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Polymeric photovoltaic panels: mechanical resistance through optimized materials selection

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Pannelli fotovoltaici polimerici: resistenza meccanica attraverso la selezione ottimizzata dei materiali

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Abstract

This thesis explores the mechanical resilience of polymeric photovoltaic (PV) panels, specifically designed for flexible and lightweight applications where conventional glass-based PV panels are unsuitable. Polymer-based panels provide versatility and reduced weight but face challenges in enduring mechanical stresses, especially impact resistance to conditions like hailstorms.

The purpose of this thesis is to better understand how Bills of Materials (BoMs) influence the impact resistance of the panel. To evaluate impact resistance, has been adapted the Ball Drop Test (BDT) taking into account the standardized hail impact test (IEC-61215). Various BoMs, comprising different encapsulant types and layer structures, has been tested. Impact resistance thresholds were established in alignment with real-world conditions.

The study reveals that textured surface finishes can effectively distribute impact energy, thereby enhancing the initial resistance to fractures. Moreover backsheet compositions contributed significantly to the impact tolerance of these panels. Electroluminescent (EL) imaging further enabled analysis of crack propagation, elucidating distinct fracture patterns based on material choices.

The results contribute to the field of sustainable energy by guiding the development of more resilient PV technologies, thus supporting their broader integration in various settings.

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Chapter 1

Navigating climate change challenges

1.1 Climate in crisis

The impacts of climate change are wide-ranging and severe, affecting natural systems, human communities, and economies around the world. Rising temperatures have led to more frequent and intense heatwaves, storms, and extreme weather events as hailstorms, threatening lives, resources and infrastructure. Melting ice caps and glaciers contribute to rising sea levels, posing a significant risk to coastal communities and ecosystems. Changes in precipitation patterns disrupt agricultural systems, leading to food insecurity and economic instability. Furthermore, hailstorms became very dangerous cause of their increase in intensity and power, becoming also a problem for some renewable technologies such as PV panels. For this reasons, adaptation measures including building resilient infrastructure, implementing early warning systems, enhancing agricultural practices, protecting natural ecosystems and improve PV systems' resilience are essential to reduce vulnerability, permit to the communities to better face the climate change impacts and continuous the evolution of humans society trough a sustainable develop.

Mitigating climate change requires urgent and concerted action to reduce greenhouse gas emissions and transition to a low-carbon economy. This involves phasing out the use of fossil fuels, increasing energy efficiency, expanding renewable energy sources, promoting sustainable land use practices, and investing in green technologies and innovation. International cooperation and policy frameworks, such as the Paris Agreement, play a crucial role in mobilizing collective action and setting ambitious targets to limit global warming.

1.2 Hailstorms

Hailstorms are formidable natural phenomena characterized by a very strong event made of frozen precipitation in the form of hailstones. These meteorological events typically occur within thunderstorms, where powerful updrafts carry water droplets to high altitudes where temperatures are below freezing. As these droplets are lifted into the freezing upper atmosphere, they undergo a process of nucleation and aggregation, resulting in the formation of hailstones. These hailstones grow in size as they collide with supercooled water droplets, eventually becoming large enough to fall to the ground and often making a problem for structures, vehicle or renewable energy technologies. The impacts of hailstorms can be devastating, causing extensive damage to property, crops, and infrastructure. Hailstones, ranging in size from tiny pellets to large chunks of ice, can shatter windows, dent vehicles, and devastate agricultural crops. The economic consequences of hailstorms are significant, with losses in the billions of dollars each year due to damage to crops and property.

Studies by the European Severe Storms Laboratory (ESSL) in Wiener Neustadt have shown a wide increase of the hailstone size with a consequently increase in damaging to cars, infrastructures and obviously crops, with then a relevant impact on the human society. For what concern northern Italy, a studied have also shown that hailstones over five centimetres in diameter is nowadays 300% higher than it was before 1990 [19], a very alarming data that is also visible in the last image (Figure 1.1). In recent years, there has been a noticeable increase in the frequency and intensity of hailstorms, a trend that is largely attributed to climate change. Warmer temperatures (principally due to the greenhouse effect) lead to increased evaporation of water from the Earth's surface, resulting in higher levels of moisture in the atmosphere. This, combined with changes in atmospheric circulation patterns, creates conditions favorable for the formation of hailstorms. Additionally, as the atmosphere warms, it can hold more water vapor, providing more fuel for thunderstorms and increasing the likelihood of severe weather events. Indeed an useful parameter to mention is the Convective Available Potential Energy (CAPE), that represent

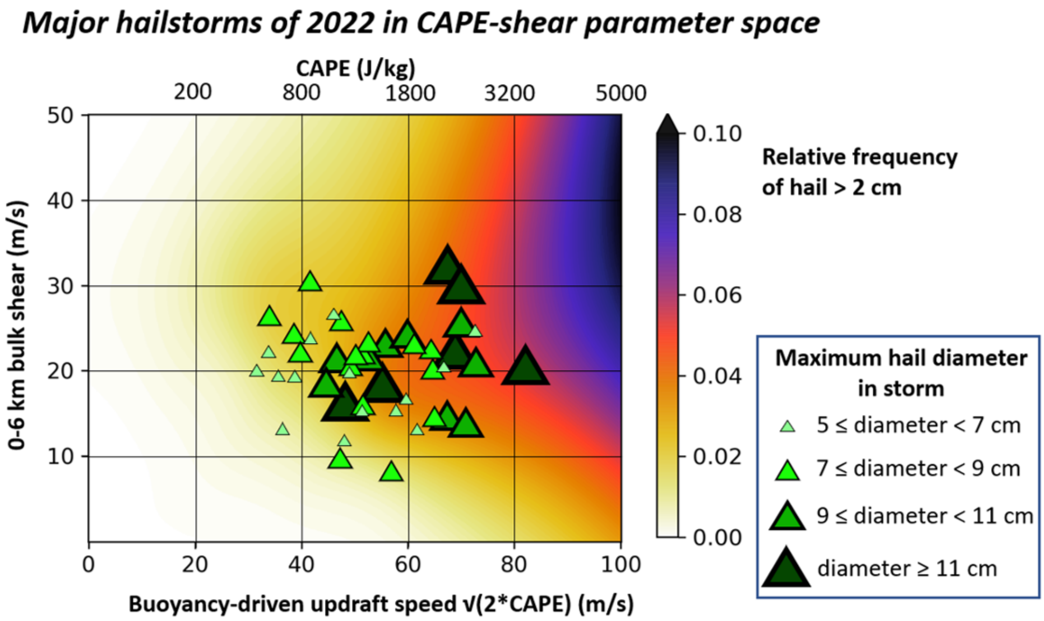


Figure 1.1: Hail frequency respect to CAPE in 2022 [13]

the measurement of the potential energy available for the development of convective movements in the atmosphere. It is expressed in joules per kilogram (J/kg).

The consequences of this trend are quite wide, impacting communities, economies, and ecosystems around the world. As hailstorms become more frequent and intense, there is a growing need for adaptation and mitigation strategies to minimize their impacts. This includes improving forecasting capabilities and design standards to withstand hail damage, and promoting sustainable land management practices to reduce vulnerability to extreme weather events. An hail reports focused on the European area, put in evidence how in the 2022, the hailstorms hit consistently the area. Also looking to the diameters of these hailstorms, the European's situation is quite alarming.

Therefore, hailstorms represent a significant threat with the potential for widespread damage and disruption. Understanding their formation, impacts, and drivers is essential for developing effective strategies to mitigate their impacts and build resilience in the face of a changing climate.

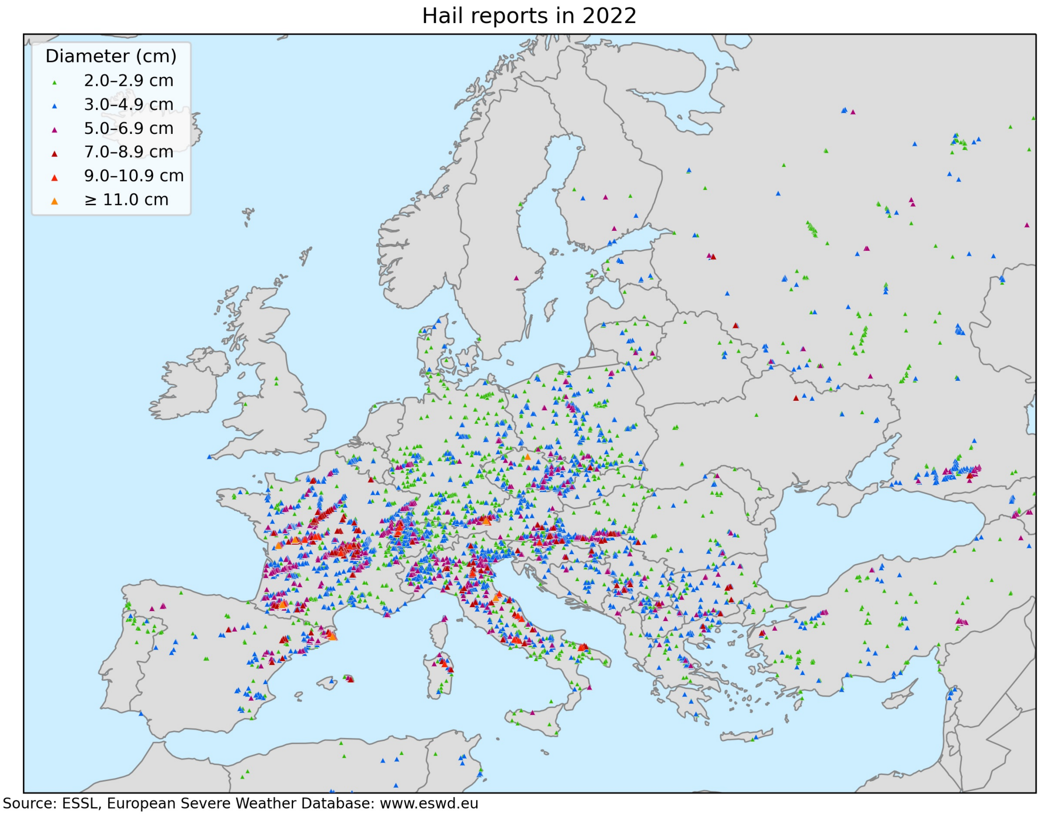


Figure 1.2: Hail map report in 2022 [13]

1.3 Polymeric panels against the crisis

This introduction pointed out the necessity of implementing photovoltaic (PV) panels to address the significant energy demands of modern society. Indeed, it emphasizes the need to meet these demands in a sustainable way that does not contribute to the environmental crisis currently face by the planet. While the classical PV technology seems quite obvious, the reality is far more complex. Photovoltaic technology has indeed become widely used and more affordable nowadays. However, challenges arise in specific scenarios. For instance, what if you need a PV panel for a marine application where the conditions are so harsh? Or if you need to install a PV panel on a compact city car, where space and weight are critical constraints? Additionally, consider the challenges of mounting a PV panel on a glider, where weight and aerodynamics are essential. These scenarios illustrate that implementing PV technology, particularly glass-based PV panels, is not always as straightforward as it is in typical residential settings. This is where polymer-based photovoltaic panels come into play, offering an additional degree of freedom and flexibility to PV technology. Polymers provide a lightweight and flexible alternative to traditional glass-based PV panels. For example, in marine applications where safety regulations and environmental conditions make the use of conventional glass PV panels impractical, polymer-based PV panels present a viable solution. Their flexibility allows for integration into various surfaces and structures, enhancing the versatility of PV applications.

Figure 1.3: Flexible polymer-based panel.

Of course this solution open so many possibilities as problems. It's actually amazing being able to put a PV panel on a compact city car, but what if the city car stay outside during an hailstorm? As the car get damage, also the panel go trough irreversible damages that make it partially or totally useless (depending on the entity of the damage) and potentially dangerous (cause of the important hot spot phenomena) later. Obviously so many problems like this are solved by adding a glass on the front, but then the weight become a problem. It's then for this reason that this work has been performed, to understand where the current polymer-based PV technology is, and also for trying to get a little bit more from this technology developing Bill of Materials more resilient to impacts. It is possible to pursue this goal by performing the hail impact test (IEC-61215) as required by the standards for photovoltaic applications; anyway this test is complex (for what concern the instruments required) and not economically cost effective. For this reason, the study has been conducted looking to the Ball Drop Test. The classical Ball Drop Test, as described in ASTM F3007-19, is a method for evaluating the impact resistance of laminated flat glass products used in architectural applications. This test involves dropping a 2.3 kg, 83 mm diameter smooth solid steel ball from a user-selected height onto the glass to assess its ability to withstand impact. This method is intended for in-plant quality control and is not a substitute for safety glazing standards such as ANSI Z97.1 or CPSC 16 CFR 1201, which have different requirements and procedures [9]. After this briefly overview on the ball drop test standard, it is then evident the necessity of an adaptation, performed as explained in the next chapters 4.2 as alternative to the hail impact test and so useful for learn the behaviour of the different analyzed materials. This paper explores various materials used in these panels through the hail impact test. Beginning with a general overview of the company, the panels, and the tests, it will then focus on a detailed discussion of the adapted Ball Drop Test.

1.4 State of the Art

It is important to understand the current state of research regarding the development of photovoltaic panels, particularly in terms of their mechanical resistance.

1.4.1 Glass based

Speaking about glass based panels, it's quite easy to obtain mechanical resistance due to the inherent strength and rigidity of glass, which provides excellent protection against external impacts. Additionally, glass has well-known properties for withstanding pressure and stress, making it a reliable choice for enhancing the durability of photovoltaic panels. Quoting The American Ceramic Society [5], in the "Analysis of the hail impacts on the performance of commercially available photovoltaic modules of varying front glass thickness" [12], they have used: "PV modules with three different thicknesses of front glass (2.8 mm, 3.2 mm, and 4 mm). Investigations were carried out following the guidelines prescribed by the IEC 61215–2:2016 and IS 14286:2019 standards. Specifically, the size, weight, and speed of the hailstones were varied within the limits given by these standards.

Hailstone size: 25–55 mm Hailstone weight: 7.5–80 gm Hailstone speed: 23–34 m/s."

1.4.2 Polymer based

Polymer-Based PV overview

Polymer-based photovoltaic panels offer a lightweight and flexible alternative to traditional glass panels, making them suitable for portable solar devices and applications in Building Integrated PV (BIPV), automotive and marine industries. These panels typically consist of a polymer encapsulant with additional polymers for the front and back layers. Their lightweight design allows for easier transportation and installation on curved surfaces. However, challenges remain regarding mechanical resistance and long-term durability due to susceptibility to environmental degradation.

Current research aims to enhance their mechanical properties through multi-layered structures and develop surface coatings for protection against UV degradation and moisture, positioning polymer-based panels to play a significant role in the future of solar energy applications.

Building Integrated PV (BIPV)

The glass-free PV (the polymer based ones) brings on the market the Building Integrated PV (BIPV), a technology discussed from Ana C. Martins et al. (2017) [1]: "As one of the critical tests for glass-free solutions is the hail test, we show how the polymeric frontsheet design and composite backsheet stiffness influence the capability of the module to resist hail impacts." Then the authors keep going by describing the composite sandwich element (based on glass fibers reinforced polymer and a honeycomb core) used for enhance the mechanical stability in the back of the module stack. Anyway this particular material will be widely discuss in the next chapter. From the study, it's then possible to observe the Figure 1.4 in which the stiff support sandwich adhesive is present as back of the panel (with its glass fiber skins) and the EVA and ETFE as encapsulant and frontsheet respectively. Then, in the paper, the hail impact has been tested following the standard IEC 61215 and more precisely: "Ice balls of 25 mm diameter are shot at a velocity of 23.4 ± 1.5 m/s."

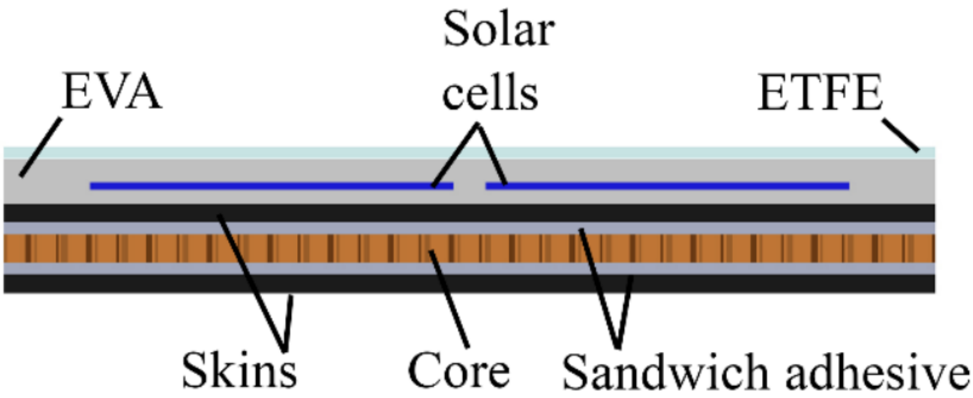


Figure 1.4: Sketch of lightweight PV module design for BIPV applications. [1]

Indeed, the results suggest that as the bending stiffness of solar panels increases, both the fill factor[1] and power output suffer more significant losses. This means that stiffer panels tend to perform worse under mechanical stress, with power losses reaching up to 8.3%.

Analyzing BIPV technology also involves discussing companies like Solarge. This Netherlands-based company has successfully implemented innovative rigid polymeric panels that eliminate the need for glass. Solarge utilizes advanced materials by avoiding the traditional aluminum frame and glass front typically used in conventional solar panels, Solarge's products are both durable and lightweight. More details can be found in Appendix A, including Figures A.1 and A.2.[3]

A BIPV study by Min-Joon Park et al. [10] investigated a module using an aluminum honeycomb core for the stiff backing. The study assessed the lightweight shingled-type PV module through standard IEC 61215 tests, mechanical load (ML 2400), damp heat (DH 1000), and temperature cycling (TC 200).

[1] The fill factor (FF) in a solar cell is a measure of the quality of the solar cell and is defined as the ratio of the actual maximum obtainable power (P_{max}) to the theoretical power that would be produced if the solar cell operated at both its open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) at the same time. Mathematically, it's expressed as:

$$\text{FF} = \frac{P_{\text{max}}}{V_{\text{oc}} \times I_{\text{sc}}}$$

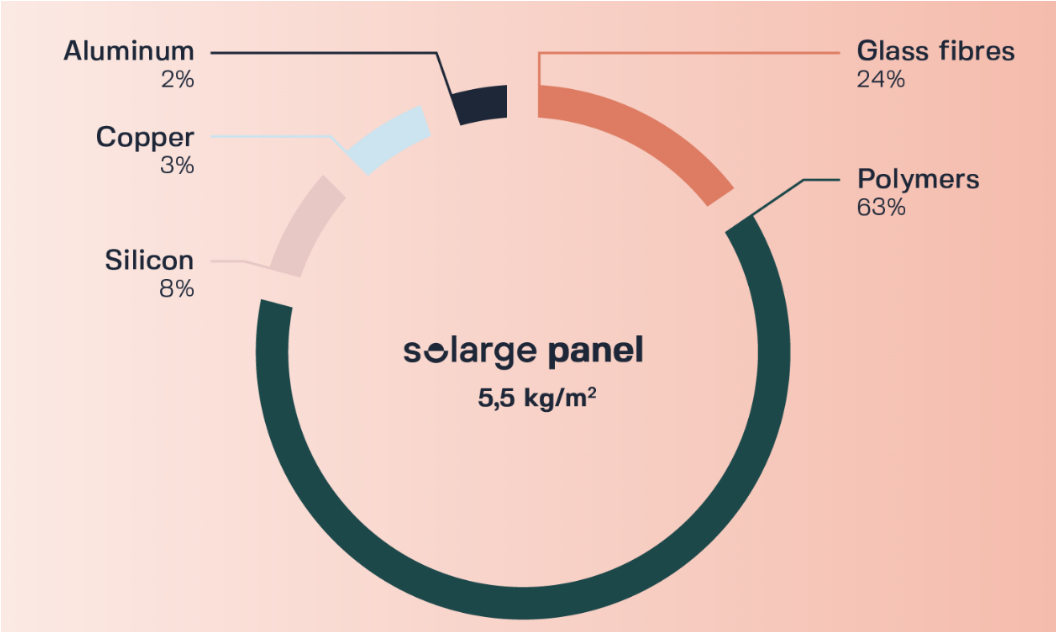


Figure 1.5: Solarge's polymeric panel composition. [16]

The mechanical load test subjected the module to 2400 Pa of pressure, causing a minor drop in fill factor (FF) and a reduction in maximum power (P_{max}) due to small cracks. Overall power losses remained below 5%, confirming the module's durability for BIPV applications.

This study is notable for using a different material than the current research, raising concerns about the cost-effectiveness of the aluminum core plate, which may not perform as well as expected.

Automotive applications

The Fraunhofer Institute conducted studies on the performance of lightweight glass-free PV modules in refrigerating trucks with a BoM very similar to the one already reported for the BIPV applications in Figure 1.4 [16]. The research highlighted the differing behaviors of semi-rigid panels under various tests showing that half-cell modules are more vulnerable to thermomechanical and environmental stress compared to shingled modules, with notable power losses in thermal cycling, damp heat, and UV tests. However, outdoor exposure over 10 months revealed no major structural issues, though minor degradation signs were observed through electroluminescence imaging. These tests indicate that while the module technology exhibited some degradation under extreme conditions, the shingled modules generally performed well.

Conclusions

All these studies are pointing out valid results in terms of durability and reliability. Furthermore, studies analyzing tests on specific compositions, such as honeycomb sandwiches for innovative applications like refrigerated trucks, have also been examined. On the other hand some studies used cells that are nowadays overcome or tests (see the ones listed above) that doesn't fulfill some valid aspects that this thesis will try to point out. For this reason, this study has been performed as an enhancement to previous research, contributing to the analysis of the impacts of hail on newer photovoltaic (PV) cells and potentially on new bills of materials (BOM).

Chapter 2

Solbian Energie Alternative srl

Introduce Solbian and its pioneering work in the solar energy industry can be done by introducing its goal: ”to provide you with the solar panel that best suits your needs. And if it doesn’t exist, to create it.” [24][1] This chapter will introduce Solbian as company [2.1] and then speak about standard’s Solbian panels 2.2 concluding with some innovative concepts 2.3.

2.1 Company overview

Solbian is known for producing high-quality flexible solar panels, a distinctive feature that sets it apart from other companies in Italy and beyond. Solbian’s panels are designed to withstand the harsh conditions at sea (actually Solbian is a leader on marine PV application), providing reliable and sustainable energy solutions to a range of marine vessels. Of course the lifetime is not as the classical glass based photovoltaic panels (where it can reach even less than half lifetime respect to the classical glass-based panels), but this can be addressed by the different conditions in which the panels work.

Solbian’s solar panels are already designed to withstand hail impact, featuring reinforced encapsulation and resilient cells. However, with the rising occurrence of extreme weather events, particularly as the company expands into the automotive sector, the need for even more sturdy panels has become evident. This situation has driven the company to enhance the durability of their panels, ensuring they can better resist these increasingly severe environmental

[1]Translated from italian [24]

conditions. In response to these needs, Solbian initiated a comprehensive study aimed at understanding and enhancing the hail resistance of its panels.
This paper presents the findings of Solbian's study, which focuses on determining the best combination of materials to achieve a good level of mechanical resistance. This research is crucial for improving the durability and reliability of Solbian's solar panels, ensuring they can withstand the impact of hailstones and continue to perform efficiently in adverse weather conditions. By conducting this study, Solbian not only addresses a critical gap in the market but also reinforces its commitment to delivering innovative and high-quality solar solutions. The findings will guide the development of more resilient panels, thereby enhancing the overall value proposition for Solbian's customers.

2.2 Solbianflex PV panels

Solbianflex PV panels are generally made by cells encapsulated in a flexible substrate, often made from PET (polyethylene terephthalate), or other similar polymers with lot of custom dimensions. This design allows the panels to conform to curved and irregular surfaces while maintaining durability and efficiency.

Metallization typologies of solar cells

In the development of photovoltaic cells, the cell's technology is quite important. Looking for practical aspects, the typical efficiency of this cells is actually around 20-22% but some differences can be observed between different cell's typologies. Moreover can be present losses due to the frontsheets polymers around 2/3% depending on a wide area of factors. For this reason, the metallization plays an important role in optimizing both efficiency and durability. Then a more accurate overview based on the main metallization typologies is subsequently proposed:

- **Busbar (BB)** [Figure B.4]: The busbar (BB) approach reduces resistive losses by decreasing current flow through the fingers and busbars. Then, increasing the busbar number, the shorter distance between them reduces the current path in the fingers, minimizing series resistance. As resistive power loss (P_{loss}) scales with I^2R, halving the current cuts losses by a factor of four.

- **Multi-wire (MW)**: This typology of cells, have usually fine wires as replace of metal ribbons (busbar). This solution permit to increases the active surface area for sunlight exposure, improving light absorption.

- **Back-contact cells** [2.1]: Shifts the electrical connections to the rear of the cell, eliminating front-side metallization. This type of metallization minimizes shading losses, maximizing the sun radiation that the cell is able to recipe. Moreover, it improves the cell's aesthetic appearance.

- **Metal Wrap Through (MWT)** [Figure B.3]: A type of back-contact cell where metal contacts are "wrapped" through holes in the cell. This metallization permit to enhances current collection efficiency by reducing front-side shading and lowering resistive losses.

These metallization strategies are essential for pushing forward both the efficiency and aesthetic integration of solar technologies in various applications.[2] [20]

Manufacturing process

The construction process of Solbian's flexible photovoltaic panels involves several key steps. It begins with the application of a frontsheet, which serves as the initial protective layer for the photovoltaic cells. This layer is usually made from transparent and durable materials like PET or similar films, which shield the cells from mechanical damage and environmental exposure.
Following this, the photovoltaic cells are sandwiched between two layers of an encapsulant material. This material, typically a plastic film or elastomeric compound (will be discuss better in the lamination section [3.1]), protects the cells from moisture, dust, and other contaminants, ensuring the longevity and reliability of the panel. The encapsulant also contributes to the panel's flexibility and overall performance.
The final stage of the construction process involves applying a backsheet, which completes the panel's structure. The backsheet is made from durable materials such as, PET, providing additional protection and stability. It prevents moisture infiltration and further shields the cells from external damage.

[2]More details about the function principle or back contact cells are present in the Appendix B, Figure B.2.

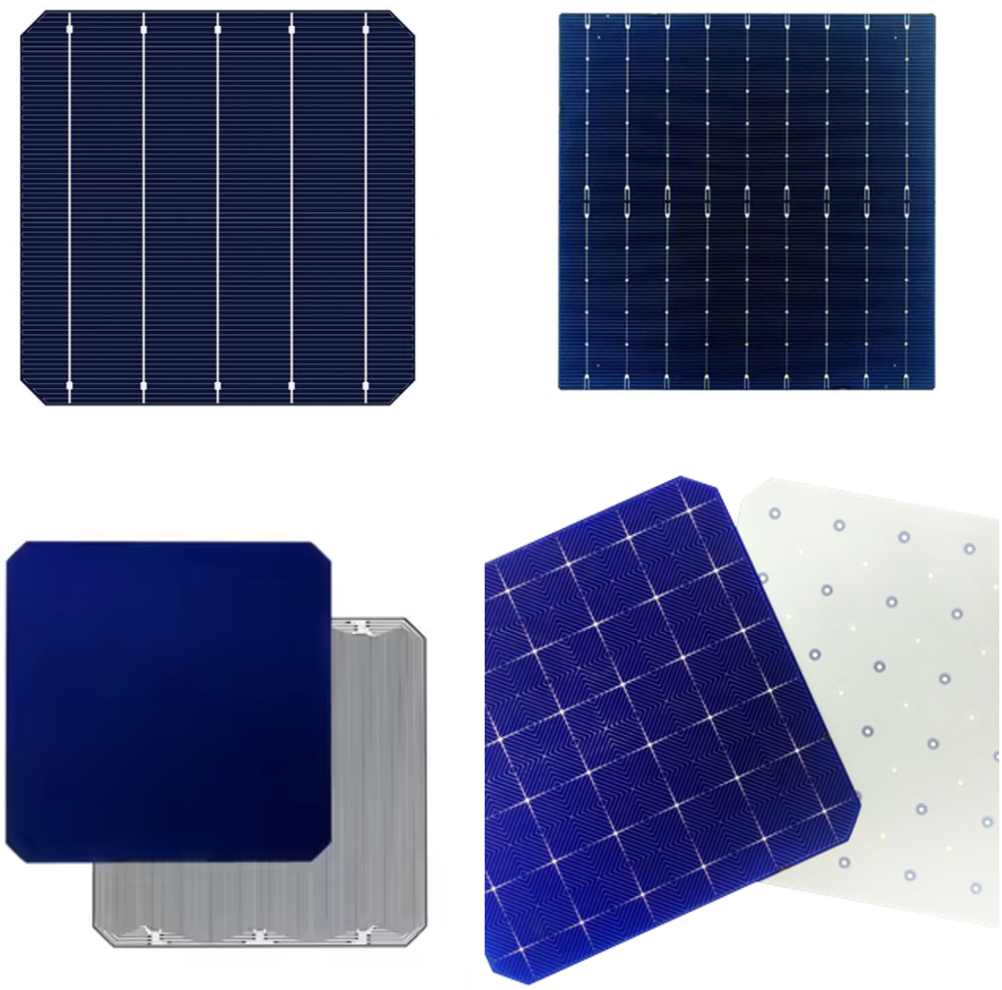


Figure 2.1: Top left: BB cell ; Top right: MW cell ; Bottom left: Back-contact cell ; Bottom right: MTW cell

Once assembled, the panels undergo rigorous testing to verify their performance and resilience. These tests assess various parameters including flexibility, durability against environmental conditions, and overall efficiency.

In summary, Solbian's flexible photovoltaic panels combine advanced materials and technologies to deliver high-performance, adaptable solutions. The rigorous construction process, from the choice of frontsheet and encapsulant to the application of the backsheet, were been and is still being carefully studied, ensuring that these panels are both effective and durable for a range

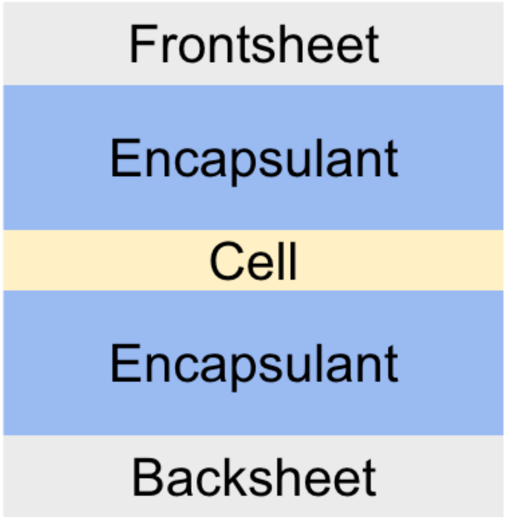


Figure 2.2: Base BoM structure[25]

of applications.

2.3 Semi-rigid PV panels

As wrote in the state of art [1.4], a particular types of semi-rigid backsheet has been subject of intense studies. Indeed, recently, the company has been interested in developing a new type of panel using this technology, useful for different applications. Refrigeration trucks and some specific marine applications are the main promoters for the researches on these new panels that are made by the so called organosandwich. In particular, these type of panels permit to use the already described BoM (see 2.2), but then, a different type of backsheet is used: the organosandwich. This backsheet gives to the panel a stiffer behavior; anyway depending on the thickness of the organosandwich, it's possible to play with the degree of stiffness of the final PV panel.

2.3.1 Organosandwich's characteristics

The organosandwich under investigation is a panel very similar to the classical ones used for packaging. This type of backsheet is made by a double layer of glass fiber (for both the panel sides) with in the middle an honeycomb core of plastic material. The production process of this panels, is an extrusion of polypropylene (PP) and then a cut followed by a particular type of process for the formation of an honeycomb core made as showed in figure (Figure 2.3).

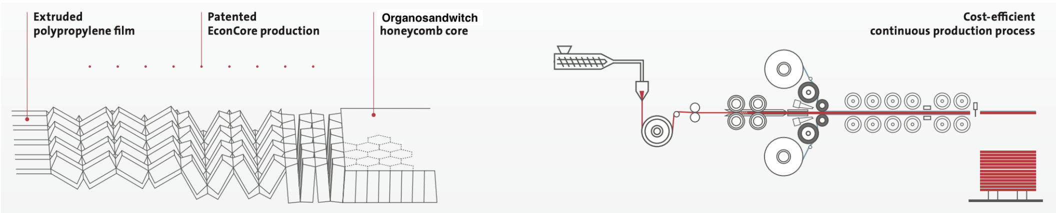


Figure 2.3: Organosandwich formation process[4]

Indeed it is composed by a double layer of glass fiber (GF) on both the sides (kept stiff and fixed by the epoxy resin) and the honeycomb thermoplastic core. This structure give to the organosandwich stiffness, which can be enhanced when integrated into the solar panel.

In the next chapters these semi-flexible / rigid panels recently developed by Solbian will be treated again for what actually are the firsts tests that this BoM have seen in the company.

2.3.2 Whisper project

As has been said, particular types of applications made as promoters to an evolution of the Solbian PV panels in stiffer final product, one of this applications was for the European Whisper project [6] in which the cargo panel applications have been considered. The cargo ships considered in the project are commercial vessels specialized in the transportation of goods and general cargo. Cargo ships, are designed to transport large quantities of goods between international ports. It is evident how important it is to implement photovoltaic technology on these types of vessels. In the following image (Figure 2.4), it is possible to see how much unused space is present (and then used) on a cargo vessel, especially during navigation. Indeed, during this time, the mechanical arms used for loading and unloading cargo are securely stored within the ship, and large steel covers ensure their protection. Photovoltaic panels can then be applied to these steel panels, taking advantage of the otherwise unused space.

The choice of backsheet material was thoroughly discussed due to the wide

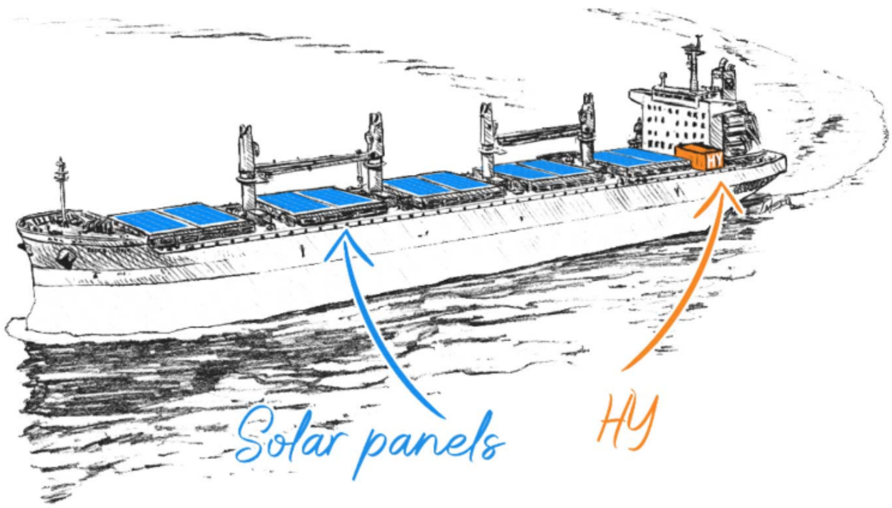


Figure 2.4: Cargo panels application example[6]

range of available options. According to Dreossi 2.4, the material ultimately used to support the cargo ships in 2021 was a marine plywood panel. Anyway, before of that, also other materials were considered. One of that was an aluminum core panel, considered for its ability to provide stiffness to the PV polymeric panel applied to the vessel. Then, another material was a polypropylene core-epoxy impregnated skins panel, quickly dismissed due to its high flammability.

Dreossi reported that the tests on this organosandwich material showed promising results (flexional and failure tests were performed), but fire concerns remained due to the core material, indeed, a flame-retardant additives can be applied to the fiberglass surface to slow the flame's spread on the front and on the back of the panel, but from the side (and so for the core) the problem persist. So that, while the organosandwich material performed well in other areas, fire issues persisted. Furthermore, while this material was considered too costly for the application, this issue was effectively solved by Solbian's approach, making it a viable option.

On Dreossi's data, which are provided in Appendix B, Table B.1, it's possible to observe the characteristics of the material tested. However, it is important to note that while the original work had limitations regarding cost and fire safety, these were addressed and improved by Solbian in their iteration of the material.

2.4 Sustainability

2.4.1 Life Cycle Assessment (LCA)

Analyzing the life cycle (LCA) of flexible photovoltaic panels is crucial to assess their overall environmental impact. LCA evaluates everything from raw material extraction to production, use, and disposal. It's interesting to observe how, the typical process represented in the Figure 2.5, pointed out the necessity of energy in each process represented, a peculiarity considered in the LCA outcome. Other aspect to consider is that Solbian's clients are mainly European, with finished products transported by truck within Italy and by air to other countries, which significantly impacts the environment.

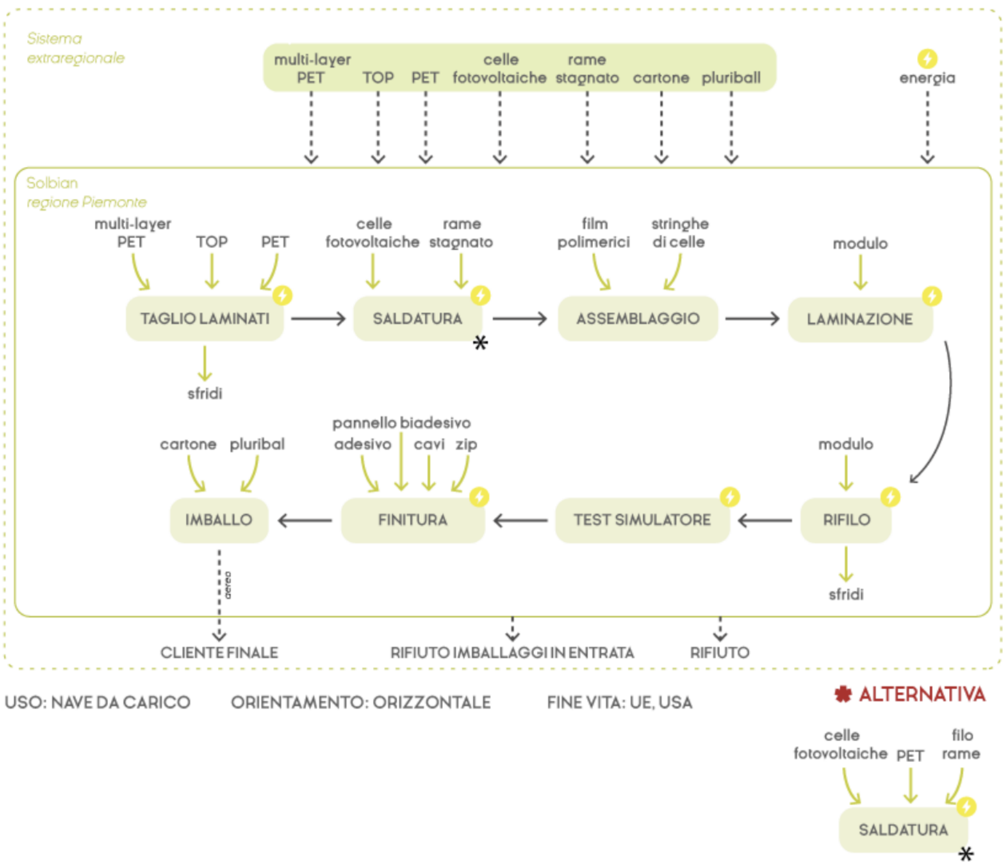


Figure 2.5: Productive process used in Solbian and considered for the LCA [23]

LCA shows that all the plastic used in the panels seems to have an environmental impact not as big as the energy used for the production of the cells, a peculiarity present also in the "classical" glass panels. Indeed it's interesting looking at the graph below (Figure 2.6), where the greater impact of packaging plastics can be observed compared to the plastics used to make the panels. To better understand that graph, it's important to understand the x-axis. It represents a series of environmental impact categories as defined in the Life Cycle Assessment (LCA) methodology. These categories include various potential environmental impacts, such as climate change (differentiated into fossil, biogenic, and land use), ozone depletion, acidification, eutrophication (freshwater, marine, terrestrial), photochemical ozone formation, resource use (both mineral and fossil), and water use. Each category quantifies the contribution of the polymeric photovoltaic panels to specific environmental burdens, providing a comprehensive view of the product's ecological footprint across its lifecycle.

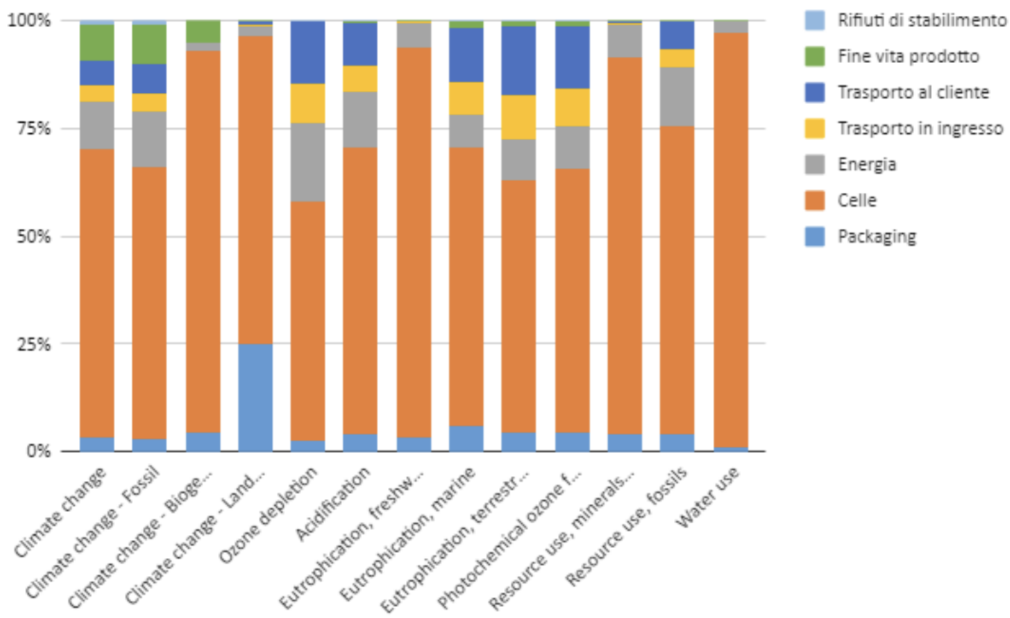


Figure 2.6: LCA graphs for environmental impact[23]

Despite the polymeric nature of flexible panels, the main environmental impacts are not just from the plastic. Manufacturing and transporting the photovoltaic cells, along with the packaging required for shipping, contribute significantly to the environmental footprint.

2.4.2 Encapsulants' recycle

Looking at the graph (Figure 2.6), seems that a sustainable design doesn't play a key role in promoting a circular economy. Anyway this is not totally true, it is very important to improve this aspect cause can have a very important impact also on the end of life of the panels. Studies have shown that encapsulation materials (treated better in the next chapter) need to meet various economic and performance standards, but recyclability is not yet a major focus. EVA (ethylene-vinyl acetate) is still the most commonly used encapsulation material. However, it presents challenges for recycling and reuse cause of its curing. There are so viable alternatives that offer competitive economic and performance benefits.

In the short term, improving recycling processes for conventional EVA modules is essential. Long-term strategies should aim to enhance design for easier and more economical recycling and reuse. PO (polyolefin) stands out as a promising alternative. PO can save energy during production (cause of a shorter lamination process [3.1]), improve module performance, avoid harmful additives, and be recycled more easily than EVA. Its peculiarity is the ability to be separated from the panel at its end of life, just by heating it up. In Solbian, some studies are carrying out for an almost complete recycle of this material with a not negligible cost, hoping maybe in a new product, instead of a classical pyrolysis (as good as well).

In summary, EVA encapsulation remains dominant nowadays due to its proven performance, cost-effectiveness, ease of manufacturing, and compatibility with existing technologies. Its reliability in protecting PV cells from environmental damage, combined with its affordability and well-established production processes, makes EVA a preferred choice in the industry. Therefore, there is a clear need for better recycling methods and design improvements to support a circular economy and PO offers a viable alternative with environmental and performance benefits. Then, incorporating LCA insights into development and transportation strategies will further enhance the sustainability of PV panels by addressing the wider impacts of their life-cycle.

Chapter 3

Lamination process

3.1 General Overview

Before starting to analyze the main tests for the mechanical resistance, it's important to have an overview on the methodology in which the panels are make. The choice of encapsulant in photovoltaic module manufacturing is crucial for performance, durability, and overall efficiency. Ethylene Vinyl Acetate (EVA) and Polyolefin (PO) are two widely used encapsulants, each with distinct properties, advantages, and drawbacks. This chapter aims to provide a general understanding of encapsulation sheet types and the lamination process, starting with a review of the previous assembly steps where the panel is integrated with various plastic layers. In the next sections will be done an overview of the main aspect that influence the material and the lamination process, then will be analyze it properly. Subsequently, an overview based on the sample preparation for the tests carried out, will be quickly performed.

Chemical proprieties

The chemical composition of these materials affects their ability to protect PV cells from environmental factors such as moisture, oxygen, and UV radiation, ensuring long-term efficiency and stability. Actually the chemical structure play also a big role in the ability of the material to cross-link or on the melting's peaks. Then, thermal behavior, dictates how well the encapsulants can withstand high temperatures during both the lamination process and the module's operational life. Furthermore, their chemical makeup impacts mechanical properties like flexibility and resistance to stress, which are vital for maintaining the structural integrity of the modules under varying environmental conditions. Later will be analyzed the EVA and PO chemical proprieties for understand the different behaviours.

Differential Scanning Calorimetry (DSC)

DSC, or Differential Scanning Calorimetry, is a thermal analysis technique used to study the thermal properties of materials. Specifically, it measures how much heat is absorbed or released by a sample as it is heated, cooled, or held at a constant temperature. In a DSC experiment, a sample and a reference material are subjected to the same temperature program, and the difference in the amount of heat required to maintain both at the same temperature is recorded. This data allows researchers to identify and quantify thermal events such as melting, crystallization, glass transitions, and chemical reactions (like cross-linking in polymers such EVA). What is important for understanding the lamination principle treated in the next chapter is then the DSC curves. In the next paragraphs will be faced the EVA and the PO characteristics based on these curves.

Lamination principle

The lamination is a process that permit the bonding of all the panel's polymers together. The process, indeed, start with the assembly of the panel, layer by layer as described in 2.2. A typical laminator can be observed by looking at the Figure 3.1. It's anyway important to remember that there are several typologies of laminators with different stages and different heating systems (different plates able to heat up), but the principle remains in each case the same.

The lamination process involves placing these layers into a laminator, where they are heated to around 150°C and subjected to vacuum and pressure to remove air bubbles and ensure full adhesion. After heating, the panels are cooled down to stabilize the materials. Anyway the specific process depends by materials and will be analyze better in the next sections.

Once the lamination process is complete (with EVA or PO), the newly laminated solar panel is carefully removed from the laminator. At this point, the panel is ready for further assembly steps or quality inspections to ensure it meets the required standards. The entire lamination process not only provides mechanical stability to the solar cells but also protects them from moisture, mechanical damage, and other environmental factors. This encapsulation is vital for the reliability and longevity of solar panels, making the laminator an important and essential machine in the manufacturing of high-quality PV modules.

Figure 3.1: Typical photovoltaic laminator
[26]

3.2 Ethylene Vinyl Acetate (EVA)

EVA has dominated the market for long time and yet now is the principal encapsulant used in the photovoltaic panels. It is used so much for its particular curing proprieties that let it melt and cross-link very well keeping compact the whole panel.

Chemical Proprieties

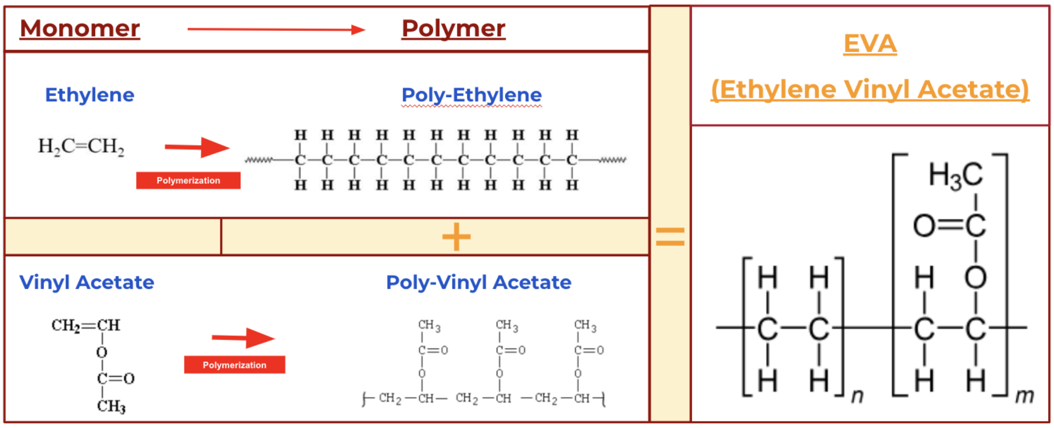


Figure 3.2: Chemical formation process for EVA

Given its unique chemical characteristics, it is produced through the polymerization of two monomers: the Ethylene and the Vinyl Acetate (VA) [Figure 3.2]. This structure make the EVA cure during the lamination process when the temperatures can reach (from literature) around 150°C. Therefore, the presence in the structure of some elements and functional groups, permits to the EVA to have some proprieties that make it peculiar[1].

Carrying on, the curing process allows the encapsulant to transition from a thermoplastic, to thermosetting[2]. Curing, the molecule is able to cross-link (just if the VA content is more than 30%) as illustrated in Figure 3.3 (for this reason is then so difficult to recycle it).

Differential Scanning Calorimetry (DSC)

DSC is particularly useful in the study of materials like EVA, as it provides insights into phase transitions and the degree of cross-linking, which are critical for understanding the material's performance. In particular, a study pointed out the importance of the different cross-linking agents, looking at its heat flow[3].

Figure 3.4 show the DSC curve for EVA before and after lamination. For

[1]More details in the Appendix B Figure C.1
[2]More details in the Appendix B Figure C.2
[3]For more detail about the DSC study look in the Appendix B, Figure C.3

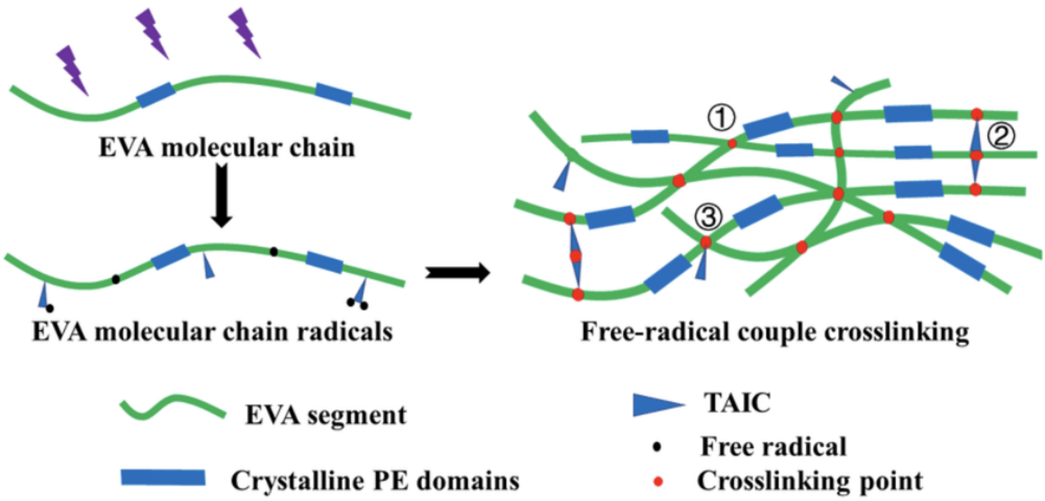


Figure 3.3: Chemical chain for EVA (cross-linking process)

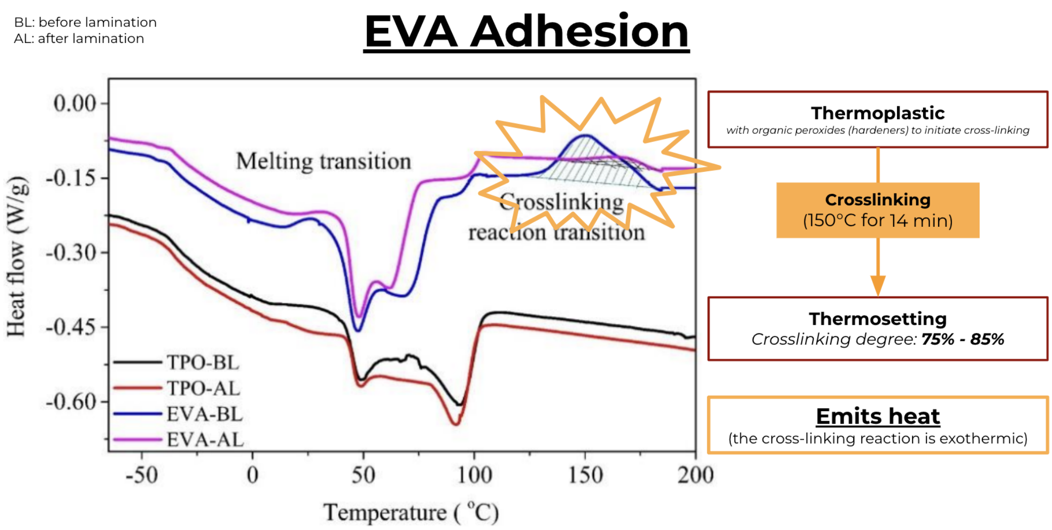


Figure 3.4: DSC graph (focus on EVA) [17]

EVA before lamination (blue curve) the graph shows an endothermic peak corresponding to the melting transition, occurring around 50°C. This is typical for EVA, indicating the phase change from a solid to a molten state. Then, as the temperature increases, a significant exothermic peak appears around 150°C. This peak corresponds to the cross-linking reaction, where the EVA undergoes a chemical transformation from a thermoplastic to a thermosetting material. During this process, organic peroxides in the EVA initiate the cross-linking reaction, which is exothermic, releasing heat as the material forms a stable, three-dimensional network. The behaviour slightly change in the post lamination. After lamination, the DSC curve for EVA (EVA-AL) shows a shift in the cross-linking peak to a higher temperature, approximately 167°C. This shift suggests that the thermal stability of EVA increases after lamination due to the cross-linking process. The thermogram also indicates that the material has fully transitioned into its thermoset form, with a higher degree of cross-linking (typically 75% to 85%). That means residual capability of the material to cross-link resulting in a very lower exothermic reaction on the DSC graph.

Lamination principle

The EVA lamination process is divided in 4 main steps:

1. **Vacuum stage:** in the initial stage, the laminator employs a vacuum system to remove all the air trapped between the layers of the assembly. This step (that can last between 180 and 360 seconds), is crucial to ensure that no air bubbles remain, which could compromise the integrity and performance of the solar panels. By creating a vacuum, the laminator ensures that the layers are tightly pressed together without any voids.

2. **High temperature and pressure stage:** next, the laminator heats the layers using heating plates (can be upper and lower or just lower in some cases), reaching the high temperature and pressure phase. These plates apply consistent heat to the EVA encapsulation sheets, causing them to melt and flow. As the EVA melts, it acts as a glue, curing and bonding all the layers of the assembly together. Precise control of temperature and pressure during this stage is essential to achieve a uniform and durable encapsulation.

3. **Maintaining temperature and pressure stage:** following the high temperature phase, the solar panel maintains the set temperature. This phase allows the melted EVA to fully bond and cure, ensuring that the layers are securely encapsulated.

4. **Cooling stage:** finally, the laminator gradually cools down the assembly, entering the cooling phase. This cooling process allows the melted EVA to solidify, encapsulating the solar cells between the protective layers of the frontsheet and backsheet. This step ensures that the laminated panel is stable and durable, solidifying the bonds formed during the heating phase.

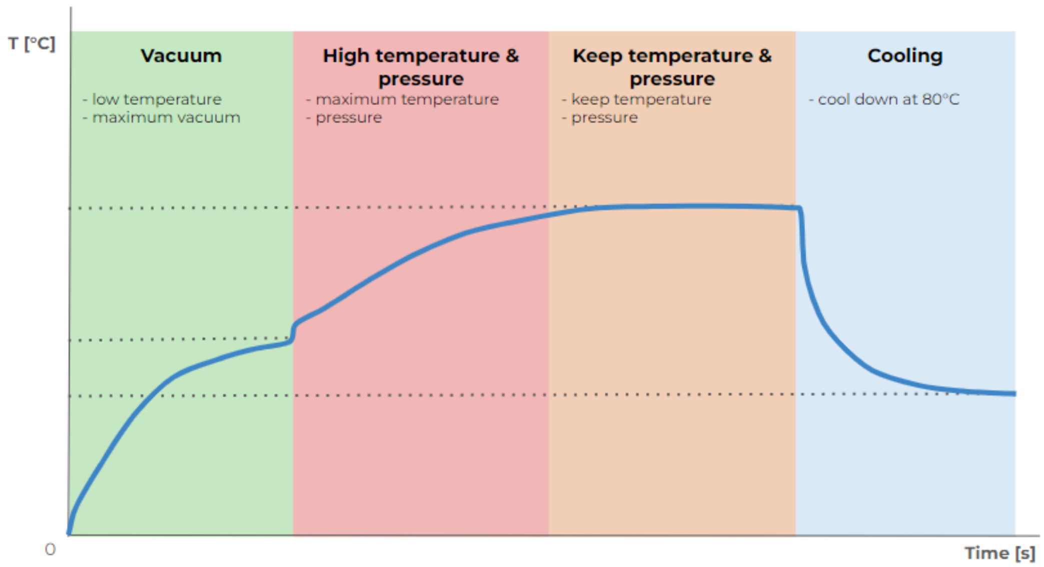


Figure 3.5: EVA lamination principle: typical curves for EVA PV panel's temperature

3.3 Polyolefins (PO)

Chemical proprieties

PO is a polymer that comes principally from the polymerization of various olefins, ethylene and propylene [Figure 3.6]. Unlike EVA, PO does not undergo a curing process during lamination. Instead, its thermoplastic nature allows it to remain flexible and moldable at elevated temperatures, which can reach around 150°C during lamination. The absence of functional groups that facilitate cross-linking means that PO retains its thermoplastic properties throughout its lifecycle. This characteristic simplifies the manufacturing and recycling processes, as the material does not transition into a thermoset. The molecular structure of PO allows it to be repeatedly melted and reformed without chemical changes, making it easier to recycle compared to cross-linked EVA as widely discussed. Its peculiarity is so on the difference principle of adhesion respect EVA due from the chemical structure of the chain, indeed it do not cross-link, but it presents a branched chain [Figure 3.7]

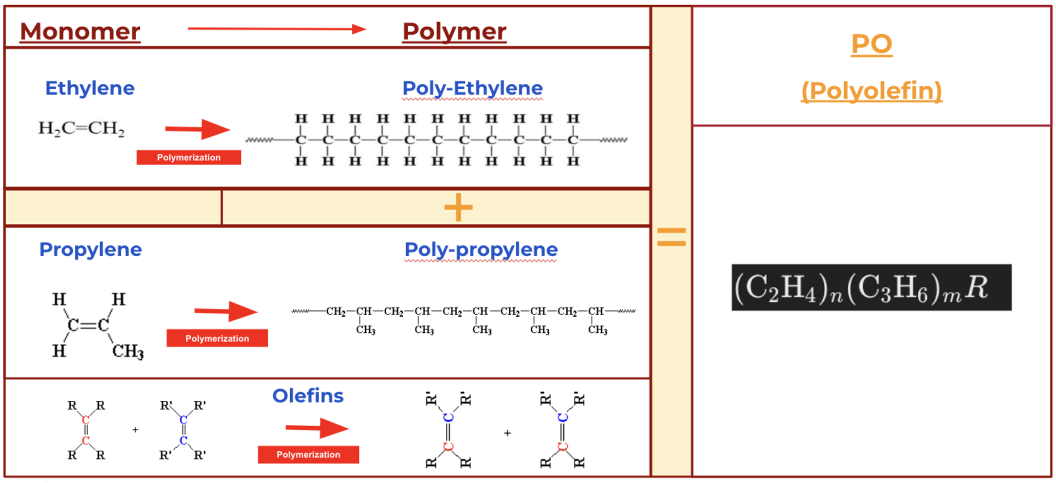


Figure 3.6: PO chemicals precursors: monomers and polymers

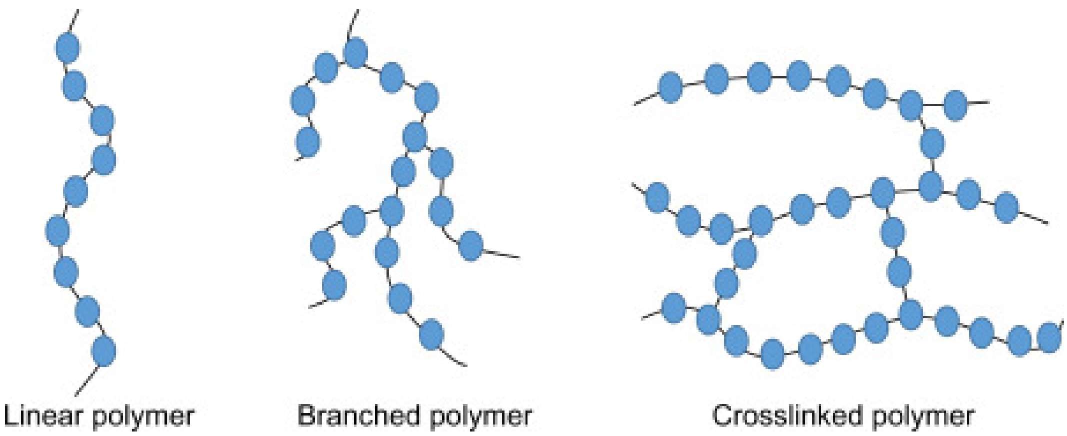


Figure 3.7: Comparison of chemical chains (linear, branched and cross-linked) [14]

Differential Scanning Calorimetry (DSC)

In the Differential Scanning Calorimetry graph for TPO (a particular type of PO, analyze in the study carried out by Baloji AdothuBaloji et al.), can be pointed out the melting transition, the absence of cross-linking and the post-lamination behavior. The DSC curve for TPO before lamination (TPO-BL) also shows an endothermic peak around 50°C, indicating the melting transition of TPO as for EVA. Unlike EVA, TPO (and so PO) does not undergo a cross-linking reaction. This is reflected in the absence of an exothermic peak in the TPO-BL curve as the temperature increases. TPO remains a thermoplastic material, meaning it can melt and re-solidify without undergoing a chemical cross-linking reaction. After lamination, the TPO-AL curve shows no significant change in the DSC profile. This indicates that lamination does not cause a chemical change in PO, and it retains its thermoplastic nature. The material's melting transition remains largely unaffected, and there is no additional thermal event like the cross-linking seen in EVA. [Figure 3.8]

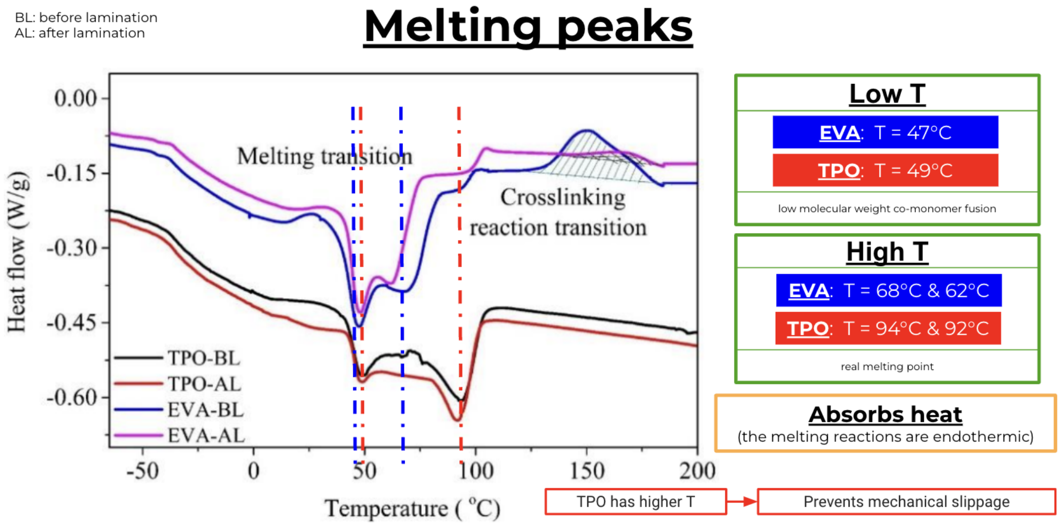


Figure 3.8: DSC graph (focus on TPO) [17]

Lamination Principle

For PO, the lamination process is slightly modified. Actually it remains quite similar, but the third stage is not necessary [Figure 3.9]. This means that the time required for the lamination is lower with a slightly decrease of the energy used during the process. Unlike EVA, PO does not require prolonged pressure and heat for cross-linking since it doesn't undergo a chemical reaction to form a solid network. Instead, PO simply melts and flows under heat, then solidifies upon cooling. This eliminates the need for the extended high-temperature and pressure stage, simplifying the lamination process and potentially reducing production time and costs.

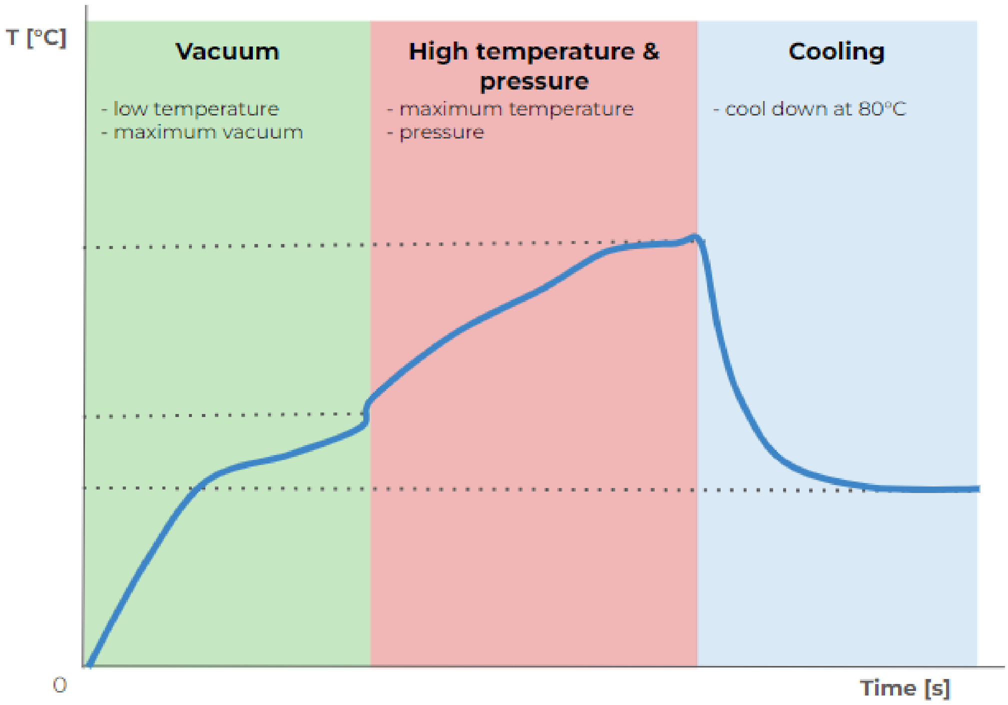


Figure 3.9: PO lamination principle: typical curves for PO PV panel's temperature

Chapter 4

Mechanical impact tests

Photovoltaic terrestrial PV panels follow specific standard to ensure durability, reliability and safety.

Concerning the mechanical durability of solar panels, a very important test is the ball drop (BD) test for mechanical resistance treated in this chapter. This test is crucial for determining the robustness of bill of material (BoM). Anyway, also other tests such as the Peel Test has been conducted to determine the durability and mechanical stability of the bond for ensure the material's long-term performance under stress especially for the new materials as the organosandwich. Furthermore, the electroluminescence technique was employed by supplying power to the cells and capturing the emitted radiation to observe the cracks within the cells. This permitted then to analyze the cracks typologies.

4.1 Research questions

Given their polymeric nature, these panels are subject to a range of mechanical stresses that differ significantly from those experienced by traditional rigid PV panels. This chapter aims to explore the following key research questions:

1. How does the organosandwich achieve effective adhesion with other encapsulants during lamination?

   The organosandwich has a peculiar structure that permit a stiff, but lightweight panel. The question it's then how much this panel is integrable in the PV sector.

2. How does adding a surface pattern to the front polymer enhance impact resistance?

   The front polymer must withstand mechanical impacts, wider the area of impact, more distributed the energy of the impact is. A surface finish on the front can play a role on this.

3. What role do encapsulants play in enhancing or degrading the mechanical resistance of polymeric PV panels?

   The way polymeric layers are combined and encapsulated plays a role in the overall mechanical performance of flexible panels.

4. How can the choice of back polymer improve the panel's impact resistance and limit cell deformation?

   The back layer provides structural stability and protection from mechanical stresses by determining how much the cell will deform itself after an impact.

4.2 Peel Test 180

The 180° peel test was conducted to evaluate the adhesion between different encapsulants and the organosandwich structure. By determining the durability and mechanical stability of the bond can be ensure the material's long-term performance under stress.

Sample Preparation

At Solbian, peel adhesion testing was conducted to assess the performance of 3 material combinations. The tested materials included:

- EVA (Ethyl Vinyl Acetate)
- PO (Polyolefine): Two types were tested, one from Supplier A and another from Supplier B, to compare their adhesive properties.

Each material was laminated singularly with the organosandwich and with a frontsheet (for pull the encapsulant away from the backsheet during the test). Strips of laminated material, 25 mm wide and approximately 250 mm long, were then prepared.

Test Execution

Once the backsheet has been fixed, the frontsheet bond with the encapsulant was pulled and a delamination occurred. The peel forces, initially measured in kilograms, were converted into Newtons:

$$F_{\mathrm{N}} = F_{\mathrm{kg}} \times 9.81\,\mathrm{m/s}^2$$

The adhesive strength σ was then calculated by dividing the force by the sample width:

$$\sigma = \frac{F_{\mathrm{N}}}{25\,\mathrm{mm}}$$

Results

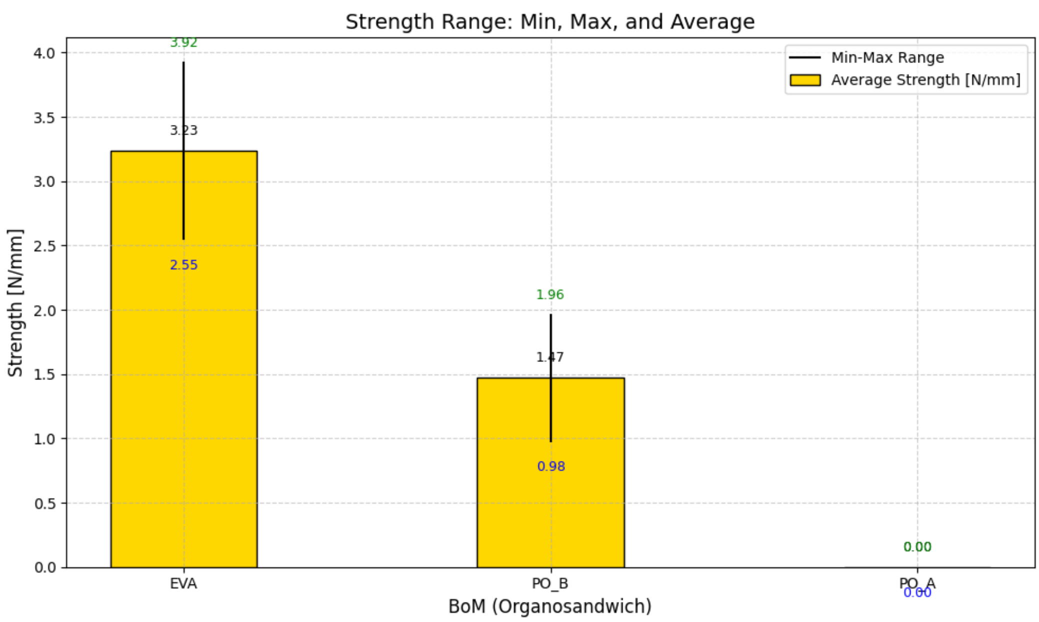


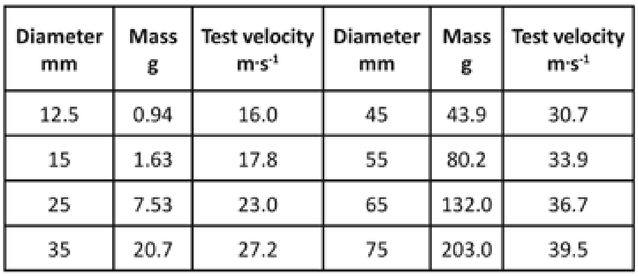
Figure 4.1: Graphs of minimum and maximum strengths in N/mm for different encapsulants

The peel test results highlighted significant differences in adhesion between the materials as can be observed by the graph 4.1. EVA showed strong adhesion, making them ideal candidate for further testing. However, one of the PO materials from Supplier A failed immediately during the test, indicating a very weak bond. The PO material from Supplier B performed better but still required further evaluation, particularly for its impact-absorbing properties, which could be beneficial in subsequent mechanical tests.

4.3 Ball Drop Test

4.3.1 IEC 61215 standard

For photovoltaic manufacturers, meeting industry standards is essential, particularly for certifying panel durability against environmental impacts like hail. The IEC 61215 standard is commonly used, and its values are outlined in Table 4.2. [8]



Diameter mm	Mass g	Test velocity m·s⁻¹	Diameter mm	Mass g	Test velocity m·s⁻¹
12.5	0.94	16.0	45	43.9	30.7
15	1.63	17.8	55	80.2	33.9
25	7.53	23.0	65	132.0	36.7
35	20.7	27.2	75	203.0	39.5

Figure 4.2: IEC 61215 [8]

Based on this standard, energy thresholds for hailstone impact were calculated using the formula:

$$E = \frac{1}{2}mv^2$$

The focus was on hailstones with diameters of 25 mm, 35 mm, and 45 mm, corresponding to energy values of approximately 2 J, 7.7 J, and 20.8 J, respectively. Panels that couldn't withstand at least 2 J, representing the impact from a 25 mm hailstone, were discarded. However, designing for 7.7 J, equivalent to a 35 mm hailstone, was deemed ambitious, as it represents a sensible upper limit for most hailstorm conditions. Designing for 20.8 J, associated with a 45 mm hailstone, was considered unnecessary and discarded for avoid over-engineer.

This approach balances durability and cost efficiency by targeting realistic impact resistance thresholds. Moreover in real-world applications, hail typically fragments upon impact, which results in a reduced impact energy on the panel. However, this study deliberately does not account for that aspect, opting instead to consider the worst-case scenario to ensure a comprehensive analysis of impact resistance.

4.3.2 Test Procedure

The test principle involves impacting the surface of the PV panel with a guided weight until signs of cracking in the solar cells appear. If the cell shows no damage after an electroluminescent imaging check (see section 4.4), the impact energy is incrementally increased.

Specimen Preparation

Specimens for the ball drop (BD) test require careful preparation to clearly distinguish impact-induced fractures. EL imaging is performed after lamination to assess the initial state of the cells. The prototype panels were designed to contain two cells (approximately 12 x 30 cm).

The preparation process includes cutting polymers and soldering cells, followed by assembly and lamination. After cooling, EL checks are conducted to confirm specimen integrity before testing.

Test Setup

The test setup comprises all necessary components, including the guiding pipe, 3D-printed impact heads, the weights and a fiberglass support of 3 mm in which the panels have been posed during the test (Figure 4.3). To simulate hail impacts, 3D-printed parts help the impact of the weights, which are customizable and dropped from varying heights to achieve desired impact energies.

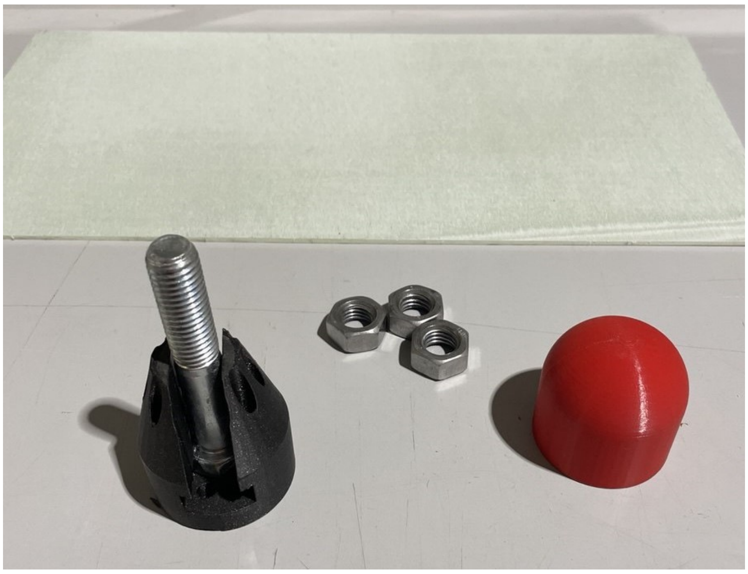


Figure 4.3: All the setup of the ball drop test: BDv1 and BDv2 (screws, nuts and holders), fiberglass pane, pipes, impact head.

Test phases & Sub-iterations

Multiple test phases were conducted, and for each new BoM, the starting impact value was the lowest one.

Within each test phase, sub-iterations were essential for ensuring statistical reliability. If a specimen fails, subsequent tests on new specimens begin at one or two impact levels lower than the failure point of the previous specimen. This approach mitigates the effects of cumulative damage, providing a thorough evaluation of the materials' mechanical resistance to impact.

This two-tiered approach (combining test phases and sub-iterations) provided a deep evaluation of the materials' mechanical resistance to impact.

4.3.3 Results

The Ball Drop test results were organized into 3 main categories:

1. Textured (surface finish)
2. EVA, PO_A, PO_B (encapsulants)
3. Organosandwich (backsheet)

Surface finish influence

Textured panels are particular BoMs that permit to create a surface finish with a pattern on the front side. As can be saw from the Figure 4.4, there is an extra layers in which is imprinted the pattern during the lamination. This panels showed higher initial impact resistance, respect to the other that will be analyzed, due to their ability to distribute stress across the irregular surface. However, after surface deformation, they progressed more quickly towards failure.

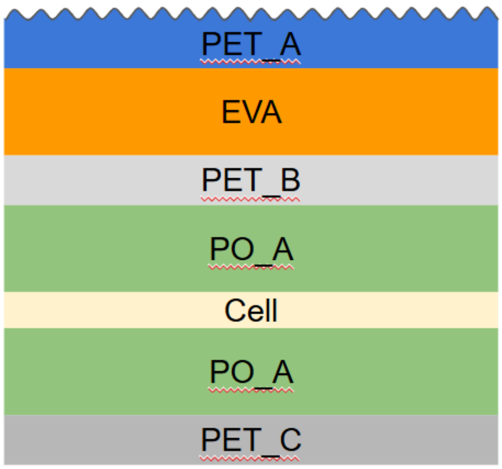


Figure 4.4: Textured BoM.

Comparing textured BoMs with PO_A BoMs, can be observed in the Table 4.5 that the initial structure is the same, then an additional layer made of EVA and ECTFE is add to the textured BoM. The textured surface shows superior impact resistance compared to the PO_A configurations, primarily due to its enhanced ability to distribute stress across a broader area upon impact. This stress distribution is facilitated by the surface pattern, which minimizes localized pressure points and reduces the likelihood of cell fractures. In contrast, PO_A panels lack this textured surface, resulting in a greater concentration of stress at impact points, as indicated by their lower average kinetic energy tolerance in 4.6.

Name	BoM						Average	MIN	MAX
Textured	ECTFE	EVA	PET_B	PO_A	PO_A	PET_C	8,1	5,6	10,6
PO_A	-	-	PET_A	PO_A	PO_A	PET_C	4,8	2,2	9,8

Figure 4.5: Textured and PO_A comparison with BoMs and energy impacts.

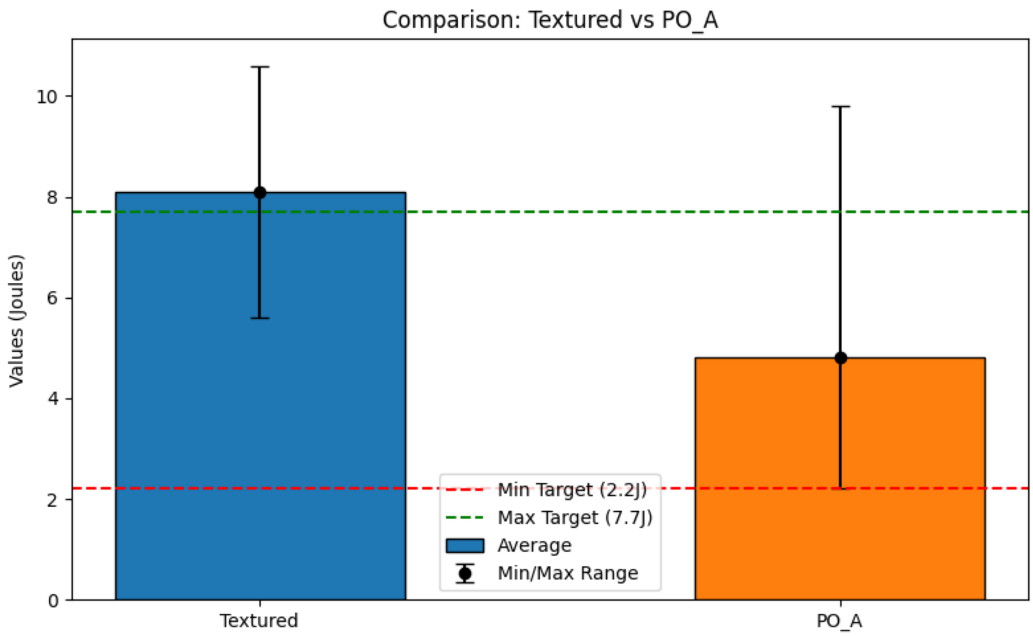


Figure 4.6: Graphical comparison between textured panels and PO_A ones.

Encapsulant influence

Looking at the Table 4.7 a wide comparison between similar BoMs with different encapsulants can be observed. All the 3 encapsulants showed similar behaviors with a slightly, but not significant, higher values for the PO_B. EVA encapsulant offered a balanced performance during impact, reaching failure at moderate energy levels but without providing significant flexibility or energy absorption. In contrast, the PO encapsulants (PO_A and PO_B) showed slightly superior performance as has been found in the literature.

Name	BoM				Average	MIN	MAX
EVA	PET_A	EVA	EVA	PET_C	5,2	1,8	8,1
PO_A	PET_A	PO_A	PO_A	PET_C	4,8	2,2	9,8
PO_B	PET_A	PO_B	PO_B	PET_C	6,2	3,9	9,8

Figure 4.7: Comparison between encapsulant BoMs.

The results presented in Figure 4.8 indicate that no definitive and clear conclusions can be drawn regarding the third research question. This outcome is due to high statistical variability and the remarkably similar behavior observed across different encapsulant types.

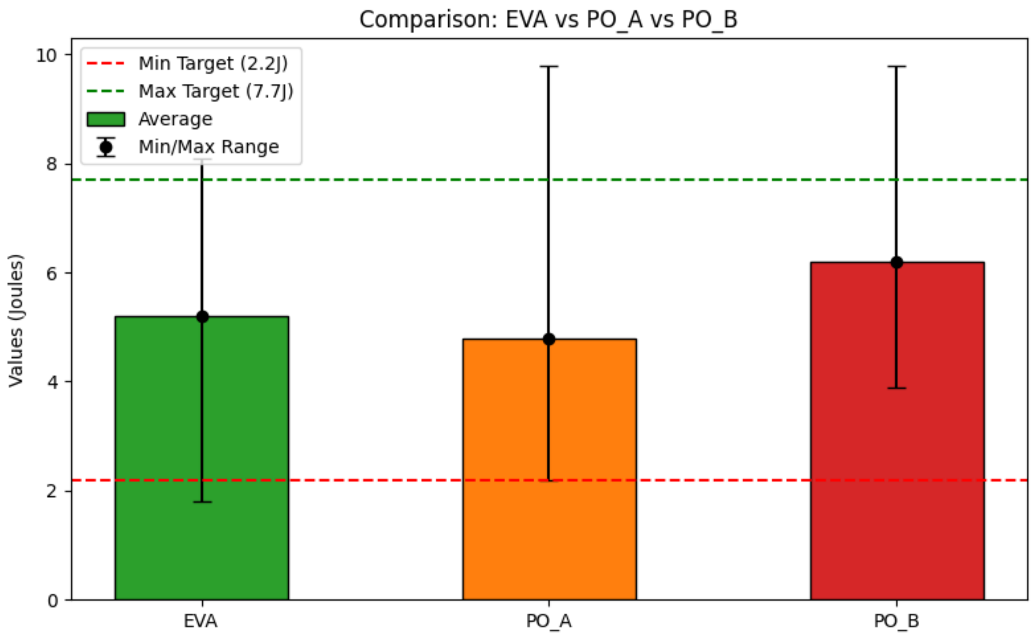


Figure 4.8: Graphical comparison between encapsulant BoMs.

Organosandwich influence

Name	BoM				Average	MIN	MAX
EVA	PET_A	EVA	EVA	PET_C	5,2	1,8	8,1
EVA_Organosandwich	PET_A	EVA	EVA	Organosandwich	2,5	1,7	3,9

Figure 4.9: Organosandwich results.

In the Table 4.9, the Organosandwich_EVA panel achieved the minimum performance value and then underperformed compared to other configurations in particular respect its counterpart EVA. The suspected cause is deformation of the polypropylene honeycomb core, which lacks the stiffness needed to protect the cells during impact. Indeed, in EVA samples, the stiff support is represented by the 3 mm GF pane, but in the Organosandwich_EVA the stiff back is the organosandwich itself that is then not able to guarantee enough stiffness. This behavior can be observed on the Figure 4.10 where values barely reach the minimum acceptable impact energy of 2.2 J.

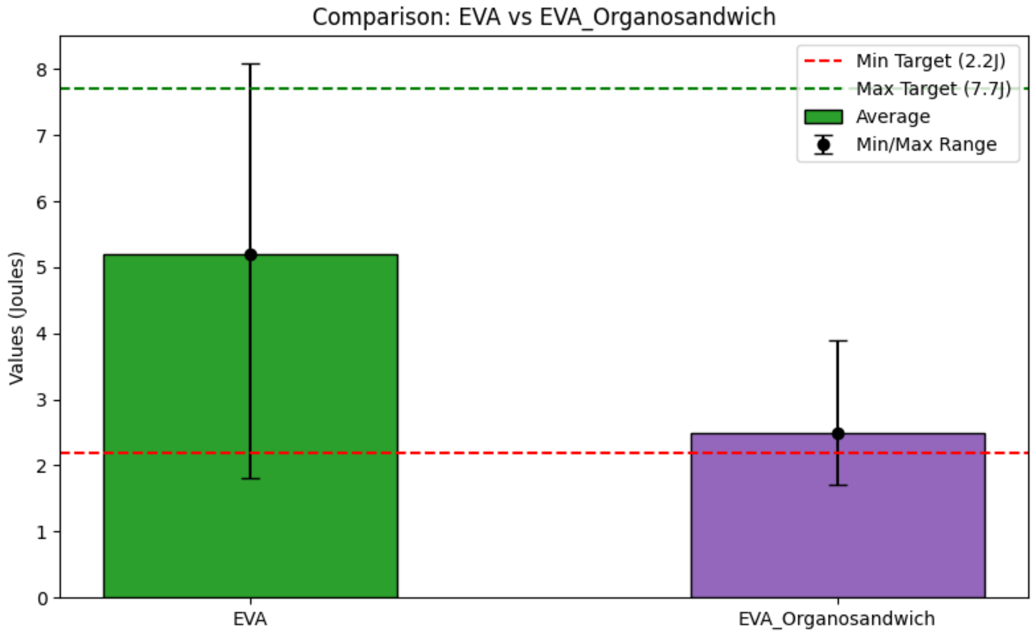


Figure 4.10: Graphical results for organosandwich BoMs.

4.4 Electroluminescent Imaging Test

4.4.1 EL principles

A photovoltaic cell operates on the principle of converting sunlight into electrical energy through the photovoltaic effect. In a typical silicon-based PV cell, a p-n junction is created by joining p-type and n-type silicon, which have been doped to introduce excess holes and electrons, respectively. This doping creates an electric field across the junction as electrons from the n-type region diffuse toward the p-type region to fill holes, forming a depletion region that acts as a barrier to further charge movement. When sunlight strikes the PV cell, photons with energy greater than the material's band gap excite electrons from the valence band into the conduction band, creating electron-hole pairs. These free electrons (in the n-type region) and holes (in the p-type region) are then separated by the electric field in the depletion region, generating a current as they move toward opposite electrodes. Under forward bias conditions, where the p-side is connected to the positive terminal of an external circuit and the n-side to the negative terminal, the electric field at the junction is reduced, allowing easier flow of current (Figure 4.11). This is the operating mode under which a PV cell generates power.

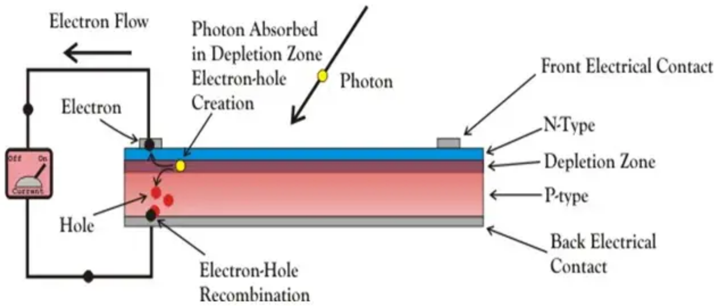


Figure 4.11: Principle of PV cell function [27]

The reverse process occurs when a PV cell is subjected to reverse bias, typically with the n-side connected to the positive terminal and the p-side to the negative terminal. In this condition, the electric field across the junction is strengthened, inhibiting the flow of charge carriers. However, if the cell is actively powered in reverse (i.e., given an external voltage source in reverse bias), the injected electrons and holes can recombine within the p-n junction. During this recombination, energy is released in the form of photons—a phenomenon that can be observed as electroluminescence (EL) (Figure 4.12). In EL testing, this emitted light provides a powerful diagnostic tool for identifying microcracks and defects within the silicon. Defective regions with broken or interrupted crystalline structure do not emit light as efficiently during recombination, appearing as dark areas in EL images as shown in the Figure 4.12. Therefore, EL testing leverages the reverse-biased injection and recombination process to visualize and assess the structural integrity of PV cells without requiring natural illumination.

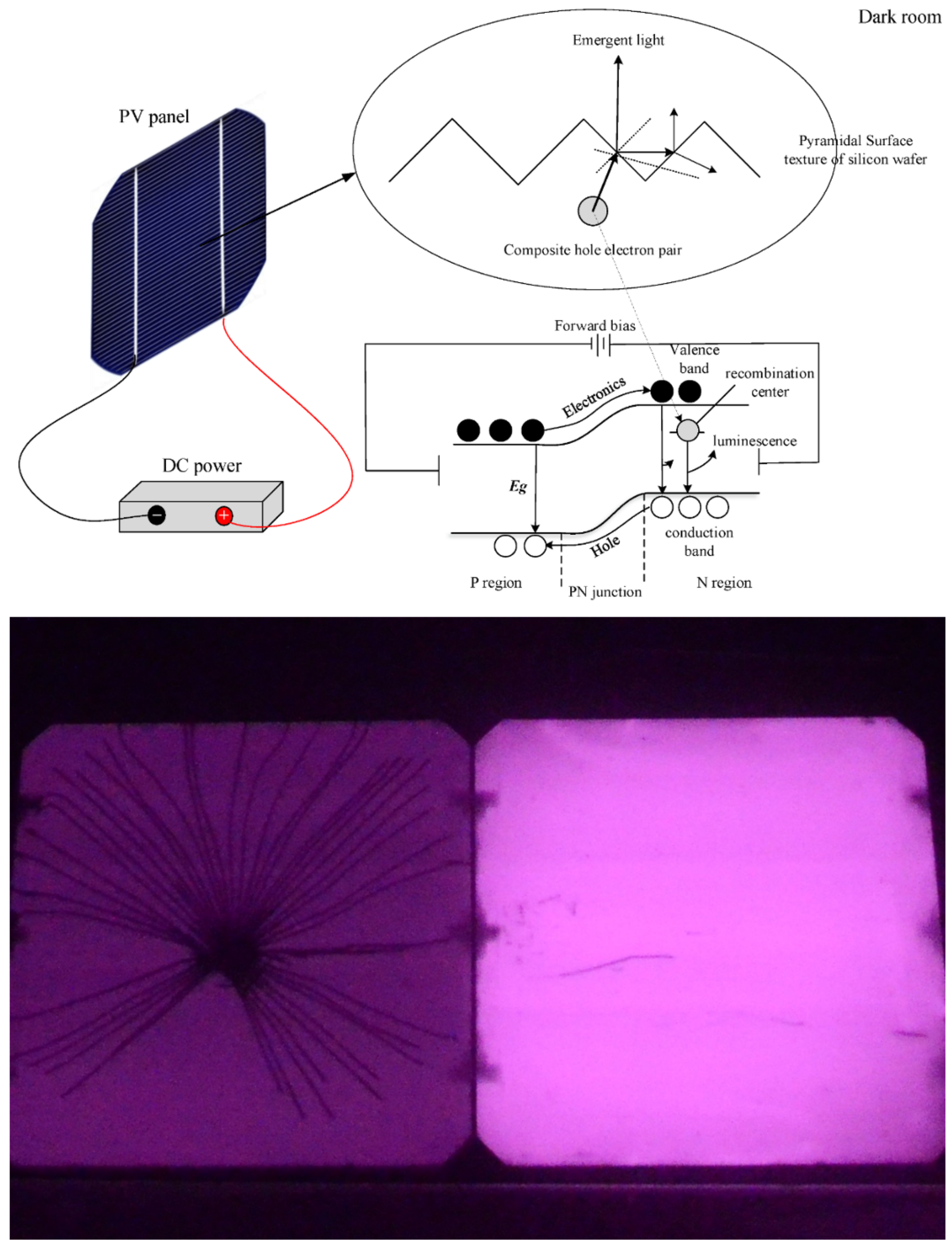


Figure 4.12: Up: principle of EL; Down: EL at comparison, crack vs health cell.

4.4.2 Crack Behavior

EL were conducted both before and after the impact tests. By comparing the images, the differences in crack formation and distribution were analyzed to understand the material responses to impact. Figure 4.12 shows a visual comparison between healthy and damaged cells post-test.

Crack behavior was interpreted through two main types of fractures: radial cracks, which propagate outward from the impact point due to tensile stress, and concentric cracks, caused by compressive stress around the impact zone as has sketched in the Figure 4.13 by the National Geographic Learning [2]. These phenomena are similar to glass fracture behavior and were used to model how PV cells respond to impact. Two critical factors were identified in influencing crack formation:

- Z-axis displacement (penetration): Higher Z displacement leads to more severe, localized cracks, especially concentric fractures.

- Load area distribution: Materials that distribute the load over a wider area induce radial cracks, reducing localized damage.

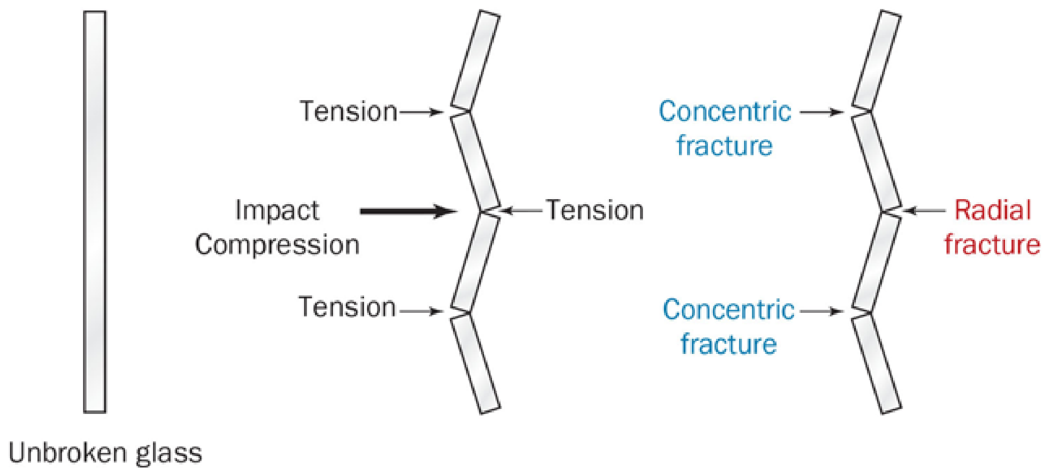


Figure 4.13: Glass crack principle

4.4.3 Results

Frontsheet and backsheet influence

The results show clear differences in crack patterns depending on the frontsheet material. Textured panels displayed the most favorable performance, with uniform radial cracking, indicating effective stress dispersion across the surface. This material effectively distributed the load, reducing localized damage. Other configurations like EVA and PO also showed moderate radial crack patterns, suggesting reasonable structural integrity.

Backsheet materials also showed significant influence on the crack patterns and overall panel behavior. Textured, EVA and PO demonstrated no circular crack patterns, with lower Z-axis penetration, presumably indicating better structural back support for the PV cells. This behavior is probably due to the 3 mm GF pane in which they were posed during the test. On the other hand, EVA_Organosandwich showed several concentric cracks, indicating higher vulnerability to localized stress and increased Z-axis displacement. This BoM appeared to allow the cell to deform excessively, both contributing to weaker impact resistance.

The EL imaging revealed that both frontsheet and backsheet configurations critically affect the mechanical performance of PV panels under impact. Frontsheets like with strong stress distribution properties, provided superior impact resistance with an alleged radial fracture and backsheets that limited Z-axis displacement proved more resilient with a alleged concentric fracture as can be clearly observed in the Figure 4.14.

Further testing and a larger sample size are needed to strengthen these conclusions and refine material choices in future panel designs.

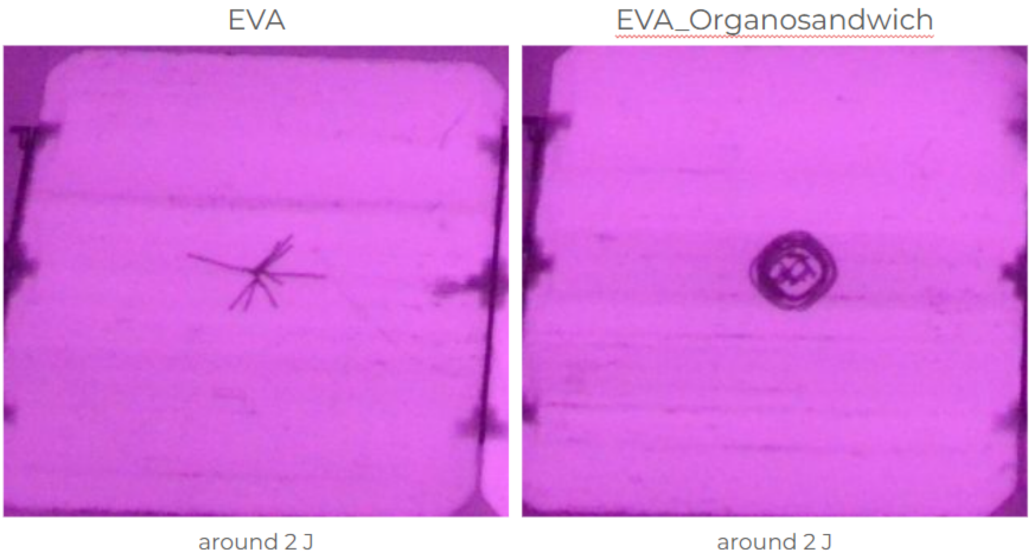


Figure 4.14: EL comparison between the EVA and the EVA_Organosandwich at almost the same energy level of impact failure

Chapter 5

Conclusions

This thesis has advanced the general understanding of the mechanical resilience of polymer-based photovoltaic panels, particularly in their ability to withstand impacts in challenging environments such as marine and urban automotive settings.

The adapted Ball Drop Test (BDT) employed in this study proved to be a practical and cost-effective option in which the general behavior of the materials can be understood. The addition of electroluminescent imaging enabled detailed observations of crack formation, providing insights into fracture patterns unique to different material combinations.

Textured surfaces were found to delay initial fractures by dispersing stress across a larger area; however, they exhibited faster degradation with repeated impacts. While encapsulants are not a primary factor in impact resistance, they contribute to the overall flexibility and stability of the panel by effectively bonding the layers. Good integration of backsheet materials, such as organosandwich with EVA and PO, has been established. Rigid backsheets emerged as a decisive factor in impact resistance, with panels featuring these materials consistently demonstrating improved performance in limiting deformation. This emphasizes the critical role of backsheet selection in ensuring robust panel configurations. In contrast, the organosandwich showed minimal values in this regard. Key findings highlight the importance of combining rigid back supports with softer front materials to effectively absorb and distribute impact energy, thereby enhancing durability without compromising flexibility.

These results suggest several practical recommendations. For impact-heavy environments, configurations with rigid backsheets and softer front materials should be prioritized, with textured surfaces reserved for areas requiring additional resistance to localized stress. Encapsulants can be optimized for lamination ease rather than impact resilience, making easier the manufacturing process. There remains significant potential for further research, particularly in examining the impact resistance in operating conditions and so at higher temperatures. Moreover, should be important investigate in alternative materials, such as recyclable polymers, glass fibers sheets integrations or aluminum backsheets.

In summary, this work provides essential insights into material and structural choices that enhance the resilience of flexible PV panels, supporting the ongoing development of durable, lightweight energy solutions suited for a wide range of applications.

Appendix A

State of the Art supplementary images

Figure A.1: Typical Solarge's polymeric panel. [16]

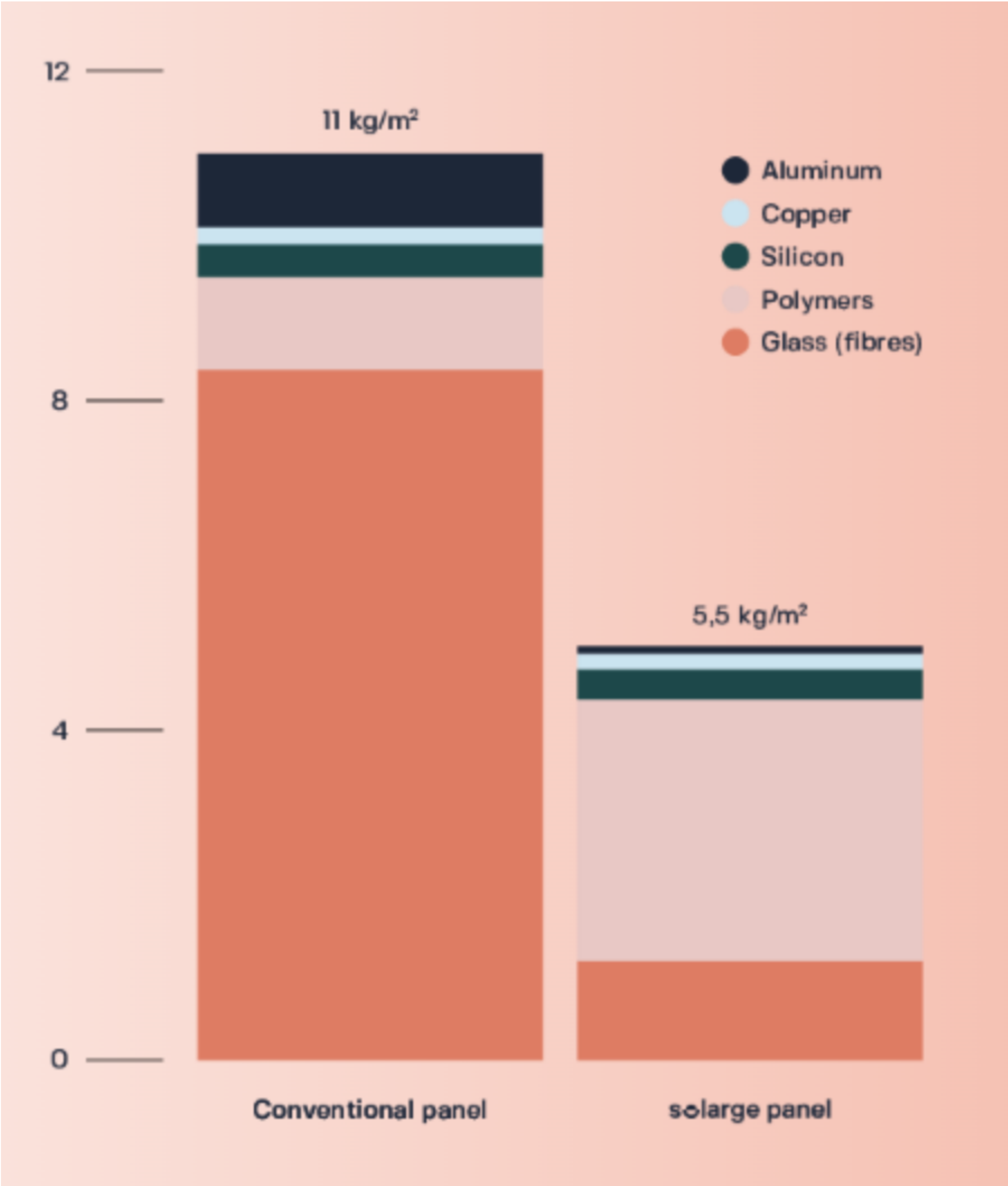


Figure A.2: Comparison between a classic panel and Solarge's panels. [16]

Appendix B

Solbian Energie Alternative srl supplementary images

Name	Skin Material	Honeycomb Material	Honeycomb Density	Issues
Marine plywood	Wood	Wood	500	Heavy and humidity
ALUSTEP-F	GF	Aluminium	from 20 to 116	Deformable and cost
Compocel AL-FR	Aluminium	Aluminium	from 20 to 163	Deformable and cost
CLEARSTEP	GF	Polypropylene	80	Fire (in the core)
GF with Aluminium Core	Double GF	Aluminium	from 20 to 116	Deformable and cost

Figure B.1: Support panels table
[6]

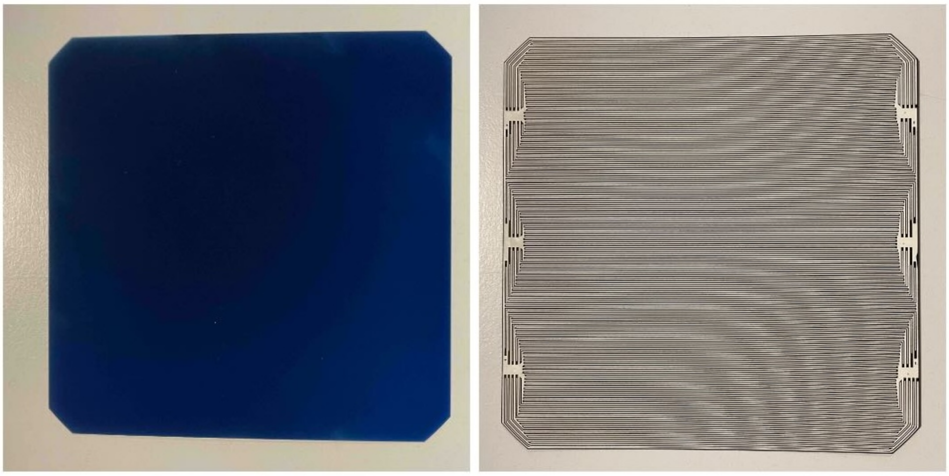


Figure B.2: Rear Contact Solar Cell [20]

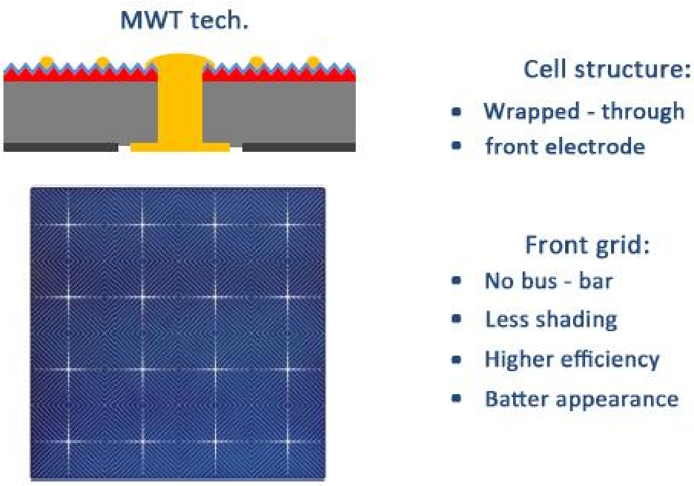


Figure B.3: MTW cell
[7]

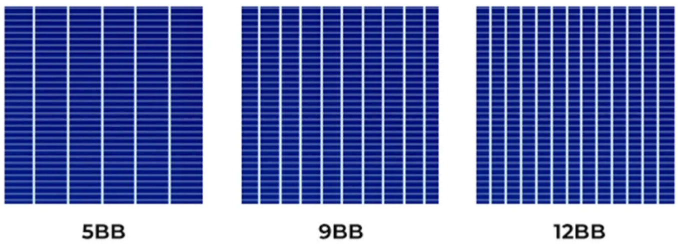


Figure B.4: MBB cells
[22]

Appendix C

Lamination process supplementary images

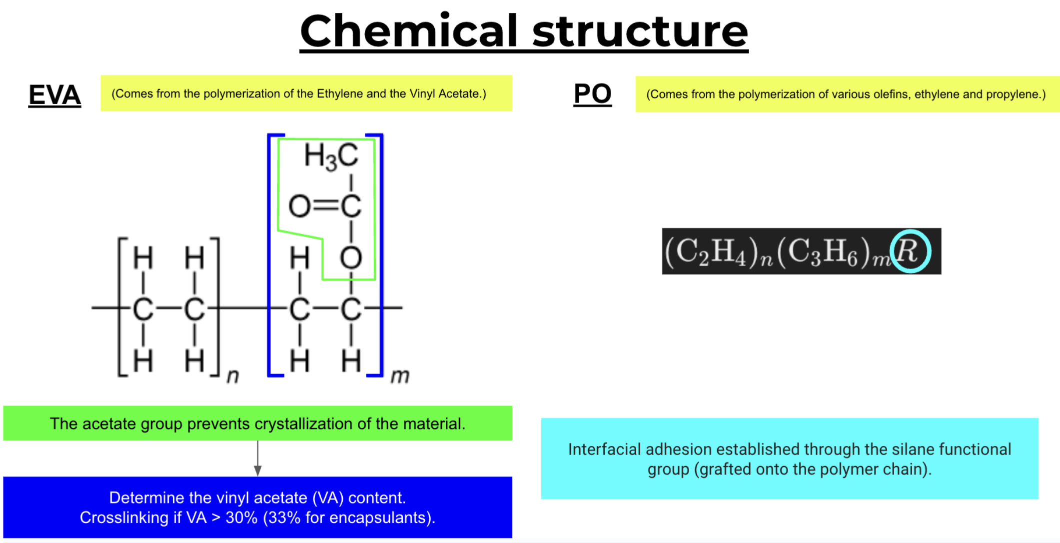


Figure C.1: Chemical details for PO and EVA

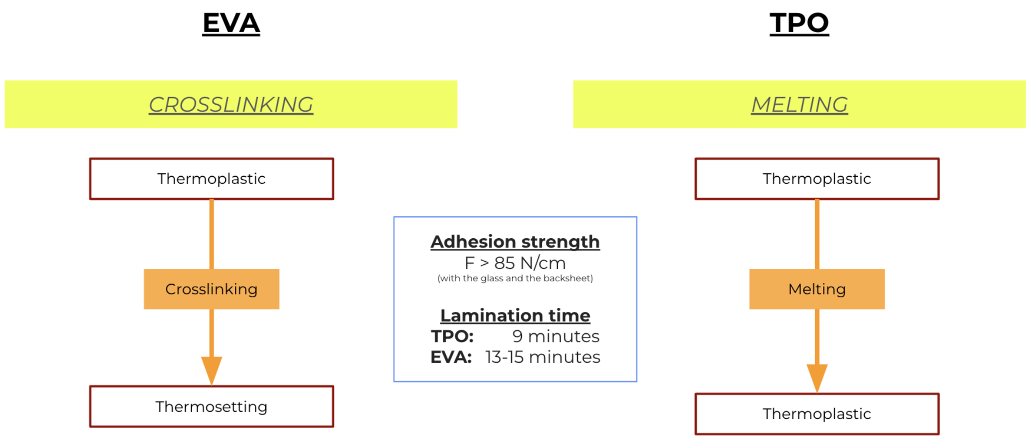


Figure C.2: Chemical cross-linking and melting for PO and EVA

Differential Scanning Calorimetry (DSC)

Crosslinking agents:

- **DCP**: dicumyl peroxide (traditional)
- **TBEC**: tetra-butylperoxy 2-ethylhexyl carbonate
- **DBPH**: 2,5 - dimethyl - 2,5 - di(tetra - butylperoxy)hexane
- **BPO**: benzoyl peroxide

Crosslinking agent	t (min)	T_{onset} (°C)	T_{peak} (°C)	ΔH (J g^{-1})
BPO	5.97	101	138	7.03
DBPH	8.15	134	190	8.07
DCP	9.81	115	167	10.09
TBEC	7.25	116	162	9.68

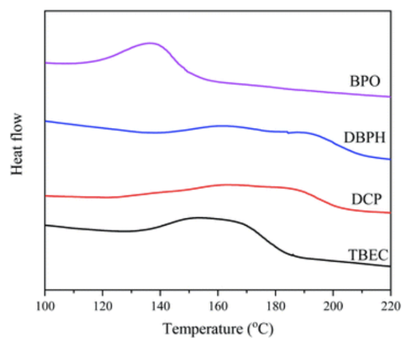


Figure C.3: DSC study on the cross-linking agents

Appendix D

Mechanical impact tests' supplementary images

Name	BoM				Average	MIN	MAX
Textured	PET_B	PO_A	PO_A	PET_C	8,1	5,6	10,6
EVA	PET_A	EVA	EVA	PET_C	5,2	1,8	8,1
PO_A	PET_A	PO_A	PO_A	PET_C	4,8	2,2	9,8
PO_B	PET_A	PO_B	PO_B	PET_C	6,2	3,9	9,8
EVA_Organosandwich	PET_A	EVA	EVA	Organosandwich	2,5	1,7	3,9

Figure D.1: Table

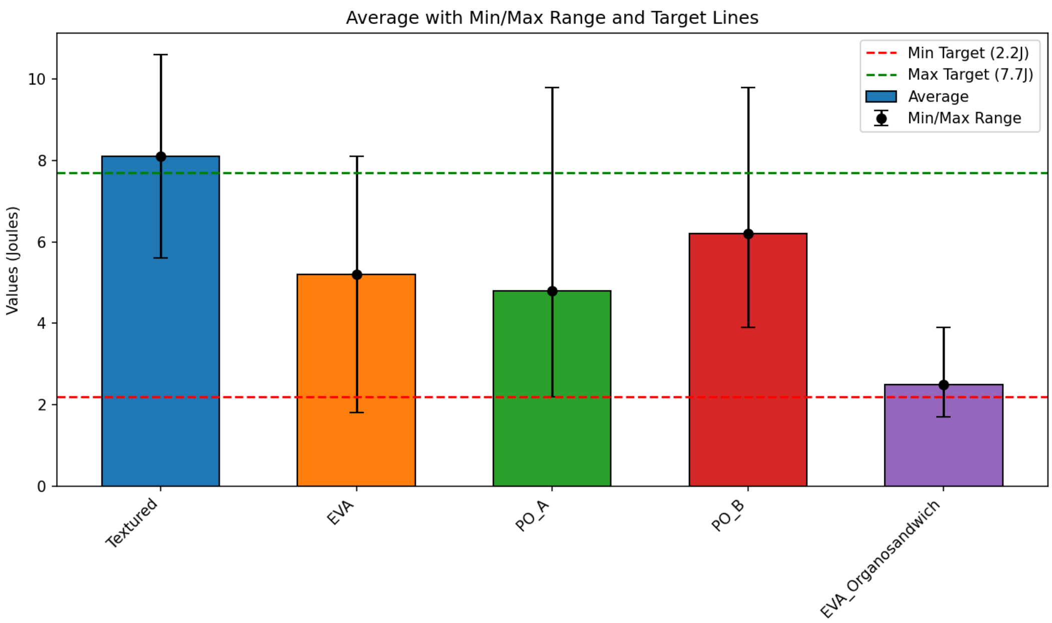


Figure D.2: Graph

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