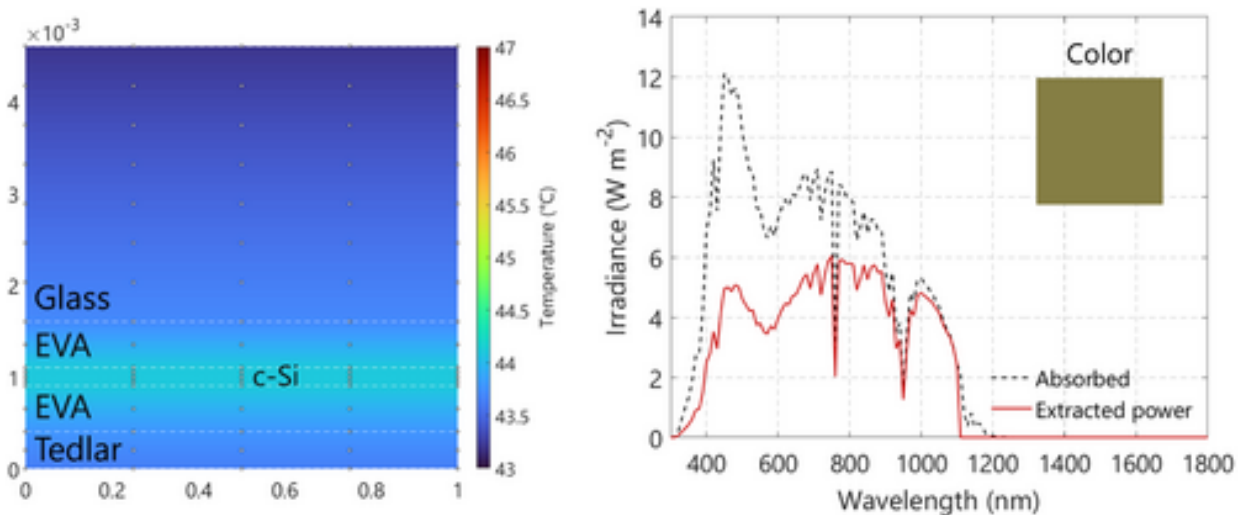


Figure 18. Temperature of the standard solar cell with brownish colour filter (on the left). Thermalized power of the crystalline silicon cell for a wavelength ranges from 300 to 1800 nm (on the right). The band gap of the cell was assumed independent from the temperature and equal to 1100 nm. [30]

Performance of coloured BIPV strongly depends on the properties of the chosen colour. Adding a colour layer to a PV module reflects some sunlight and lowers the efficiency of the cell. Reflectance is dependent on the chosen colour of the filter. The brightness of a colour significantly impacts efficiency loss and higher lightness results in greater losses.

Additionally, the colour tone determines which wavelengths of light are reflected. In a study the performance of different coloured PV modules was evaluated by investigating light reflectance [31]. The study showed that green to yellowish coloured PV modules had the lowest impact on performance, and pink or white coloured PV modules resulted in the highest efficiency losses, when same lightness of a colour was compared. The study also found that coloured PV modules showed high reflectance at near-infrared wavelengths, which caused significant energy losses. It was pointed out that reducing near-infrared reflectance is crucial for improving the efficiency of coloured PV modules. [31]

Amara et al. studied the temperature effect of different coloured Si solar cells for building integrated photovoltaics [32]. The testing was fully simulation-based using thermal, optical and electrical models. The test was carried out by simulating only the solar cell without encapsulant or glass. Different colours were achieved using antireflective coating (ARC) of varying thicknesses on top of the cell. As ARC thickness affects the wavelengths of light that are reflected, the researchers tuned the thickness of the ARC and controlled the wavelengths that were absorbed and those that were reflected, thereby achieving the desired colours. They found that dark blue had the worst effect on operating temperature, as it absorbed shorter wavelength photons, which led to high thermalization losses. The highest operating temperature in dark blue coloured cells led to the lowest energy conversion. Red and green coloured cells performed slightly better as they reflected shorter wavelength light which led to lower heat build-up. Yellow and cyan coloured cells maintained a balance between brightness and efficiency and had the lowest operating temperature of all colours. However, in the study it was found that non-coloured cells had the lowest operating temperature because they were designed to absorb the maximum amount of light and therefore had the best efficiency. [32]

The performance of solar cells is strongly influenced by the angle at which light strikes their surface. In the case of coloured solar cells with optical filters, this angular dependence is more complex compared to standard cells. A study found that standard solar cells exhibit a current reduction that follows a simple cosine relationship with the angle of incidence, whereas coloured solar cells show greater deviations that vary with the angle of incidence [30]. This occurs due to the spectral effects of the optical filters. Filters are designed to reflect certain wavelengths to produce colour, which alters how the cell interacts with incoming light at different angles. As the angle of incidence increases, the wavelength range of high reflectance shifts, affecting the amount of light absorbed by the cell. At higher angles, more light is reflected away rather than being absorbed, leading to a greater reduction in current generation

than in standard cells. The study highlights that while optical filters enhance aesthetic appeal, they introduce performance variations depending on the sun's position and installation angle. This effect is particularly important for building integrated photovoltaics, where modules are often installed at non-optimal angles. [30]

When using coloured solar panels in BIPV, it is expected that they will perform worse than non-coloured modules. The performance of the coloured cells highly depends on the colour and the technology that is used. Different colours absorb and reflect light differently. Some colours can even lower the operating temperature of solar cell by increasing reflection in some wavelengths, but this results in lower power production. With carefully selected colour and technology, coloured BIPV can have properties quite similar to non-coloured modules, while still offering the visual appearance of colours.

4.2.2 Black backsheet

Black is aesthetically preferred colour in solar panels, especially in building integrated photovoltaics [33,34]. One way to achieve black solar panels is by using black coloured backsheet. Changing the backsheet colour involves balancing between performance and aesthetics. The backsheet's main function is to provide mechanical support and electrical insulation to the solar cell, but it can also reflect or absorb irradiation and affect the performance of the solar cell. Black coloured backsheets absorb more light than typical white backsheets. Therefore, they heat up more and can cause higher degradation rate and lower efficiency of the PV modules. [26]

Lim et al. studied the reflectance of white versus black coloured back sheets in PV modules [26]. They found that the black backsheet had average reflectance of 42.43%, whereas the white backsheet had an average reflectance of 85.39%. In terms of performance, the white backsheet had better properties compared to the black backsheet, because it was able to reflect more light to the solar cell, which means more power produced. [26] However, it should be noted that most of the light goes straight to the solar cells and only a fraction reaches the back sheet. It also matters what type of light the backsheet reflects, because solar cells cannot use all light, only the wavelengths that match their band gap energy. In the study, they found that the black backsheet had over 80% reflectance when the wavelength was above 850 nm, compared to the white backsheet, which had more constant reflectance, with reflectance being over 80% for wavelengths above 450 nm [26]. The reflectance of black and white backsheets can be seen in Figure 19. It can be noted that the white backsheet has much higher reflectance

in the visible range, but at higher wavelengths, the black backsheet reflects almost the same amount of light. Reflectance of the backsheet also affects temperature of the backsheet and the solar cell. Since black reflects less light, it absorbs more, which is converted into heat, raising the temperature of the whole module and the cell. This leads to lower efficiency and faster degradation rate. But it should be noted that the white backsheet reflected more light onto the cell, which also contributed to heating the cell. However, this only has minimum effect on the temperature of the cell.

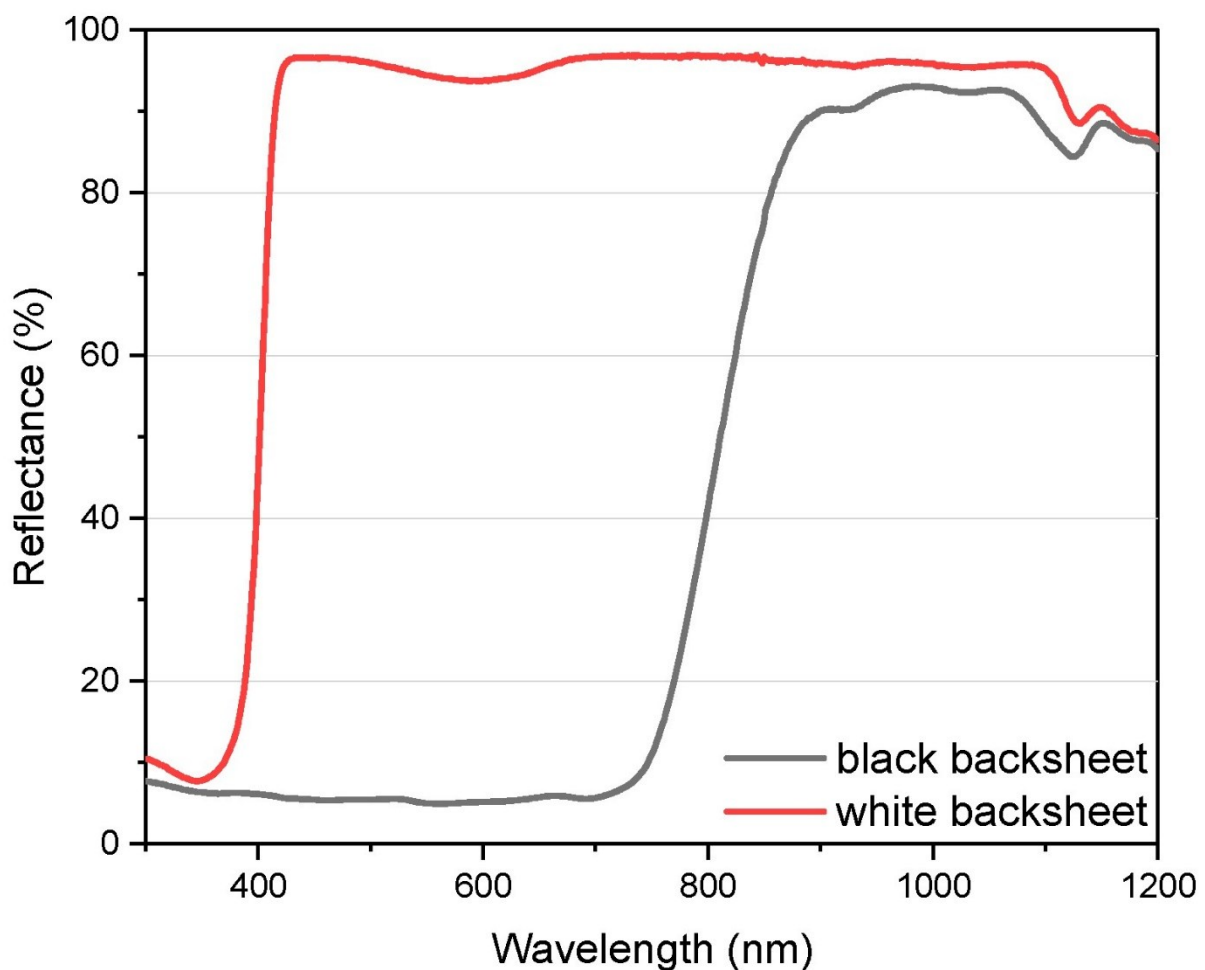


Figure 19. Reflectance of black and white PV module backsheets in visible – near-infrared range. [26]

López-Escalante et al. studied the performance of black versus white backsheets [33]. They investigated replacing traditional white backsheets in PV modules with black ones, which are often preferred for better building integration and aesthetic design. However, this change usually causes power loss and faster degradation due to higher absorption of solar light and therefore increased temperatures in the PV module. The study was carried out under standard conditions according to the IEC 60.904 standard. They found that using black backsheet

caused reduced power output of 8.66 W in a single module compared to white backsheet, while the rated power of the used PV modules was between 245 W and 255 W. In percentage terms, this power loss was 3.4 %. The main reason for this power loss in the PV module with black backsheet was its lower reflectance, which indicates that it absorbs more light causing excess heating in the PV module, which is known to reduce efficiency in silicon solar cells. In the study, UV degradation test was carried out only over black backsheet samples according to the IEC 61215 normative using a UV laboratory chamber. The test was done only for the backsheet material and not for the whole PV module. After the UV degradation test, no visible discolouration, bubbles or any kind of aesthetic degradation was observed. The study also evaluated degradation of black versus white backsheet PV modules through accelerated aging tests. In the damp heat test PV modules were exposed to 1000 hours at 85°C with 85% humidity. White backsheet showed minimal power loss of -0.92 %, compared to black backsheet, which had slightly higher power loss of -2.33 %, indicating it was more affected by heat and moisture ingress. A thermal cycling test was also done with 200 cycles ranging from -40°C to +85°C. Again, PV module with white backsheet performed slightly better with power loss of -3.31%, while black backsheet experienced power loss of -4.91 %, indicating higher degradation. Degradation of PV modules can be seen in Figure 20, where electroluminescence images of black (B) and white (A) backsheets were taken before and after aging tests. Especially number of inactive cells in black backsheet is significantly higher after the aging tests. [33] It should be noted that damp heat and thermal cycling accelerated aging tests are done in dark conditions without irradiation. This means that faster degradation rate observed in this study, as a result of damp heat and thermal cycling tests cannot be explained by the higher absorption of the black backsheet. Instead, the reasons for higher degradation must be due to the material properties of the black backsheet.

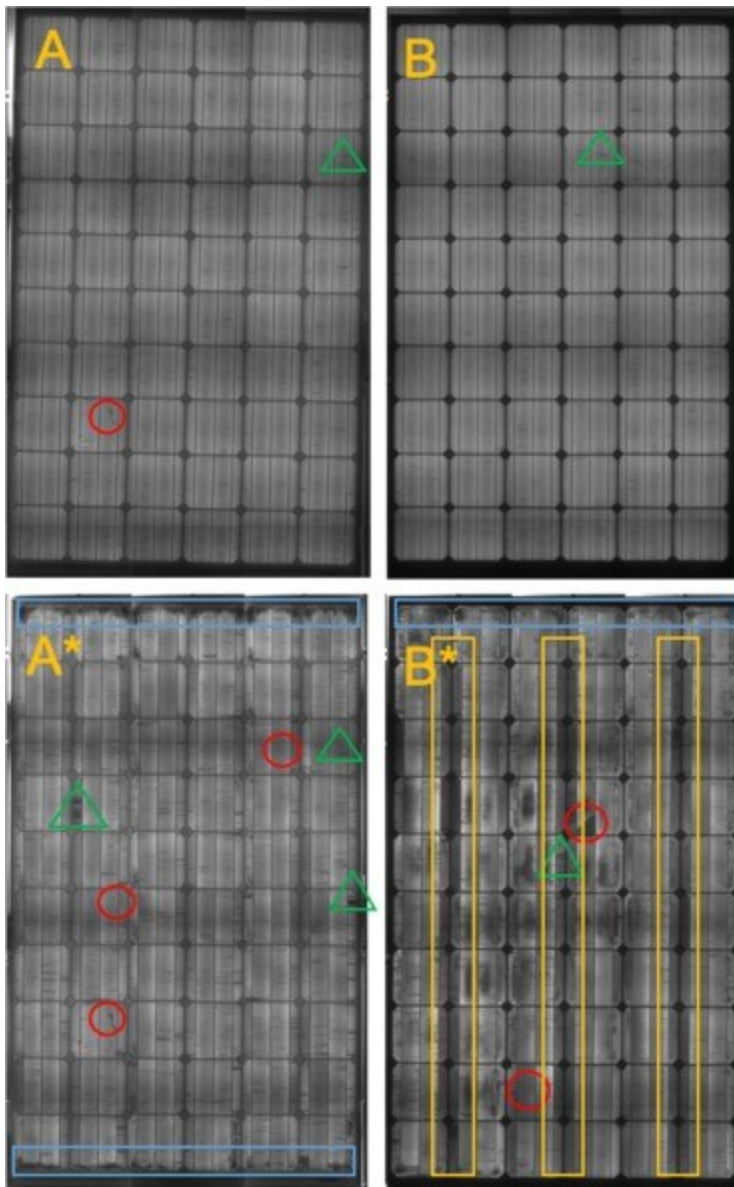


Figure 20. Electroluminescence images of the PV modules: A white backsheet before accelerated aging tests, A* white backsheet after accelerated aging tests, B black backsheet before accelerated aging tests, B* black backsheet after accelerated aging tests. Inactive areas: blue and yellow rectangles; cell breakage: red circles; metallic serigraphy defects: green triangles. [33]

Although, black coloured backsheets usually lead to higher operating temperatures, lower performance and faster degradation. Some methods can be used to compensate for these losses. Especially through material selection and choosing the right material properties, black coloured backsheet can be achieved without significant performance loss. However, this usually means higher manufacturing costs and PV module prices. Makrides et al. studied performance of monocrystalline PV modules with different backsheets over five-year period in Cyprus [34]. The study evaluated the influence of different backsheet configurations on thermal behaviour, energy yield, and degradation rates. Four different backsheet materials were used, as shown in Table 1, where setup 1 was designed with black heat reflective

backsheet, with white rear side. Other setups were PV modules with control backsheets to compare with setup 1. Setup 3 had normal fully white backsheet. Setup 4 had normal fully black backsheet and setup 2 had backsheet with non-reflective black cell-side and white rear-side. Indoor and outdoor testing methodologies were used, including STC (Standard Test Conditions) power measurements before and after the five-year period. PV modules were installed open-rack at an optimal tilt angle of 27.5°. [34]

Table 1. PV module backsheet materials and description. [34]

Setup	Backsheet colour	Material	Description
Setup 1	Black cell-side/White rear-side	Cell-side: black heat reflective material Core: clear PET Rear-side: white PE	Material that reflects IR-radiation to reduce heat absorption
Setup 2	Black cell-side/White rear-side	Cell-side: black PE Core: clear PET Rear-side: white Tedlar	Black control backsheet with white rear-side
Setup 3	White	Cell-side: white PE Core: clear PET Rear-side: white Tedlar	Fully white control backsheet
Setup 4	Black	Cell-side: black Tedlar Core: clear PET Rear-side: black Tedlar	Fully black control backsheet

In the study they found that setup 1 had the lowest operating temperature of all the modules. It was due to heat reflective cell-side material which reflected IR radiation and therefore reduced heat absorption and operating temperature. Setup 1 had average cell temperature of 40.4°C in five years of study, and compared to the second-best fully white (setup 3) with average cell temperature of 41.1°C. Fully black backsheet (setup 4) had the worst average cell temperature of 43.1°C. The highest temperature difference between setup 1 and 4 reached up to 10°C on the hottest days. It can be stated that with material selection, normal full black backsheet's thermal properties can be improved either by adding heat reflective material or changing the rear side to white, but this had only minimal effect. However, in all cases, white rear side doesn't have same kind of effect as in this study, because PV modules were open-rack mounted and exposed to reflected irradiation. Close-roof mounted PV modules' rear side are exposed to very minimal reflected irradiation, so rear side backsheet colour does not have significant effect on temperature. In the study they also measured energy yield of the PV

modules. Setup 3 with fully white backsheets had the best energy yield and setup 1 with black heat reflective cell-side was the second. Again, fully black PV module was the worst due to its highest operating temperature. In the study they did not find significant differences in degradation rates. Setup 1 had degradation rate of 0.52 %/yr, setup 2 had 0.50 %/yr, setup 3 had 0.50 %/yr, setup 4 had 0.51 %/yr. Setup 4 (full black) was the only one where visible signs of degradation were observed, as minor cracks had formed. [34] Based on the study, black coloured backsheets PV modules have higher operating temperature and lower energy yield than typical white backsheet PV module, but with material selection such as heat reflective coating, black coloured backsheets can perform almost the same as white backsheets while maintaining their aesthetic appearance.

4.3 BIPV Skylights

One common trend with building integrated photovoltaics is glass ceilings or canopies. Solar cells are placed between two layers of glass with cell spacing to allow natural light to flow through. The integration of photovoltaic systems into glass roofs combines functionality with aesthetics, offering way to harness solar power without sacrificing natural light. Again, like in other building integrated photovoltaics, BIPV skylights balance between aesthetics and performance. They balance between several key factors: electrical production, natural daylight, and indoor temperature. By generating renewable energy, they contribute to reducing a building's grid electricity consumption. At the same time, they allow natural daylight into the building, reducing the need for artificial lighting and creating a brighter, more pleasant indoor environment. Additionally, by absorbing sunlight, BIPV skylights help reduce unwanted heat, maintaining a comfortable indoor temperature. The design of BIPV skylights, like other forms of BIPV, requires careful consideration of these elements to ensure optimal performance and aesthetic harmony within the building's structure. Typical BIPV skylight structure is shown in Figure 21, where BIPV skylight is designed for outdoor canopy.

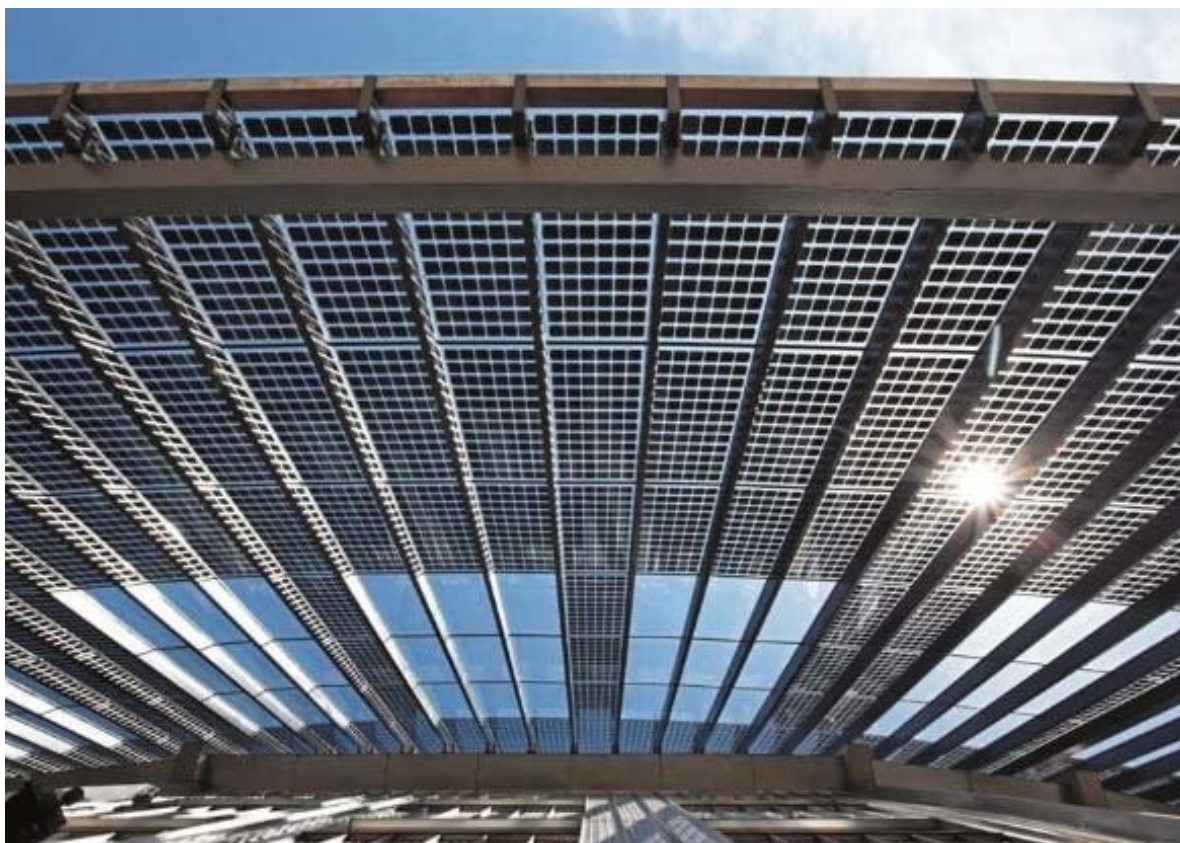


Figure 21. BIPV skylight system. [35]

The energy efficiency of BIPV skylights is largely determined by the cell coverage ratio, which indicates the proportion of the skylight area covered by solar cells. This ratio is influenced by two key factors: the spacing between the cells and the size of each individual cell. Adjusting these variables allows for control over both energy production and natural daylight penetration. A higher cell coverage ratio increases the system's electrical output, as more solar energy is captured and converted into electricity. [26] However, this comes at the expense of reduced daylight transmission into the indoor space, which may affect lighting conditions and the overall ambiance. Conversely, a lower cell coverage ratio allows more sunlight to pass through, enhancing natural lighting but reducing the amount of solar energy harnessed for electricity generation. The balance between these factors is crucial in optimizing both energy performance and indoor lighting comfort.

High coverage ratio usually means high electricity production for the whole module, but wider cell spacing can improve power production of a single cell, even though the power production of the whole module decreases as area of the modules decreases. This is due to the fact that wider cell spacing allows more light to pass through around the cell, eventually some

of it reflecting back to the cell. [26] Additionally, with wider cell spacing, heat distribution is more effective. The cell heats less and produces more electricity. [4] So, the higher the area of the cells is, the higher the power production of the whole system. But with wider cell spacing, which means less total cell area, single cells produce more electricity.

BIPV skylights not only generate electricity but also contribute to reducing indoor heat gain. Traditional glass skylights allow all incoming sunlight to pass through, leading to increased indoor temperatures and higher cooling demands. In contrast, BIPV skylights absorb a portion of the sunlight, converting it into electricity, which reduces the amount of solar radiation entering the indoor space. This dual function helps lower cooling loads, resulting in reduced energy consumption for air conditioning and overall improved energy efficiency in buildings. By minimizing heat gain while simultaneously generating renewable energy, BIPV skylights offer a sustainable solution for optimizing building performance. [4]

The cell coverage ratio in BIPV skylights significantly influences the operating temperature of the solar cells, thereby affecting their efficiency and longevity. A higher cell coverage ratio means a larger portion of the skylight's surface is covered by PV cells, leading to increased absorption of sunlight. While this enhances electrical output, it also results in greater heat accumulation within the cells. Elevated operating temperatures can decrease the efficiency of photovoltaic cells, as their performance typically declines with rising temperatures. Moreover, sustained exposure to high temperatures can accelerate the degradation of cell materials, potentially shortening the system's operational lifespan. Conversely, a lower cell coverage ratio allows more sunlight to pass through the skylight, distributing heat more evenly across the glass surface rather than concentrating it within the cells. This design choice facilitates lower operating temperatures for the PV module components. By mitigating excessive heat build-up, the cells can operate more efficiently and with reduced thermal-induced stress, thereby enhancing their durability over time. [4]

Although changing cell coverage ratio can influence heat accumulation in the cells and indoors, BIPV skylights still have poor ventilation compared to open-rack mounted PV modules and this causes them to heat up more. Especially when they are integrated into indoor buildings. Zhen et al. studied glass/cell/glass structured photovoltaics in different setups to test operating temperature of BIPV and compare their performance to normal PV modules [25]. They built open-rack PV module as a reference and BIPV house model to compare operating temperatures of the solar cells. Mounting configurations can be seen in

Figure 22. The modules were prepared with cell spacing. Test was carried out under outdoor conditions in Changzhou China, using optimal 30° tilt angle. Thermocouples were placed into the solar cells, to get accurate cell operating temperature. As a result, it was found that BIPV module had 15°C higher maximum operating temperature than open-rack PV module during the measurements, mostly because of the natural ventilation of open-rack mounted PV was much more efficient. Built BIPV house had poor ventilation and airflow at the rear side of the PV modules, which is the main reason for higher cell temperature. But it should be noted that the built BIPV house was relatively small, and might not accurately represent real building, and could have same kind of heating effect as greenhouses. In the study they also found out that BIPV modules at the middle of the array had higher cell temperature than modules at the edges due to worse heat dissipation at the centre of array. The temperature difference between edge and centre modules was roughly from 3°C to 4°C. [25]



(a)



(b)

Figure 22. (a) test module of glass/cell/glass on open-rack mounting. (b) glass/cell/glass test module of simulated BIPV house. [25]

The article also criticizes standard NOCT (Nominal Operating Cell Temperature) testing method's suitability for BIPV applications. They believe that the method does not take into account the operating conditions of BIPV modules accurately, which differ significantly from conventional solar panels, for which the test was designed. Therefore, they suggest that the temperature of BIPV modules should be evaluated under actual operating conditions. Under NOCT conditions, solar panel temperature is measured based on standard factors: irradiance of 800 W/m^2 , ambient temperature of 20°C , 1 m/s wind speed, sunlight angle of 45° , open-rack mounting configuration, and open-circuit condition. Solar panel temperature is also measured at the rear side of the panel. NOCT assumes that PV modules are installed using open-rack mounting, and as previously mentioned, this assumption does not fit well with BIPV modules, because of the lack of ventilation at the rear side of the panels. In the study the maximum solar cell temperature difference between open-rack PV and BIPV was 15°C under same conditions. NOCT measurement does not consider the PV module positioning within the array, as the study found modules in the middle of BIPV had higher temperature due to worse heat dissipation. Measuring operating temperature at the rear side of the panel does not always represent accurate operating cell temperature. In the study they measured BIPV module temperature inside the solar cell and at the rear side of the panel. In some cases, temperature was 15°C higher at the cell than at the rear side. Especially in BIPV skylights some kind of insulating glass structures are preferred for thermal insulation of the building. In these cases, if the cell and rear glass have insulating material in between them, heat is not conducted efficiently from the cell to the rear side glass. So, in case of BIPV, assuming that the rear side panel temperature gives accurate results of cell temperature is unreliable.

4.4 Comparison of different BIPV technologies

Maturi et al. studied the performance and module temperature of BIPV in 2014 [6]. In the study they used different PV technologies under same weather conditions in Bolzano, Italy: monocrystalline silicon glass/cell/Tedlar (mc-Si3), monocrystalline silicon glass/cell/glass (mc-Si1) and monocrystalline silicon glass/cell/glass with black backsheet behind the rear glass (mc-Si2). All the modules were open-rack mounted with 30° inclination and mc-Si3 module was the only one with metal frame. Mounting configurations are shown in Figure 23. Temperature of the PV modules was measured from rear side using temperature sensors. [6]



Figure 23. PV module arrays: mc-Si3 (left), mc-Si1 (middle), mc-Si2 (right). [6]

They found that mc-Si3 stayed the coolest during measurements due to its glass/Tedlar structure and presence of a metal frame that helped heat dissipation. The metal frame at the side of PV module has good thermal conductivity and therefore helps with cooling the module. Therefore mc-Si3 experienced uniform heat dissipation through the module. Mc-Si2 experienced the highest temperatures mainly because of its black backsheet that absorbs more light, compared to traditional white backsheet. Mc-Si2 had no metal frame, and this led to uneven heat dissipation through the panel. This can be seen in Figure 24, where on the left (a) is IR image of mc-Si2 module and on the right (b) is temperature distribution referred to line 1 in the IR image. The figure clearly shows that the middle of the PV module operates at higher temperature (roughly 7°C) than the edges.

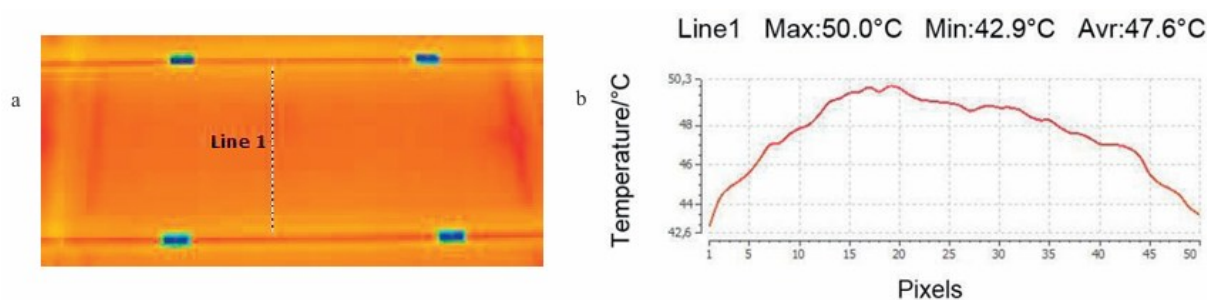


Figure 24. Temperature of a single mc-Si2 module measured with IR-imaging (a), temperature distribution of line 1 in IR image (b). [6]

Without a frame, the centre of the panel tends to be hotter than the edges, causing peaks in temperature, potentially affecting efficiency. Mc-Si1 heated up slightly less than Mc-Si2 due to its glass/glass structure, which does not absorb as much heat as the black backsheet. Mc-Si1 had the same uneven heat dissipation as mc-Si2 due to the lack of metal frame and therefore operated at higher temperatures than mc-Si3 module with a frame, but it was also estimated that higher operating temperatures are due to higher inertia of mc-Si1. Glass/glass

modules tend to capture more heat than glass/Tedlar modules. This is due to higher thermal inertia of glass, making cooling less efficient. [6] The study gives good understanding of how typical monocrystalline silicon PV modules perform compared to black backsheets and glass/cell/glass type panels that are used in BIPV. But to understand more about their properties, we need to view BIPVs in more realistic conditions as usually those are not open-rack mounted.

Özkalay et al. investigated operating temperature of PV modules in open-rack mounting versus BIPV configurations over a period of 2-5 years in Switzerland [7]. Three different test stands were used in the experiment; the first two were monitored for five years, and the third for two years. As BIPV modules, they used two different mounting configurations: ventilated and insulated. In insulated BIPV configuration, only the front side had natural ventilation and rear side was insulated. Ventilated BIPV had gap behind the panels (6-12 cm), allowing some natural ventilation at the rear side. As a reference point, they used open-rack mounted PV with natural ventilation on all sides. Mounting configurations are shown in Figure 25. [7]

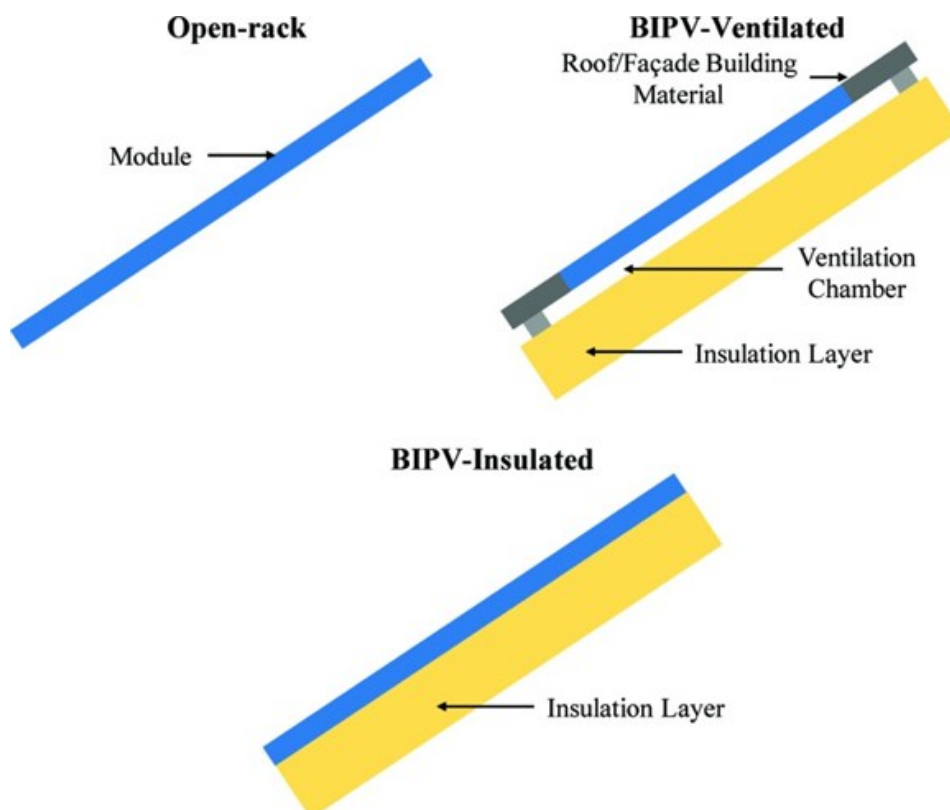


Figure 25. Illustrated PV installation configuration of open-rack, BIPV-ventilated and BIPV-insulated. [7]

In the study they had 3 different test stands with different types of module technologies. The first stand consisted of two module types and was installed in open-rack and insulated conditions: Al-BSF (Aluminium Back Surface Field) glass/ethylene-vinyl acetate/backsheet module, where aluminium was used at the back side to reflect light back to the cell, and the other module was glass/polyvinyl-butylal/glass. The second test stand consisted of two module types: HJT (Heterojunction Technology) glass/glass modules, where crystalline silicon was combined with an amorphous silicon thin-film layer, and passivated emitter and rear contact (PERC) cells in a glass/EVA/backsheet configuration. HJT modules were installed in open-rack and ventilated configurations and PERC module was installed in ventilated configuration. The third test stand consisted of PERC glass/polyvinyl-butylal/glass module in ventilated configuration, mounted at 90° tilt angle to represent the same kind of installation as in BIPV façade. [7]

Results showed clear difference between the operating temperatures of open-rack and BIPV modules. Open-rack had clearly the lowest temperatures, where maximum temperatures observed were at 62-66°C. Ventilated BIPV modules had slightly higher maximum temperatures of 68-83°C. Insulated BIPV modules reached maximum temperatures of 80°C-92°C. The difference in operating temperatures was found to be due to lack of ventilation in BIPV modules. The study estimated higher degradation rate for BIPV, because of the elevated temperatures and suggested revising testing standards for BIPV, as they operate in higher temperatures. They suggest that BIPV safety tests should be performed at harsher testing conditions, such as at higher temperatures. It should be noted that temperature was measured from rear side of the PV modules and therefore it does not necessary indicate accurate operating temperatures. Because in BIPV front side was completely exposed to natural ventilation and could have different temperature than rear side. [7]

5 PV module temperature calculation

5.1 Sandia model

When designing a PV module system, it is important to estimate module temperatures to be able calculate energy yield and degradation of the system. The so-called Sandia model, developed by Sandia National Laboratories is used to estimate solar cell operating temperature. The Sandia model takes into account ambient temperature, wind speed and solar irradiance. Sandia model can be used to model both normal PV systems and BIPV systems, because the model has been developed for different kinds of technologies and mounting configurations. Sandia model is not applicable to all PV technologies, and site dependent variables are not easy to consider. It has equations for PV module back surface temperature (Equation 4) and PV module cell temperature (Equation 5) calculation. [36]

$$T_m = E * e^{(-a-b*WS)} + T_a \quad (4)$$

Where T_m is the rear side module surface temperature, T_a is ambient temperature, E is solar irradiance on the module surface, WS is wind speed measured at standard 10 m height, a is empirically determined coefficient establishing the upper limit for module temperature at low wind speeds and high solar irradiance, b is empirically determined coefficient establishing the rate at which module temperature drops as wind speed increases. Table 2 shows coefficient a and b values for different technologies and mounting configurations. [36]

$$T_c = T_m + \frac{E}{E_0} \Delta T \quad (5)$$

Where T_c is cell temperature, T_m the rear side module surface temperature, E is measured solar irradiance on the module, E_0 is reference solar irradiance on the module of 1000 W/m², ΔT is temperature difference between the cell and the module back surface at an irradiance level of 1000 W/m². Combining Equations 4 and 5 gives Equation 6 as PV module cell temperature: [36]

$$T_c = E * e^{(-a-b*WS)} + \frac{E}{E_0} \Delta T + T_a \quad (6)$$

Table 2. Empirically determined coefficients for different technologies and mounting configurations, used to estimate PV module cell temperature as a function of irradiance, ambient temperature, and wind speed.

Type of model	Mounting configuration	Coefficient a	Coefficient b	Temperature difference (ΔT)	Reference
glass/cell/polymer sheet	open-rack	3.56	0.0750	3	[36,37]
glass/cell/glass	open-rack	3.47	0.0594	3	[36,37]
glass/cell/glass	close-roof	2.98	0.0471	1	[22,36]
glass/cell/polymer sheet	insulated back	2.81	0.0455	0	[22]

5.2 Solar cell operating temperature calculation

In this chapter, solar cell operating temperature is calculated using the Sandia model (Equation 6) with different PV module structures. Typical PV module glass/cell/polymer sheet structure with open-rack (gcp open-rack) mounting configuration is used as reference point and it is compared to glass/cell/glass close-roof (gcg close-roof) structure and glass/cell/polymer sheet insulated back (gcp insulated) structure. Coefficients for the Sandia model are used according to the Table 2 for each setup. Calculations are done with two different variables (irradiance and wind speed). Two different calculations are done, keeping one of variables constant and changing one of the variables, to see how different PV modules are dependent on each variable. For constant variables NOCT values are used (irradiance of 800 W/m^2 , ambient temperature of 20°C , and 1 m/s wind speed). The results are presented in Figure 26, where cell temperature is presented as a function of irradiance, with constant ambient temperature and wind speed, and in Figure 27, where cell temperature is presented as a function of wind speed, with constant irradiance and ambient temperature.

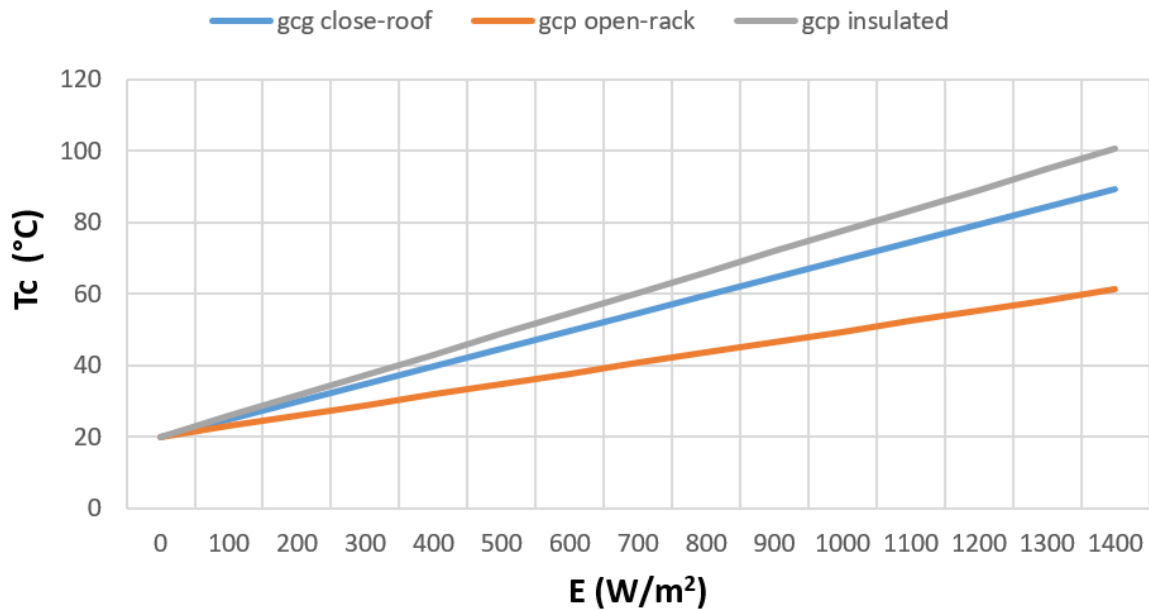


Figure 26. Cell temperature for each technique calculated using the Sandia model with different values of irradiance with constant wind speed of 1 m/s and ambient temperature of 20°C. gcp (glass/cell/polymer sheet) open-rack: $a=3.56$, $b=0.0750$, $\Delta T=3$. gcg (glass/cell/glass) close-roof: $a=2.98$, $b=0.0471$, $\Delta T=1$. gcp (glass/cell/polymer sheet) insulated: $a=2.81$, $b=0.0455$, $\Delta T=0$.

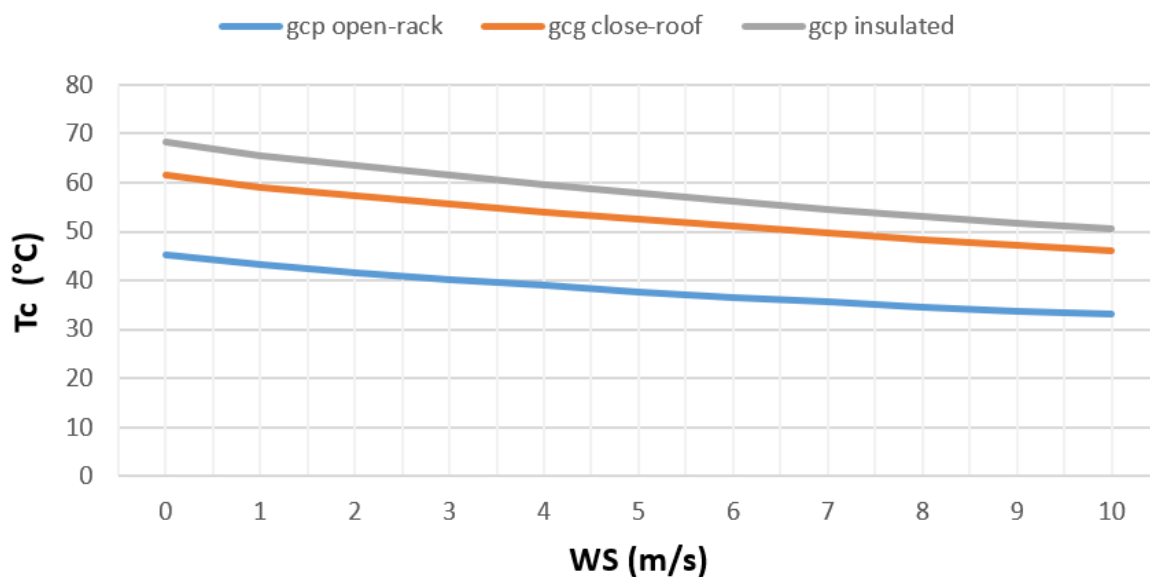


Figure 27. Cell temperature for each technique calculated using the Sandia model with different values of wind speed with constant irradiance of 800 W/m^2 and ambient temperature of 20°C. gcp (glass/cell/polymer sheet) open-rack: $a=3.56$, $b=0.0750$, $\Delta T=3$. gcg (glass/cell/glass) close-roof: $a=2.98$, $b=0.0471$, $\Delta T=1$. gcp (glass/cell/polymer sheet) insulated: $a=2.81$, $b=0.0455$, $\Delta T=0$.

The results are similar to those previously discussed. Typical open-rack mounted PV modules have the lowest cell temperatures. From Figure 26, it can be seen that the cell temperature

increases linearly in proportion to the irradiance. Also, it can be noted that when irradiance increases, the temperature difference between open-rack and other techniques increases. While gcp open-rack has cell temperature of 49°C, cell temperature reaches up to 69°C in gcp close-roof and up to 78°C in gcp insulated structure with irradiance levels of 1000 W/m². Figure 27 shows also similar results as before. In the figure, irradiance and ambient temperature are kept constant and wind speed increases. The cooling effect is the most efficient with open-rack module, and less efficient with close-roof and insulated back mounting configurations. It can be noted that curves are not linear, and rate of increased cooling decreases at high wind speeds. However, at normal wind speeds, the temperature difference is quite significant.

The Sandia model gives a good approximation of PV module cell temperature with different kinds of technologies and mounting configurations. It can also be used to approximate cell temperature of building integrated photovoltaics. BIPV skylights have similar structure to glass/cell/glass close-roof modules used in the calculations above. BIPV skylights have glass structure on both sides of the cell and same kind of restricted airflow at the rear side of the panel as close-roof systems. With BIPV skylights, the distance between the cells is adjustable to control the amount of light that reaches indoors. If the distance between the cells is increased and is to be taken into account in the Sandia model, coefficient a should increase slightly. This is because increasing the distance between the cells lowers the cell temperature, and the higher the coefficient a is, the lower the cell temperature. Glass/cell/polymer sheet insulated back structure can be used to approximate for example BIPV façade structures, because they have similar structure and insulation at the rear side to prevent heat conduction from the building. In the case of black coloured BIPV façade modules coefficient a should decrease, because black coloured PV absorbs more heat and increases the cell temperature, and the lower the coefficient a is, the higher the cell temperature.

6 Discussion

Building integrated photovoltaics systems generally operate at higher temperatures than traditional rack-mounted PV systems. [5–7] The main reasons for higher temperatures are reduced cooling and material properties of BIPV modules [28,30,32]. Higher operating temperatures cause reduced efficiency due to changes in the band gap of the silicon cell and increased resistivity [3,21]. Faster degradation of BIPV modules is also a consequence of higher operating temperatures. Mounting configuration and natural cooling of airflow have key role on the operating temperature of a PV module. BIPV systems are installed close to a building with restricted or no natural ventilation at the rear side, which is one of the main reasons for high operating temperatures, compared to traditional open-rack mounted PV systems that have airflow on both sides of the panel, leading to lower temperatures and better efficiency [25]. In case of BIPV, ventilation can also be limited due to direction of the wind. Especially facades can be installed on the side of the building that is rarely exposed to wind, or in a direction where wind is blocked by other buildings or terrain [7].

Material selection also plays key role when it comes to temperature effects of building integrated photovoltaics. Coloured BIPV modules can be made with various techniques, and their properties have high variation. Coloured filters can have quite different properties depending on the colour tone and brightness. Different colours reflect and absorb different wavelengths of light, causing various effects. Short wavelengths absorbed by the filter have higher energy and lead to thermalization losses and elevated temperatures. Reflected light causes losses in PV module efficiency. This kind of performance loss is unavoidable and non-coloured PV modules generally have better performance, but with right colour and material selection, coloured filters can have balance between aesthetic look and performance. Another common way to make BIPV fit into building's design is to use coloured backsheets, especially black backsheets are commonly used. The main problem with black coloured backsheet is that it absorbs much more light compared to traditional white backsheets, which again leads to higher operating temperatures. [7,26,30,32,33]

BIPV systems are commonly used in glass roofs or skylights, as they can be integrated with glass/cell/glass structure. BIPV skylights balance between energy production and natural light transmission. High cell cover ratio increases energy production but at the same time reduces the amount of light passing through the PV module. Higher cell spacing allows better heat distribution in the module. Like other BIPV systems, BIPV skylights generally operate at

higher temperatures than traditional PV modules. But with BIPV skylights the main cause for this is poor ventilation. In the case of indoor BIPV skylights, ventilation at the rear side of the module is restricted to indoor ventilation. [25,26]

It is crucial to understand the temperature effects of BIPV to be able to reduce their degradation. Key strategies to reduce degradation include carefully considering airflow around the module and material selection. Increasing airflow around the module can be done with design modifications, such as adding spacing at the rear side of the module or considering wind direction when installing the modules. Selecting materials with lower thermal inertia and materials that absorb less heat is crucial for maintaining lower operating temperatures. Although BIPV modules cannot compete with open-rack PV systems in performance and operating temperatures. With proper design and compromises between aesthetics and performance, BIPV can achieve degradation levels close to open-rack PV systems but still be able to blend into the urban environment. [28,30,32]

Although excessive heat buildup in BIPV is often considered a drawback due to its negative impact on performance and longevity, there are certain applications that could benefit from this excess heat. Especially in colder climates, excess heat provided by BIPV modules could be used as heat source for the building. Different heat recovery technologies could help reduce the heating needs of the building. By integrating heat recovery systems into BIPV modules, such as air or water-based heat exchangers, the recovered heat could reduce heating demand and increase energy efficiency and sustainability even more. Further development of BIPV systems could make them even more viable solution for energy-efficient buildings in colder regions.

PV module temperature increase caused by the restriction of solar power production have also become more common problem. Solar curtailment and solar clipping and occur more often, as the amount of solar energy has increased rapidly. The effects of solar curtailment on PV module longevity and degradation have not been extensively studied. However, it has been shown that solar curtailment increases PV module's temperature as current does not flow and eventually turns into heat. [10] Viable solutions to decrease solar curtailment include using different azimuth angles and energy storage systems. Many PV systems are optimized to produce maximum amount of energy, meaning that they are directed towards the south. Using different azimuth angles and directing more solar systems towards the east or west could help reduce solar curtailment. Solar power production would be more stable during the day as solar

power system with different azimuth angles produce power at different times of the day. Solar power producers could also benefit from this as electricity prices can be higher during the morning and evening than during midday, when there is the most solar production. Solar curtailment could also be reduced by increasing the number of energy storage systems. When there is overproduction energy can be stored, and when demand increases, energy can be directed back to the grid, leading to a more stable energy supply and demand, and decreased need for solar curtailment.

Solar clipping has also increased as solar panels have become so cheap compared to the inverter, and therefore solar systems are often oversized relative to the inverter's capacity, leading to solar clipping and higher PV module temperatures. Optimizing the inverter to match solar system is the key to reducing clipping. [8,9] Making more powerful inverters and cutting down manufacturing costs are key factors that could help reduce clipping.

7 Conclusions

The operating temperature of PV modules depends on the material, structure, and colour that is used in the panel, but also on mounting configuration, ambient temperature, wind speed, irradiation, all of which affect the operating temperature. Building integrated photovoltaics (BIPV) face unique challenges related to temperature and degradation compared to traditional photovoltaic systems. Due to their integration into buildings, these systems often experience reduced airflow, leading to higher operating temperatures. This heat build-up negatively affects efficiency and accelerates the aging of materials, reducing system performance over time. The most common degradation mechanisms that are affected by heat include hotspots, delamination of the encapsulant, broken cells, encapsulant discoloration, corrosion, and bypass diode failures. Factors such as material selection, mounting configuration, and ventilation play a crucial role in determining how well a BIPV system can manage heat. Specific materials used in BIPV tend to absorb more heat, further increasing temperature-related stress. To minimize these effects, thoughtful system design is essential, including strategies to enhance cooling through rear side panel ventilation, and to improve thermal management by using materials with low light absorption. However, BIPV systems still usually have higher operating temperatures than traditional PV systems. Despite these challenges, BIPV remains a promising solution for combining renewable energy generation with modern architecture, provided that temperature-related issues are carefully addressed.

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