PV SOLAR EXPLORATION:

The Circular Photovoltaic-Thermal panel of the future

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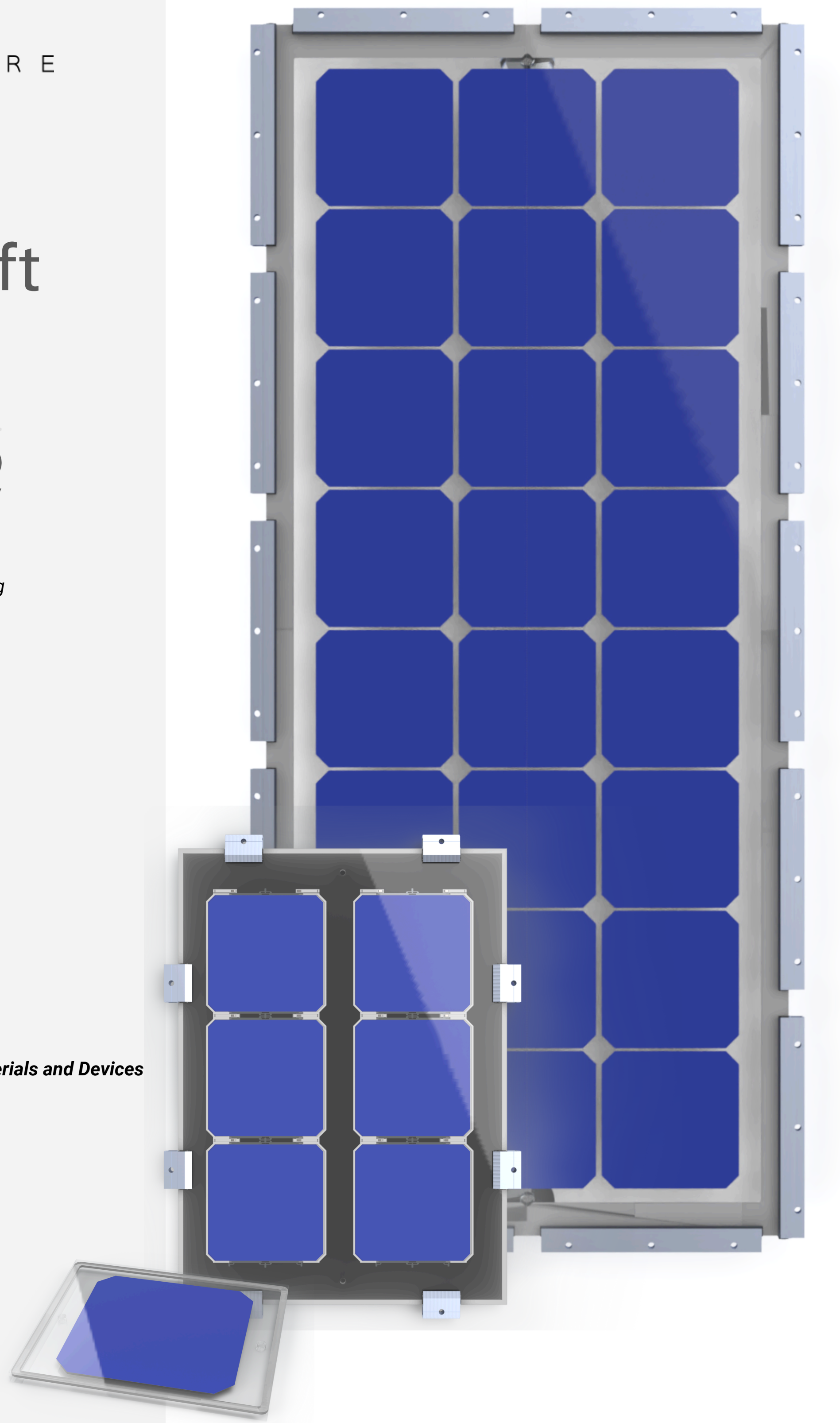

Abstract

This graduation project presented the development of a new Photovoltaic-Thermal panel (PVT) module design, aimed at addressing sustainability challenges in conventional solar panels. The research focused on improving repairability and recyclability by replacing the standard ethylene-vinyl acetate (EVA) laminate with a liquid encapsulant. This transformation enhanced the module's thermal stability and light transmittance and innovatively converted the panel into a pioneering photovoltaic-thermal (PVT) system. Experimental prototypes, conducted at the Photovoltaic Materials and Devices - TU Delft, demonstrated the feasibility of this concept. The outcome of this graduation project, conducted for Biosphere Solar, laid a robust foundation for future developments in sustainable solar energy solutions.

Acknowledgments

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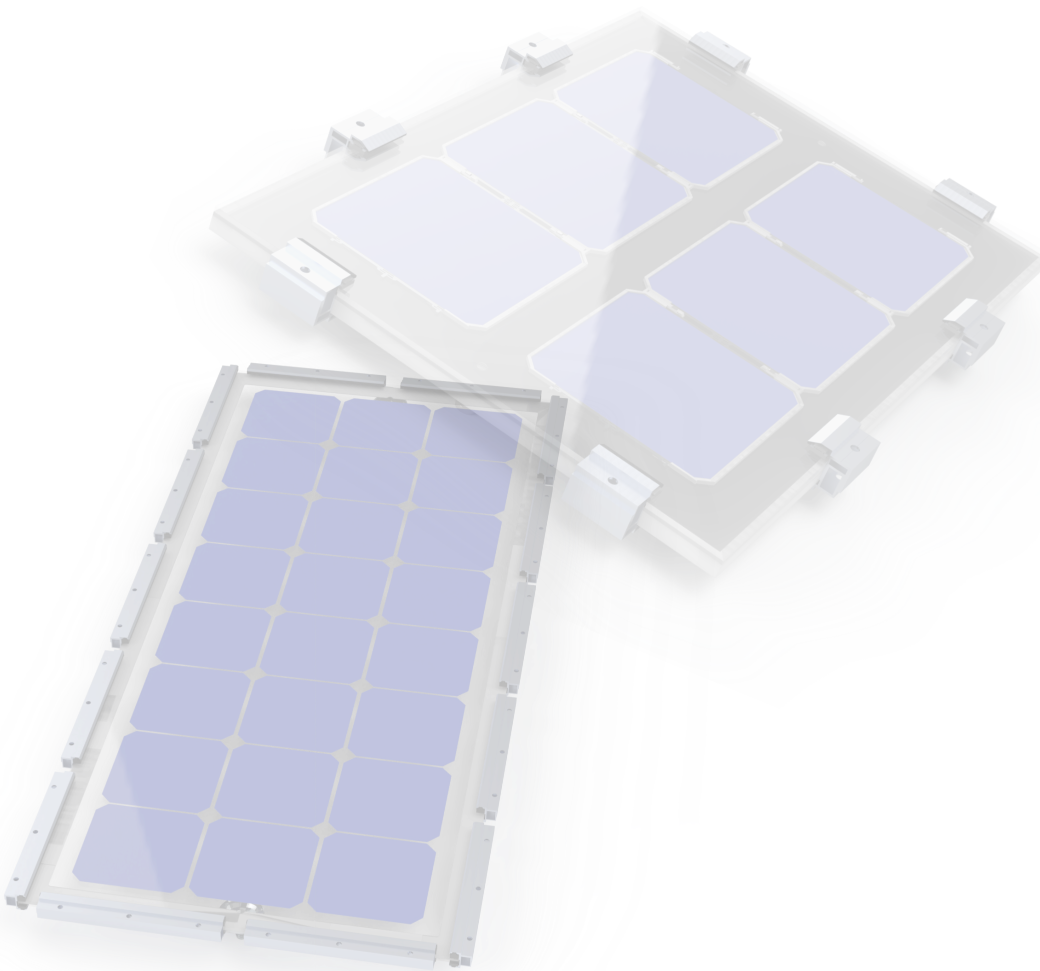

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Chapter 1 | General Introduction

As the world shifts towards more sustainable energy sources, solar energy has been and will be a vital contributor to this change. Nonetheless, ongoing concern remains regarding the repairability and recyclability of conventional solar panels.

Solar panels have gained widespread popularity as a clean and renewable energy source, contributing to reducing greenhouse gas emissions. Among recent innovations in the field, Photovoltaic-Thermal (PVT) panels stand out. These panels uniquely combine the ability to generate electricity and harness thermal energy in a single integrated system. However, despite their environmental benefits, conventional solar and PVT panels are not without sustainability issues (Calı et al., 2022). This emphasizes the need for advancements in solar technology and manufacturing processes to minimize their environmental impact, especially concerning End-of-Life considerations. Some of the key concerns include:

- Resource Intensive Manufacturing: Conventional solar panels, typically made from crystalline silicon, require significant amounts of raw materials such as silicon, silver, aluminum, and glass. The extraction and processing of these materials can lead to habitat destruction, water pollution, and energy consumption.

- Energy-Intensive Production: The production of solar panels involves energy-intensive processes, including the growth of silicon crystals, the manufacturing of semiconductor wafers, and the assembly of solar cells. Many solar panel manufacturing facilities rely on fossil fuels, which can undermine the overall sustainability of solar energy generation. Moreover, the energy payback period (the time it takes for a solar panel to generate as much energy as was used in its production) can be relatively long, depending on the panel's efficiency and the energy mix during manufacturing.

- Limited lifespan: Over time, solar panels degrade, losing efficiency, and ultimately needing replacement. The disposal of old panels presents a challenge, as they contain hazardous materials, such as lead, which can harm the environment if not properly managed.

- Longevity and Thermal Stress: Studies have evaluated the remarkable sensitivity of PV panel durability to thermal stress. They suggest that installing smaller PV modules with increased thicknesses is advantageous in terms of both initial installation cost and subsequent replacements, reducing energy production losses in case of panel damage. (Calı et al., 2022)

- E-Waste and Recycling: Solar panels have a finite lifespan, after which they become Electronic waste (E-waste). E-waste disposal and recycling infrastructure may not be adequately developed in many regions, leading to the improper disposal of solar panels and the release of toxic substances into the environment. This challenge is compounded by the presence of materials like EVA laminate. The laminate's adhesive nature and specific recycling requirements further complicate the proper disposal and recycling of solar panels. (Calı et al., 2022)

Traditional solar panels rely on an intermediary material known as ethylene-vinyl acetate laminate (EVA), which plays an essential role in their functionality. Solar EVA sheets enhance the durability and performance of solar modules. They enable the solar cells to 'float' between the glass and the back sheet, soften shocks and vibrations, and protect the fragile cells and their circuits (Module Materials | PVEDucation, z.d.-b). At first glance, the use of EVA in solar panels offers significant benefits. However, over time, the EVA can experience degradation and harm overall performance and longevity (Berghold et al., 2010). The four primary factors contributing to degradation are thermal cycling, damp heat, humidity freeze, and ultraviolet (UV) exposure. These factors, over time, eventually result in a critical issue known as delamination. Delamination occurs when the laminate layer, which bonds the various components of the solar panel together, starts to weaken or separate. In particular, UV radiation and higher temperatures can damage the polymeric materials in photovoltaic (PV) modules. This damage leads to the modules turning yellow or brown, a visual sign of degradation, which negatively impacts their efficiency and reliability (De Oliveira et al., 2018). Furthermore the breakdown of EVA results in the creation of acetic acid and other gases (De & Diniz, 2018). These substances accumulate within the panel, leading to layers separating (delamination) or bubble formation, which lowers the panel's efficiency. Moreover, the acetic acid can corrode the metal contacts within the panel, further harming its performance (De Oliveira et al., 2018). The actual lifespan of PV power plants tends to be around half of the initially planned duration, with issues such as delamination, moisture penetration, and contact corrosion emerging after approximately 10 years of operation (Libra et al., 2023). Data from 85 PV power plants in central Europe indicate that electricity production aligns with expectations for the first decade but experiences a notable increase in serious failures thereafter(Libra et al., 2023). Despite manufacturer claims, the real lifetime falls short, prompting suggestions for improving the quality of PV modules and exploring repair technologies. Extreme tropical climates further diminish field lifetime, leading to negative economic impacts. While current high electricity prices yield a favorable payback period for PV investments, any reduction in panel lifespan diminishes returns. The expected yearly yield decrease for photovoltaic systems is a median degradation rate of 0.5% per year. This finding is based on an analysis of nearly 2000 degradation rates from various photovoltaic systems and modules over 40 years (Jordan & Kurtz, 2011).

Another drawback of the laminate is that solar cell replacement is challenging, often necessitating the replacement of entire panels. Additionally, the presence of EVA can complicate the recycling process of solar panels, increasing the difficulty of reusing valuable materials. The most common recycling approach involves crushing modules and using them as mixed glass cullets, limiting the recovery of valuable semiconductor materials. (Isherwood, 2022).

The output of PV solar panels is temperature-dependent, with higher temperatures resulting in reduced electricity production. As solar panels heat up under sunlight, their efficiency decreases, causing a drop in energy output (Singh & Ravindra, 2012). This phenomenon occurs because the electrical characteristics of the semiconductor materials in PV cells change with temperature. To optimize PV system performance, it's essential to consider and manage temperature effects. Mounting conventional panels with appropriate spacing for airflow, opting for additional cooling systems, and choosing location and orientation wisely can help mitigate temperature-related losses and ensure consistent solar energy generation (Dubey et al., 2013). The power output of a PV module depends linearly on the operating temperature.

Biosphere Solar is a start-up that aims to revolutionize solar energy by creating a repairable and recyclable PV module. They are developing a modular, circular, and transparent solar panel with an open-source approach and sustainable production practices to make clean energy available. To increase PV circularity, Biosphere Solar has introduced an EVA-less panel architecture. This design has the potential to enhance recycling but, regrettably, reduces both optical and thermal performance due to the presence of air in the system. Therefore, specific improvements need to be designed and industrialized for the panel to compete with more traditional panels. Their current design contains an intermediate layer of air, instead of EVA. Due to this layer less light is transmitted through to the solar cells. Additionally, the air acts as thermal insulation, causing the system to overheat and degrade performance. This IDE master graduation project involves experimental prototyping aimed at addressing these issues. In summary, the identified functionality issues encompass performance and thermal stability. These concerns are closely tied to optical, thermal, and structural challenges. Essentially, these issues can be traced back to the existing characteristics resulting from the current design.

- **Optical:** As the refractive index of air (1.0) significantly differs from that of glass (approximately 1.5), a substantial amount of incident light experiences reflection when it encounters the air-glass interface. In contrast, the refractive index of the EVA laminate (approximately 1.5) is more closely matched to that of glass. This disparity results in less light being transmitted through the solar cell, leading to a decrease in efficiency.
- **Thermal:** The air acts as thermal insulation, causing the system to more easily overheat and degrade performance while also increasing thermal stress on the system.
- **Structural**: Without the laminate, the panel lacks structural integrity. To ensure a robust design, various measures, such as using a thicker front glass or framing must be considered.

Aim and research questions

The primary objective of this research is to devise effective solutions for the encapsulation and cooling of solar cells, with a specific focus on transmitting light to solar cells efficiently and mitigating thermal loads. The construction of functional prototypes serves as a methodological approach to realize and test solutions, aiming to facilitate repairability and performance. The novel panel should maintain its structural integrity, remain properly sealed, and function effectively all while minimizing the complexity and resources within the system. Achieving high repairability often involves designing products to be easily disassembled, which can introduce vulnerabilities. These vulnerabilities, if not properly managed, could potentially reduce the panel's life expectancy. Given that longevity is a crucial consideration, addressing these conflicting requirements presents a design challenge. In addressing the design challenge of enhancing circularity in the panel, the focus was placed on two key aspects of the 9 R strategies of circularity: repair and recycling. These strategies emphasize the importance of creating products that are not only environmentally sustainable but also economically viable. It was recognized that these enhancements must be balanced against potential vulnerabilities that could diminish the panel's longevity.

This thesis is guided by the following research questions:

1. Identify design opportunities for novel liquid-encapsulated panel architecture.

2. Identify opportunities for thermal exchange with liquid-encapsulated PV module design.

The research questions will be answered through background research and experimental testing, multiple methods have been exploited and will be explained in the following chapters.

Chapter 2 | Project Methodology

In collaboration with Biosphere Solar and Photovoltaic Materials and Devices (PVMD - Tu Delft), the project focuses on innovating panel architectures for improved repair, structural integrity, and thermal performance. This thesis commences with two core components: analytical research and creative design solutions. The initial analytical stage encompasses a detailed study of PV(T) systems, covering aspects of sealing, cooling, and liquid selection. From this groundwork, the creative design phase evolves. Insights from the research inform the development of a new system, defining its requirements. The methodology involved analyzing existing panels, designing novel configurations informed by industrial design principles, and subjecting prototypes to structural and performance testing. Multiple solutions were generated and assessed, leading to the selection of the most viable prototypes for testing. To validate these advancements, performance tests have been conducted at the PVMD Laboratorium. This approach demanded optimal time management and specific testing to develop and assess numerous prototypes efficiently. Given the multitude of testing methods available for solar panels, it was imperative to prioritize and select only one or two methods to effectively validate the prototypes in this early concept stage.

In pursuit of an effective design, a significant portion of my research was dedicated to the validation process, employing a methodology centered around prototyping. The methodology employed in this project underscores the development and evaluation of functional prototypes at an early stage. This approach prioritizes the validation of concepts through tangible proofs-of-concept. Through the practice of iterative prototyping, valuable insights were gained to inform the refinement of the overall design and concept. This methodology not only accelerated the decision-making process but also ensured that the final design was grounded in practicality and functionality. Before initiating prototype development, a rigorous examination of the design components was undertaken to ensure robustness and relevance. This preparation includes setting definitive objectives for subsequent testing and underlining a methodical and strategic approach. Such planning is crucial to prevent premature or uninformed experimentation.

A second approach involved investigating and interviewing industry experts in the field, particularly focusing on PVT-Systems and Circular PV modules from Biosphere Solar. Through analysis and interviews, these experts and innovations provided valuable insights that served as starting points in the development of the novel prototypes.

To consistently highlight and emphasize the critical design engineering aspects identified in each chapter, a structured approach has been employed. After a chapter, a distinctive conclusion box is presented to provide a concise summary of the key findings and a detailed discussion on the critical identified design engineering aspects. Design choices are distinguished by a light blue boxed background, while variations in design that undergo thorough study are highlighted with a light yellow background. The use of these boxes aims to visually emphasize the importance of these summarizations and decisions, creating a clear and organized presentation of the engineering considerations throughout the project.

Given the project's complexity and the numerous critical aspects involved, the work was structured into distinct stages, approximately 1 month per stage. Throughout all stages of the project, a consistent and holistic approach is maintained, addressing critical considerations such as designing for circularity, ensuring that the design is readily manufacturable, and ensuring product longevity. Additionally, continuous assessments of economic viability, user appeal, and technical feasibility are conducted. The five stages of this project closely align with the double-diamond design process, refer to Figure 1, general overview.

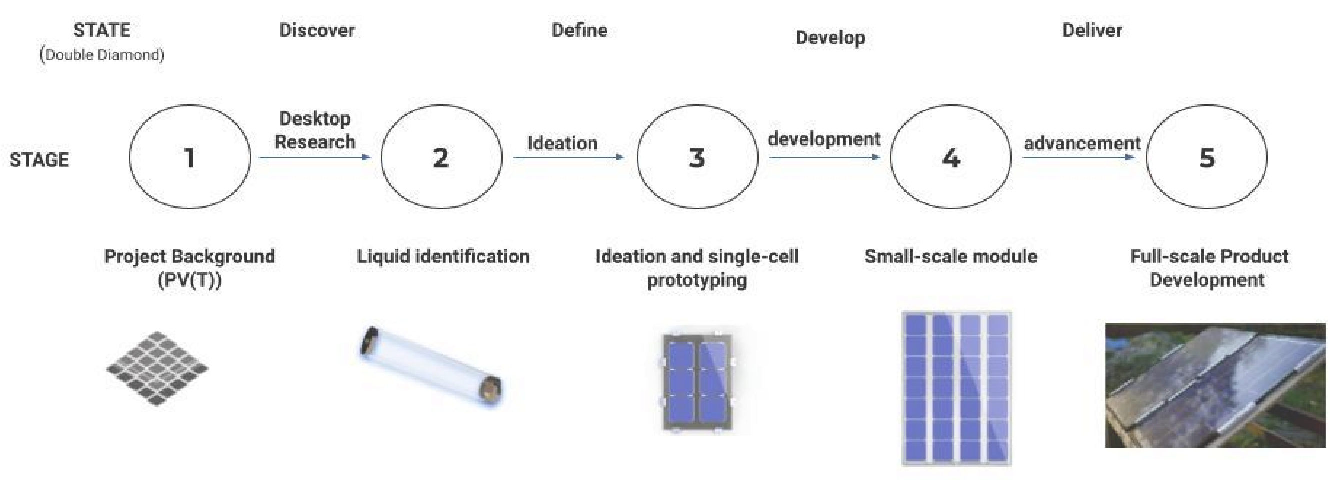


Figure 1, general overview

Chapter 3 | Project Background - PV(T)

In this chapter, the groundwork is laid for a global understanding of photovoltaic systems. Chapter 3.1 provides an overview, introducing the chemical and physical processes that cause the generation of solar power. Gaining a general understanding of the working principles and the materials used in solar panels is essential, as it lays a cell-level basis for the subsequent exploration of developing novel PV system configurations.

Moving from cell knowledge, Chapter 3.2 shifted the focus to the broader context of solar module and panel construction. The goal was to pinpoint the design elements contributing to the efficiency and functionality of solar panels. Understanding this architecture became important in assessing, altering, and potentially enhancing the design of photovoltaic modules.

Chapter 3.3 extended the research into solar panel cooling and heat utilization (PVT). This exploration was particularly relevant in the context of Biosphere Solar's current design, where the intermediate air layer introduced thermal challenges. By examining methods of cooling and harnessing heat efficiently, solutions could be ideated that not only optimized energy conversion but also addressed thermal aspects of PV innovations.

Chapter 3.4 covers numerous sealing principles and their relevance to the project. The exploration reviews various sealing principles, ranging from welding and adhesives to compression seals, with a focus on understanding their effectiveness in preserving the structural integrity and functionality of PV(T) Concepts. The chapter concludes with an experimental section in which two types of sealants and configurations were tested.

3.1 | Chemical and Physical Overview of Solar Cells

In this section, the employed method revolves around component analysis, a focused examination of the individual solar cells within a PV system, delving into materials, functions, behaviors, and interactions. Understanding the materials and structure of solar cells is crucial for ideating novel photovoltaic (PV) panel architectures. Any alterations to the panel can impact the protection and function of the delicate cells. It's essential to be aware of the materials and their vulnerabilities to deterioration, such as corrosion, as these must be anticipated in advance. A breakdown of the layers/components of a typical silicon solar cell, including the materials used and how they are applied is illustrated in Figure 2, which presents a basic schematic of a silicon solar cell cross-section (Silicon Solar Cell Parameters | PVEDucation, z.d.).:

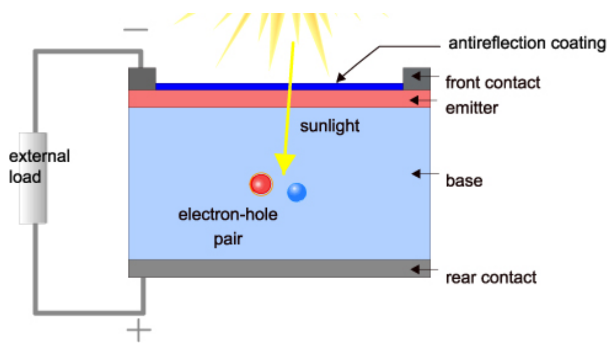


Figure 2, Basic schematic of a silicon solar cell cross-section (Silicon Solar Cell Parameters | PVEDucation, z.d.)

- **Front Contact**: A metal grid of aluminum (Al) or silver(Ag) is placed on the surface to conduct away the current. The metal grid shades the cell from the incoming light so there is a compromise between light collection and resistance of the metal grid.
- **Base:** The semiconductor material is typically crystalline silicon, which can be either monocrystalline or polycrystalline. The thickness of a standard silicon solar cell typically ranges from about 150 to 300 micrometers (µm). This relatively thin profile is integral to the lightweight and flexible nature of solar panels, allowing for installation versatility. However, it also makes them very fragile. Typically, front and back contact solar cells measure 156 mm by 156 mm, while back contact solar cells are slightly smaller, with dimensions of 125 mm by 125 mm.
- **Rear Contact**: Typically, a grid-like pattern of aluminum (Al) or silver (Ag) paste. The back contact is screen-printed onto the back surface of the solar cell to collect the electrons generated by the absorption. It provides electrical connectivity to the external circuit. The significance of the rear contact is lacking compared to the front contact, given its greater distance from the junction and the absence of a requirement for transparency.
- **Busbar:** Wires used to connect individual solar cells are commonly referred to as "busbars". Busbars are made of tinned copper or aluminum flat wire. Tinning involves coating the wires with a thin layer of tin, providing corrosion resistance and enhancing solderability.

PV-Cell design conclusion: In summary, protection against corrosion is crucial for electrical contacts and bus bars especially in moist or other polluted environments, as the moisture can instigate corrosive processes; further, since these components are charged, ensuring proper insulation is essential for reliable and safe performance. With a thickness of only 150 to 300 micrometers, solar cells are very light, and flexible, yet lack durability. Hence design considerations need to be taken to protect the cells against shocks and vibrations.

Moreover, the semiconductor material inhibits a specific chemical layout to function properly; this layer should be protected and retain its chemical compound. For a more in-depth overview of the chemistry and working principles surrounding solar cells, see Appendix C, "Working Principles of Photovoltaic Systems." However, this thesis exclusively focuses on the potential corrosion of the metal contacts, potential effects on the N/P-type doped silicon faces and anti-reflection coating are not acknowledged.

3.2 | Overview of Solar Module and Panel Architecture

To understand solar energy systems comprehensively, this section covers the components and materials of PV systems. From the front surface materials that provide mechanical support and protection for solar cells to the role of anti-reflective coatings, frames, back sheets, encapsulation materials, and wiring, each element plays a part in the functionality of the system. This chapter provides an insightful overview of the conventional components and materials employed in solar modules, shedding light on their significance. Understanding their function, properties, and materials is necessary to iterate new designs in PV panel architecture.

A solar module is an element of a PV panel. A module consists of solar cells and associated components, typically designed for small-scale electricity generation. In contrast, a solar panel is a larger structure that comprises multiple interconnected solar modules, intended for more extensive electricity production in residential, commercial, or utility-scale solar installations. A solar array refers to a collection or arrangement of multiple solar panels interconnected to work together as a single unit (see Figure 3, From solar cell to a PV system). A comprehensive understanding of each component within a PV panel is necessary for engineering solar systems. Refer to Figure 4, Solar panel construction for an overview of each component.

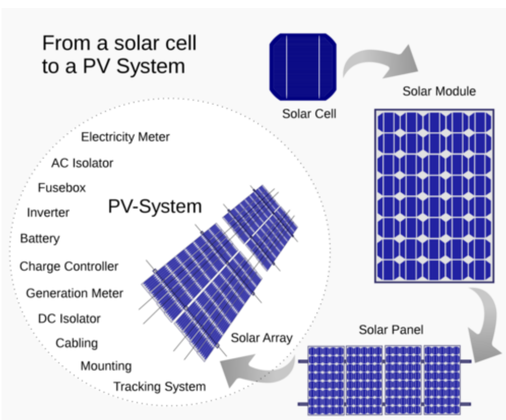


Figure 3, From solar cell to a PV system (Wikipedia contributors, 2014)

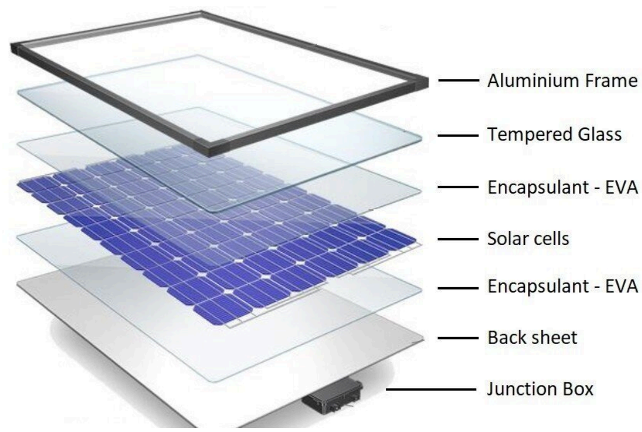


Figure 4, Solar panel construction (Clean Energy Reviews, 2024)

- **Front surface materials:** The front panel must provide mechanical support and protection for the solar cells. The material must have high transmittance, for silicon solar cells in the wavelength range of 350 nm to 1200 nm. Additionally, to further enhance transmittance, an anti-reflective coating can be applied. This coating reduces reflections, allowing more light to penetrate. Another method to increase transmittance is to roughen the surface allowing more light to be captured. Besides the reflection and transmission properties, the top surface material should be water-resistant, impact-resistant, and stable under long-term UV exposure. Various materials, such as acrylic, and glass, can be used for the top surface of a solar panel. However, the most frequently used material is tempered, low iron-content glass. This choice is popular due to its cost-effectiveness, strength, stability, high transparency, resistance to water and gases, and advantageous self-cleaning properties. Solar panel glass is typically in the range of 3.2 mm thickness for most standard crystalline silicon solar panels. This thickness strikes a balance between durability, light transmittance, costs, and weight. (Module Materials | PVEDucation, z.d.)

- **Anti-reflective coating (ARCs):** ARCs employed in solar panels typically consist of alternating layers of high and low refractive index materials. This design is specifically tailored to minimize angle-dependent reflection through interference, enhancing the overall efficiency of light absorption.

- **Frame and backsheet:** The frame is typically made of aluminum or similar material, while the backsheet is often composed of a polymer material. The frame provides structural support and protection for the solar module, while the back sheet acts as a rear barrier to moisture and contaminants.

- **Encapsulation material:** A layer of encapsulation material, often made of EVA, surrounds and holds the solar cells in place. It helps to ensure good electrical connections/insulation and protects the cells from environmental factors. EVA layer is an essential material that binds and protects the total panel architecture and all its components. While the EVA layer is essential for binding and protecting the entire panel architecture, it is so effective in its role that it can make the panel challenging to recycle and repair in the event of partial delamination.

- **Wiring and connections:** Within the solar panel, the electrical connections from each solar module are interconnected to create a common electrical output. A set of wires extends from the solar panel, enabling the panel to connect to the broader solar power system. The output of a solar panel typically utilizes specialized solar MC4 connectors. These connectors are known for their durability and weather resistance, making them suitable for outdoor and solar panel applications. For individual cells, the specific wires used for interconnection are referred to as "busbars," while for some types of IBC cells, they are known as "dog-bones."

- **Junction Box:** Typically made of polypropylene or a similar non-conductive material. The junction box is adhered to the back of the solar module and houses electrical connections and diodes. It ensures electrical connections between the solar panel and external wiring. Additionally, the junction box offers water resistance(IP 65) to the wiring, and the bypass diode is incorporated to provide a path for electrical current in the event of partial shading or a malfunction in one part of the solar panel.

PV-module design conclusion: The exploration of solar module architecture reveals the interplay of various components and materials. The delicate balance between durability, efficiency, and cost underscores the importance of informed decision-making in the pursuit of innovative and effective solar energy systems.

The traditional EVA laminate encapsulant fulfills numerous essential tasks. When deviating from the traditional design (Biosphere Solar) without an EVA laminate, it's vital to consider the fragility of the cells, accounting for protection against shocks and addressing potential thermal stress and expansion. Without this bonding laminate other structural panel components need to take this into account, meaning that increasing the total front panel thickness to enhance durability is a smart consideration in new designs. Additionally, placing greater emphasis on structural edge sealing is a necessity.

3.3 | PVT Background

This chapter starts with a systematic approach to the identification and evaluation of numerous possible cooling principles for PV(T) systems. The research methodology involves an exploration of diverse cooling strategies. Subsequently, expert interviews are conducted to gain insights into PVT panel functionality and engineering. As previously mentioned, maintaining optimal operating temperatures is crucial for solar panels' performance. However, within Biosphere Solar panels, direct cooling is hindered by the insulating layer of air. Therefore, the ideal approach for the new design involves incorporating cooling mechanisms. In this section, innovative technologies related to PV cooling will be analyzed. This innovation serves as valuable design inspiration for the upcoming ideation phases.

- **Passive cooling:** Passive cooling is the simplest method for cooling a flat plate and requires no additional moving parts. Traditional solar panels utilize passive cooling to maintain their operational temperature. Therefore, it is necessary to mount the panels at some distance from the surface, allowing wind and air to reach the back panel for heat dissipation. Instead, PVT panels rely on active cooling to manage and absorb heat exchange. In the current design of Biosphere Solar panels, the outside wind cannot easily reach the solar cells since they are insulated in air which is a poor thermal conductor.

- **Active cooling:** Active cooling methods use mechanical devices, such as fans or pumps, to enhance heat dissipation and are often used in combination with passive cooling. Liquid cooling is a type of active cooling, and it typically includes a pump to circulate a liquid coolant through a closed-loop system. One major advantage of a liquid cooling loop is that it can efficiently transfer heat to another location in the loop, where it can be utilized, for example, in heating water.

- **Phase-change cooling:** One complex yet effective method of cooling is phase-change cooling. It relies on the principle of a substance changing from a liquid to a vapor or vice versa, efficiently transferring heat energy in the process. This phase-change phenomenon is what drives refrigerators, air conditioners, and heat pumps.

- **Thermal insulators:** Thermal insulators are chosen for their ability to minimize heat conduction, often leveraging materials with low thermal conductivity properties. This is particularly valuable in scenarios where heat retention or isolation is desired rather than dissipation. Applications for thermal insulator layers can be found in various contexts, such as in the design of thermal barriers or insulating materials to prevent the loss of heat from specific components or systems. In PVT systems, integrating thermal insulators in the cooling loop system and thermal buffer is crucial to minimize heat loss.

Cooling conclusion for ideation: The selection of appropriate cooling methods is a critical factor in solar panel efficiency. Liquid cooling loops are highly efficient in dissipating heat and offer the added benefit of repurposing the absorbed heat energy. Passive cooling, using the natural flow of outside air, is an eco-friendly option but does not allow for the utilization of the heat generated. A hybrid approach, combining active and passive cooling, can be highly effective. This method, especially when complemented with thermal insulators, prevents unwanted heat loss through the back of the panel and within the hoses, making it a robust solution.

PVT panel technology embodies a different approach. These panels typically utilize active cooling and heat exchange mechanisms. The technology is specifically designed to maximize energy efficiency by not only generating electrical energy but also harnessing thermal energy. This distinct functionality necessitates a specialized cooling strategy, different from traditional solar panels, to maintain optimal operational temperatures and efficiency.

To gain a comprehensive understanding of the working principles behind photovoltaic-thermal (PVT) panels, an interview was conducted with a PVT expert from a Dutch solar thermal company. In addition to becoming acquainted with the working principles of PVT systems, these sessions also provided insights into PVT panel construction and requirements (refer to Figure 5, PVT Panel and heat pump full system).

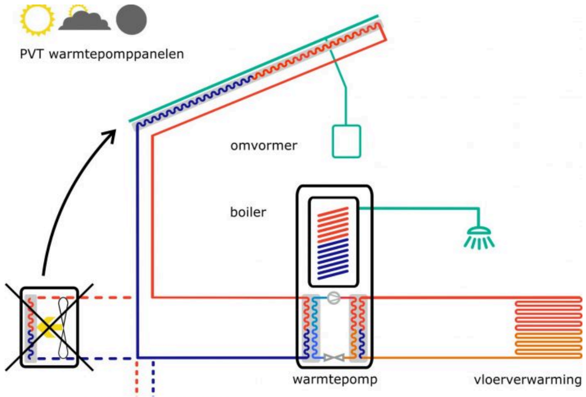


Figure 5, PVT Panel and heat pump full system (Triple Solar BV, 2024)

The PVT panel is a hybrid solar technology that combines photovoltaic cells for electricity generation with a thermal collector for heat production. This dual-functionality allows the panel to generate both electrical power and usable heat. When integrated with a heat pump, the excess heat produced by the PVT panel can be efficiently harnessed to enhance the overall heating system's performance. The heat pump extracts heat from the PVT panel and further increases its temperature, contributing to space heating or hot water production. (Bakker & Strootman, 2003) Heat pumps and PVT Panels are gaining popularity due to their energy efficiency, environmental friendliness, and versatility. They can significantly reduce energy consumption compared to traditional heating and cooling systems, making them a sustainable choice for residential and commercial applications. A thermal energy storage system is designed to store excess heat generated by a heat pump or other thermal systems for later use. In the context of a heat pump with PVT panels, thermal energy storage becomes necessary to capture and store surplus heat produced during periods of high solar radiation. During sunny days, when the PVT panels generate more heat than immediately required, the excess heat can be stored in the thermal energy storage system.

During my research, I interviewed an expert from a company specializing in PVT panel manufacturing. This discussion offered crucial insights into the workings of PVT panels, which combine photovoltaic cells for electricity generation and a thermal exchange unit for heat production. The conversation highlighted the intricacies of PVT design and operation, emphasizing their efficiency in producing both electricity and heat simultaneously. The PVT panel design starts with the front panel which is a standard PV panel. Positioned at the rear of the panel, the back radiator plays a crucial role in the system. It is constructed from interlocking aluminum extrusions that incorporate channels for the flow of a heat transfer liquid. These extrusions are intertwined and bonded to the back of the panel whilst ensuring a secure and efficient thermal connection. (See figure 6)

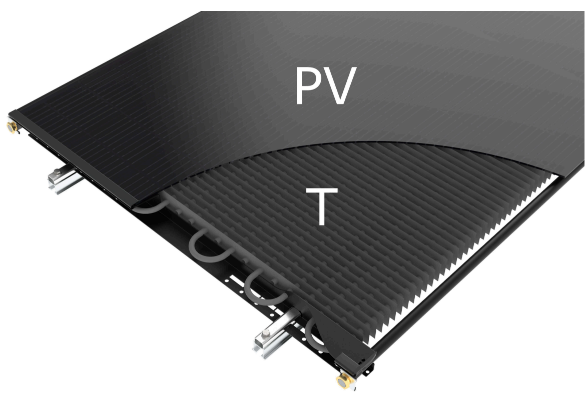


Figure 6, PVT panel section view (Triple Solar BV, 2024)

During the interview, several critical factors that significantly influence the performance of PVT panels came to light. First, a cooling mixture of glycol and water is employed within the radiator connected to the panel. This mixture serves a dual purpose: it enhances the panel's thermal capabilities while also preventing the mixture from freezing in colder climates. This ensures that the panel can operate effectively in a variety of environmental conditions. Secondly, maintaining a consistent temperature within the panel is crucial. Extremes of temperature, whether too high or too low, can negatively impact panel performance. If the temperature difference between the panel and the coolant is too low, there is little heat transfer potential, resulting in very little usable heat. On the other hand, if the difference is too high, the panel's electricity output decreases as a result of the solar panel becoming excessively hot. There exists an optimal temperature range where the panel operates most efficiently and generates a substantial amount of heat. To control this system, a smart pump and algorithm are necessary to regulate the flow and monitor all the temperatures. Moreover, to achieve optimal performance, it is essential to maintain a laminar flow of the heat transfer liquid within the panel's channels. A laminar flow (where turbulence is minimized) pattern ensures that heat is efficiently transferred from the back radiator to the liquid. Additionally, fine-tuning the flow rate is crucial to optimizing flow behavior.

PVT-design engineering conclusion: The insights gained from this interview provided a deeper understanding of the complexity behind PVT panel design and operation. It highlights the importance of precise material selection and accurate temperature/flow control. Typically, photovoltaic cells operate efficiently at around 25°C. Excessive heat can reduce their efficiency, so maintaining a temperature below 25-30°C is often desired. In the thermal system, the flow rate of the heat-transfer fluid (like water or glycol mixtures) needs to be optimized. Too low a flow rate might not remove heat efficiently, while too high a flow rate can increase energy consumption for pumping. The optimal rate depends on system design but is usually calculated to maximize heat extraction without excessive energy use. These findings will play a role in the development of new PV concepts where adequate cooling is applied and additional functionality is presented, making it a promising innovation and therefore noteworthy to try to accommodate in the new designs.

3.4 | Research of existing sealing concepts

In PV panel construction, a hermetic seal is a necessity; it safeguards the cells against potential air, moisture, and gas ingress that could compromise structural integrity and functionality. Moisture ingress is a primary cause of degradation in traditional PV modules, leading to issues such as metal grid corrosion, delamination, discoloration of encapsulants, potential induced degradation, and optical and adhesion losses. It is a critical factor contributing to power degradation in PV modules (Segbefia et al., 2021). Therefore permeability against moisture is an important factor and it is often quantified in the water vapor transmission rate (WVTR). Additionally, it's noteworthy that another medium that can cause corrosion is oxygen. Therefore, a low oxygen transmission rate (OTR) is preferred when sealing a PV cell (Peike et al., 2012). This exploration covers multiple principles for hermetic seals, from welding and adhesives to compression seals. Understanding these techniques is crucial, to select the most effective cell sealing for the concepts.

A hermetic seal is an airtight or gas-tight seal that completely isolates the contents of a container or system from the external environment (Apec_Access, 2023). It prevents the entry of air, moisture, or gases, as well as the leakage of the contents sealed within. Hermetic seals are commonly used in various applications, such as in electronic components, refrigeration systems, and medical devices, to maintain the integrity and protect the contents from contamination or degradation. Approaches to obtain a hermetic seal include welding, soldering, brazing, glass-to-metal sealing, compression seals, adhesives, induction sealing, ultrasonic welding, sealants, and laser bonding. In the context of a Liquid Encapsulated PV panel where reparability stands as a central goal, permanently fusing materials is impractical and expensive. Consequently, the viable options narrowed down to adhesive sealants and compression seals. Given the necessity for repairability, these solutions offer the flexibility required for disassembly and maintenance. Moreover, it is important that the selected sealant not only provides an effective hermetic barrier but also exhibits some flexibility to accommodate the movements induced by the thermal expansion of the panel's structural components.

- **Adhesives:** Adhesive bonds can be hermetic, commonly used examples of adhesives are epoxy and cyanoacrylate (Apec_Access, 2023).
- **Sealants:** Specific adhesives that prioritize creating a barrier to prevent the passage of substances between surfaces. Sealants are versatile materials used to create airtight or watertight seals, preventing the passage of air, water, dust, or other environmental elements. While they may not offer the same level of structural bonding as adhesives, sealants are designed to be flexible, making them well-suited for applications where movement is present. Two commonly utilized sealants are silicone sealants, and butyl rubber sealants, known for their versatility, adhesion, and sealing properties.
- **Compression seals:** Compression seals employ gaskets, materials with elastic properties often elastomers, and in more specific scenarios soft metal for example copper. These elastomeric components are compressed between two components, forming a robust and airtight seal when exposed to pressure. This sealing mechanism can effectively block the passage of air, water, or gasses. Compression seals do require additional mechanisms to facilitate the compression process; however, this characteristic makes them modular and repairable. These seals can withstand high-pressure differentials and types of physical stress such as shock Daly (2024).

Conclusion for ideation: Adhesives like epoxy are known for their strength but lack flexibility and are not always environmentally friendly. Sealants offer excellent sealing properties, are flexible, and can accommodate slight movement, but once cured, they are more challenging to disassemble. Compression seals create airtight or watertight seals under pressure but require additional components and mechanisms to provide the compression.

In assessing the trade-offs, it became clear that functionality and durability often take priority over modularity and repairability in PV applications. Therefore, opting for sealants like silicone and butyl emerged as an attractive choice. These sealants not only offer excellent sealing properties and flexibility but also strike a balance between strength and disassembly. Furthermore, it's essential to note that compression seals necessitate a substantial amount of pressure to perform optimally, often requiring the use of large clamping structures to generate the required force. This dependency on significant pressure can pose impractical design challenges, especially in scenarios where the application or system cannot accommodate or easily provide such pressure. For a more detailed exploration of this aspect, please refer to Appendix H, titled "Seal Testing”. When choosing the sealant for the prototypes, it is crucial to opt for a material with a prolonged life expectancy, strong adhesion to glass, and enduring UV resistance.

To evaluate the effectiveness of Poly isobutylene-isoprene (Butyl) and Polydimethylsiloxane (Silicone) as sealants, pressure tests were carried out using small-scale dummy panels. This was to analyze and compare silicone and butyl rubber properties under pressure. The choice of these adhesives is informed by their current use in Biosphere Solar panels, with butyl used internally and silicone externally. This testing is critical to ascertain their effectiveness against pressure and liquid. Notably, Nitrile Rubber, often used in pressure sealing, was excluded from these tests due to its poor UV resistance(*Nitrile Rubber | Nitrile ‘O’ Rings | TRP Polymer Solutions*, 2021). For detailed comparisons, refer to Table 1, titled 'Sealant comparison'.

Table 1, Sealant comparison

Material	**Poly isobutylene-isoprene (butyl)**	**Polydimethylsiloxane (silicone)**
Characteristics	Moisture resistance: Excellent Low gas permeability: Excellent Abundant and non-toxic: Butyl rubber is derived from petroleum, which is relatively abundant. It is generally considered non-toxic and safe for many applications.	Moisture resistance: Excellent Low gas permeability: Good to excellent Abundant and non-toxic: Silicones are derived from abundant materials, and they are generally considered non-toxic once cured.
Water absorption A24hrs	0.01-0.02% (Ansys)	0.1-0.15% (Ansys)
Water vapor transmission lb. in/ft^2.day	1.61e-8 - 3.23e-8 (Ansys)	1.21e-5 - 2.82e-5 (Ansys)
Permeability (oxygen) ft^2/day.atm	5.06e-8 - 1.91e-7 (Ansys)	1.39e-4 - 3.24e-4 (Ansys)

Three seal tests were conducted to explore and compare the sealing capabilities of different materials. The selected materials for these tests were silicone, butyl rubber, and a combination of both:

- **Silicone seal test:** Silicone, is known for its excellent adhesion and water resistance.
- **Butyl rubber seal test:** Butyl rubber, is chosen for its exceptional gas sealing properties.
- **Hybrid seal Test (silicone and butyl):** Recognizing the strengths of both silicone and butyl rubber, a hybrid seal test was conducted to explore the combined benefits of these materials.

During the testing, the samples were first injected with water and then subjected to pressure. The process was carefully monitored and recorded, and pressure readings from the manometer could be extracted from the recorded footage. (refer to Figure 7, seal pressure test setup). It was observed that butyl rubber quickly failed under a relatively low pressure of 15 psi. In contrast, both silicone and the hybrid mixture of silicone and butyl withstood the maximum pressure of 20 psi applied in the setup (Table 2). The pressure testing conducted on the sealants showed clear differences in adhesion properties. For the final design, the pressure safety margin needs to be determined by relevant regulations. Additionally, incorporating a thermal expansion buffer in the design can help manage large pressure differences effectively.

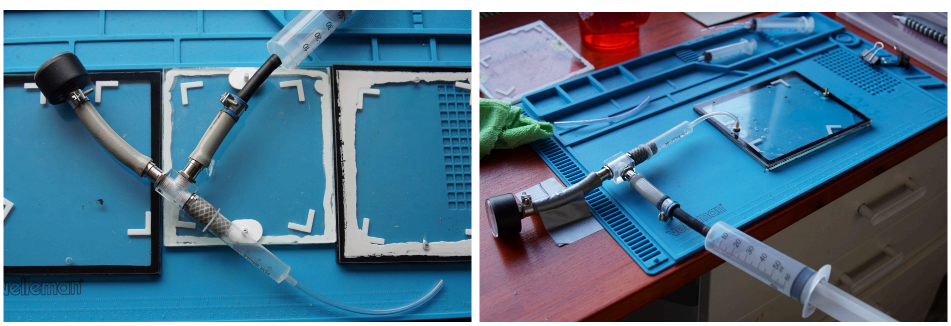


Figure 7, Seal pressure test setup

Table 2, Sealant experimentation

Sealing	**Silicone seal test:**	**Butyl rubber seal test:**	**Hybrid seal test (silicone and butyl)**
pressure (Psi)	20 passed	15 failed	20 Passed

Seal-conclusion: Silicone demonstrated excellent adhesion to glass, whereas butyl rubber's flexibility led to potential leakage risks without external compression. The hybrid seal emerged as the strongest option. The data revealed that butyl rubber could provide excellent gas impermeability from the outside, while silicone offers water resistance from the inside. Additionally, this combination increased the rigidity of the total panel due to the superior adhesion to glass. Unfortunately, the setup could not apply pressure beyond 20 psi, but these tests were instrumental in illustrating the flexible nature of butyl rubber. Combined with data on permeability, it can be concluded that a hybrid seal warrants further exploration on a larger scale.

Chapter 4 Cooling System

In this chapter, the objective is to identify suitable liquids for direct liquid encapsulation, with a focus on improving system performance and exploring commonly used cooling liquids. These insights will lay the foundation for a systematic approach to liquid selection based on specific properties. The outcome of this chapter will contribute to a framework for selecting liquids that will be necessary for subsequent testing phases. Noteworthy, the initial goal of the selection process is to test the functionality of the integrated cooling flow system, prioritizing function over optimal optical and electrical performance at this stage. Once a functional system is established, there is more flexibility to explore different liquid options, potentially incorporating design changes to accommodate variations in specific properties.

4.1: Liquid Selection

This section will delve into the prioritization of various criteria essential for liquid selection. Criteria such as thermal conductivity, specific heat capacity, viscosity, and environmental impact will be examined for their relevance to effective PVT cooling. By prioritizing these criteria, the liquid selection process becomes more tailored to the specific requirements of the project. An overview will be implemented to objectively evaluate multiple liquid's performance against the identified criteria.

4.2: Ensuring Consistent Liquid Flow within the Panel

Consistent liquid flow within panel gaps and cavities is crucial for effective direct PV(T) cooling. This chapter will explore strategies and considerations for maintaining a uniform flow of the selected liquid within the intricate architecture of the panels. Additionally, it will cover various design features that could aid in establishing and optimizing liquid flow.

4.1 | Liquid Selection

This section aims to define the critical considerations in identifying a liquid for liquid-encapsulated PV prototypes. The outset provides an overview of common types of cooling liquids (Table 3, Common Types of Cooling fluids), pinpointing their characteristics and applications. The second section explored an examination of important properties, forming the foundation for the evaluation ranking matrix. Subsequently, five different liquids were selected and analyzed, with a particular focus on their suitability for liquid encapsulation.

Table 3, Common Types of Cooling Fluids

Cooling Type	Characteristics	Applications and considerations
Water	- Readily available - Cost-effective - Good heat-carrying capacity - Non-toxic	- Open-loop or closed-loop systems - Potential corrosiveness to certain materials may limit compatibility with specific metal components
Heat Transfer Fluids	- Specialized fluids (glycol-based solutions or synthetic oils) - Lower freezing points - Anti-corrosion and antifreeze properties	- Closed-loop cooling systems - Suitable for cold climates - Versatile in various environmental conditions - electrical insulation
Glycol/Water Mixture	- Commonly referred to as antifreeze - Enhanced with corrosion inhibitors - Extends operational lifespan	- Commonly used in various industrial and commercial applications, primarily for their antifreeze properties.
Refrigerants	- Phase change from liquid to gas and vice versa	- Commonly employed in refrigeration and air conditioning systems - Used in heat pumps
Air	- Utilizes air as a cooling medium through convection - Simplicity - Low maintenance requirements	- Suitable for certain PV systems - Less efficient than liquid cooling, but advantageous in specific applications

In conclusion, the variety of cooling liquids presents a spectrum of options with distinct characteristics tailored for specific applications. Water, with its ready availability and cost-effectiveness, remains a versatile choice, yet with potential corrosiveness concerns. Heat transfer fluids, glycol/water mixtures, and refrigerants offer specialized solutions catering to diverse needs such as anti-corrosion properties, extended operational lifespan, and electrical insulative properties. This brief investigation into common liquids revealed that when searching for a specific heat transfer fluid or electrical insulator oils, it is advisable to consult experts in the field of optical measurement devices and high-voltage insulator assemblies. Through these connections, general information about the fluids could be promptly acquired, and test samples could be obtained. In this section, a matrix is presented, detailing various properties and their respective role in the PV system. The matrix offers a structured overview of the property context and priority.

Property Matrix	Definition and role in PVT system	Supplementary PVT context
Thermal conductivity	**Thermal conductivity requirements for cooling liquids:** Thermal conductivity refers to a material's ability to conduct heat. In the context of a coolant, high thermal conductivity means the coolant can rapidly and effectively absorb heat from a hot source (In a PVT system the back of a solar panel) and transport it away.	In the context of a PVT system, the primary focus is on maximizing the electrical output of the PV component. Moreover, to increase heat exchange, numerous other properties become relevant, and both the panel design and its materials play equally essential roles.
Heat capacity	**Evaluating the importance of heat capacity in cooling liquids:** A coolant should have a relatively high heat capacity, which means it can absorb and store a significant amount of heat energy without experiencing a large temperature change. This property allows it to stabilize temperatures in the system it's cooling.	In the context of a PVT system, where maintaining optimal temperatures is crucial, heat capacity holds a moderate level of priority. The specific requirements depend on more factors such as system volume, flow velocity, and cooling. Essentially, adapting the architecture becomes more important and necessary to achieve optimal performance, regardless of the liquid chosen.
Thermal expansion	**Evaluating thermal expansion of cooling liquids:** Thermal expansion is the property of a substance to change in volume in response to changes in temperature. A low thermal expansion is preferred in practical cooling loop applications. Higher thermal expansion liquids would require an additional buffer expansion mechanism.	Analyzing and calculating thermal expansion is necessary and the liquid loop should potentially need a **thermal expansion tank or mechanism to** accommodate the changes in volume.

Boiling point & freezing point	**Assessing boiling and freezing points to Suit PV Solar panel cooling systems:** Boiling and freezing points play a crucial role in determining the suitability of a coolant for use in PV(T) solar panel cooling systems, especially in regions with varying environmental temperatures. In such systems, the boiling point and freezing point of the coolant need to be within a specific temperature range, considering the environmental conditions and allowing for a margin of safety.	In the hierarchy of priorities for a PVT system, boiling and freezing points are considered, but their significance lies more in serving as exclusion criteria than scoring factors.
Refractive index	**The refractive index is a** fundamental optical property that quantifies how much a medium can bend or refract light when it passes from one medium (e.g., air) into another (e.g., glass or a liquid coolant). Matching the refractive index of the encapsulant with the front panel (typically glass) is essential for high transmittance. Standard soda lime glass also known as float glass has a refraction index of approx. 1.52	Highly important and the main goal in the function of the novel PVT panel. The selected alternative encapsulant (liquid) should have a refractive index of approximately 1.52 (n). It's noteworthy that deviation in the refractive index can be compensated for through the use of anti-reflection coatings (AR).
Absorbance	**Assessing the amount of absorbance:** Absorbance measures how much light a material absorbs at a specific wavelength. A higher absorbance indicates more absorbed light and less transmitted or reflected light. It's important for the cooling liquid inside a PV system to exhibit low absorbance, especially in the wavelengths that silicone PV cells can absorb for energy yield (approximately 380 nanometers (nm) to 1200 nm.).	Highly important in the context of a liquid-encapsulated PV system, as low absorbance is crucial for maximizing energy yield from silicone PV cells.
Viscosity	**The role of low viscosity in enhancing liquid circulation in PVT systems:** Viscosity describes the resistance to the flow of a fluid. It measures the internal friction or "stickiness" of a fluid, indicating how easily the fluid molecules can move past each other. Viscosity is typically measured in units of Pascal-seconds (Pa·s) or poise (P), with lower values representing lower viscosity and greater fluid mobility. Low-viscosity coolants, such as water or specially formulated heat transfer fluids, flow more easily through the cooling loop. This characteristic is advantageous for several reasons: **Efficient heat transfer:** Low-viscosity coolants can rapidly circulate through heat exchangers and cooling systems. **Reduced pumping energy:** The circulation of low-viscosity coolants requires less energy to pump. **Minimized heat loss:** Low-viscosity coolants experience less friction as they flow through the system.	Selecting a liquid with low viscosity is favorable in PVT systems as it enhances fluid circulation, and facilitates efficient heat transfer through the system. Additionally, low viscosity complements the filling and pumping of the entire system. It is important to note that Viscosity can differ significantly over a different range of temperatures.
Electrochemical behavior	**Refers to liquids' ability to conduct and facilitate chemical reactions when an electric current is applied.** This behavior is crucial in determining how the liquid interacts with charged components, like busbars in solar systems. In water-based liquids, the presence of ions makes them conductive, which can lead to undesirable electrochemical reactions such as corrosion or short-circuiting when in contact with electrically charged components.	Having a water-based liquid encapsulant is also impossible as it can react with the charged connections(Busbars) in the system.
Chemical reactivity	**The liquid employed should exhibit non-oxidizing properties:** This means that it should remain chemically unreactive when in contact with critical components, such as silicon, anti-reflection coating, and metal contacts (commonly composed of silver or aluminum). This non-oxidizing is necessary to prevent unwanted chemical reactions that could degrade or compromise the performance of these elements within the system.	Since the solar cells are directly encapsulated by the liquid, they should not chemically react with the cells. Analyzing the reactivity of substances/components is a complex and time-intensive process which is not the main focus of this project and will therefore be partly mentioned.
Toxicity	**Environmental and toxicological considerations:** Environmental and toxicological considerations involve assessing the potential impact of the selected liquid on the environment and human health. This includes evaluating the fluid's biodegradability, ecological effects, and toxicity levels.	Given that the liquid flows throughout the entire system and may come in contact with installers and end users, non-toxicity is a necessity. Choosing a non-toxic liquid is beneficial for both environmental sustainability and human safety. Extra precautions need to be taken into account when selecting toxic coolants.

Additional Strategies for Minimizing Corrosion are corrosion inhibitors and a getter. Corrosion inhibitors are substances designed to mitigate the effects of corrosion on metal surfaces. They achieve this by forming a protective layer on metal surfaces, preventing corrosive reactions. Regular monitoring and maintenance of coolant are crucial to sustaining the effectiveness of corrosion inhibitors. In the case of a fully closed loop system with high corrosion sensitivity, it is even more valuable to integrate a getter into the design. A getter is a reactive material formed within a system to absorb or chemically bond excess residual gases like water vapor and oxygen.

At the cell level, the voltage is approximately 0.5 to 0.6 volts. However, inside individual solar panels, the typical voltage ranges from 30 to 40 volts. To optimize efficiency and minimize resistive losses within the connecting cables, panels are often arranged in series. Because of these high voltages, it is important for the panel and its connection to be properly insulated from one another and the environment. On a larger scale, such as in solar farms, the operational voltage can reach levels from 600 volts to 1.5 kilovolts. At these higher voltages, the dielectric characteristics of the insulating medium become even more critical, since there is a greater potential for electrical breakdown or arcing to occur. A high breakdown voltage ensures that the insulating material can handle these high operational voltages without undergoing electrical breakdown (arcing).

To be able to assess the ability of cooling fluids to achieve high heat exchange paired with low pumping powers, a study introduces a physically-based figure of Merit (FOM), assessing cooling performance by evaluating the ratio of achieved heat flux to required pumping power (Ehrenpreis et al., 2020). The FOM, derived analytically, is solely dependent on thermal fluid properties, making it applicable to various cooling configurations with laminar flow conditions. To align with the context of a direct liquid-encapsulated PV module, considerations for heat dissipation and fluid properties become crucial, emphasizing the need for efficient cooling in photovoltaic systems. In the context of direct liquid-encapsulated PV modules, the figure of Merit (FOM) provides an effective way to assess the cooling performance of selected liquids.

$$FOM = (\rho * Cp^2 * k^2)/v)^1/4$$

ρ= is the density of the fluid. (kg/m3)
Cp= is the specific heat of the fluid. (J/kg)
k= is the thermal conductivity of the fluid. (w/m K)
v= is the kinematic viscosity of the fluid. (m^2/s)

The Property Evaluation Matrix has been established to aid in more in-depth decisions when optimizing liquid selection in the future.
For detailed information on the four selected liquid options, please refer to Table 3 in the document titled "Liquid Selection."

Table 3, Liquid selection, detailing 4 selected liquid options

FLUID Brand name Applications	**GLYCOL-WATER** (NALCO 460-TFS200 Treated Water Solution, CCLS, Biocide/Corrosion Inhibitor)	**ESTER OIL** MIDEL 7131 (Synthetic Ester Transformer Fluid Fire safe and Biodegradable)	**FLUORINERT** (3M™ Fluorinert™ Electronic Liquid FC-72)	**SILICONE OIL** (XIAMETER™ 561 Silicone Transformer Liquid) (Polydimethylsiloxane)
Viscosity (cSt)	0.9 (21 °C)	74.7 (20 °C) 29 (40°C)	0.38 (25°C)	49.0 (23°C)
Refraction index (n)	1.33 (http://www.refractometer.pl/refraction-datasheet-ethylene-glycol)	1.4555	1.25	1.404
Dielectric Breakdown (kV)	No data	75	40	35
Boiling Point (°C)	95°C	300°C	56 °C	> 65 °C
Pour Point (°C)	5°C	56°C	-90 °C	No data
Thermal conductivity W/(m.K)	No data	No data	0.057	0.151
Specific Heat (J kg-1 °C-1)	No data	No data	1100	1510
Density (kg/dm3)	1	0.97	1.68	0.96
FOM (ρ*Cp^2*k^2)/v)^1/4	ρ= 1000 Cp= No date k= No date v= 9×10 −7 m 2 /s No data	ρ= 970 kg/m³ Cp= 1919 J/(kg·°C) k= 0.147 W/(m·K) v= 9×10 −7 m 2 /s ((970 * 1919^2 * 0.147^2) / 9 * 10^-7)^0.25≈**0.962**	ρ= 1680 kg/m³ Cp= 1100 J/(kg·°C) k= 0.057 W/(m·K) v= 3.8×10 −7 m 2 /s ((1680 * 1100^2 * 0.057^2) / 3.8 * 10^-7)^0.25≈ **0.645**	vρ= 960 kg/m³ Cp= 1510 J/(kg·°C) k= 0.151 W/(m·K) v= 49.0×10 −6 m 2 /s ((960*1510^2*0.151^2)/49*10^-6)^0.25≈ **1.001**

Liquid-conclusion for ideation: Considering the outlined criteria and their respective importance levels, silicone oil(XIAMETER™ 561 Silicone Transformer Liquid) and fluorinert (FC-72) emerge as the most suitable options for the PVT prototypes. These liquids demonstrate favorable characteristics, particularly in terms of low viscosity, suitable refractive indices, high dielectric breakdown, and practical boiling and pour points. Both silicone and ester oil are suitable candidates; however, silicone takes the lead with its lower viscosity and higher transmittance, as ester oil has a slight yellowish tint. The glycol-water mixture, even with corrosion inhibitors, still presents a considerable risk. Initial single-cell testing revealed signs of corrosion, during evaporation validating the concerns and future exclusion of all water-based liquids. Based on the calculated FOM both liquids possess adequate cooling performance however Silicone oil surpasses fluorinert due to its higher outcome, lower toxicity, and reduced environmental impact. Additionally, its significantly lower cost enhances its economic appeal.

Given the limited availability of data in the manufacturer's data sheets, certain aspects of the ranking of these liquids may not be as extensively clarified. Additionally, it is important to acknowledge that temperature variations can influence the physical properties of these liquids, the viscosity in particular. To address uncertainties, it's advised in future testing to measure refractive index and transmittance, using a spectrophotometer for accurate readings, enhancing the ranking process. Additionally, long-term testing is advisable to truly shed light on the capabilities of the liquid in the specific liquid encapsulation scenario.

In conclusion, the evaluation and matrix provide a comprehensive overview of various properties crucial for selecting a liquid. The prioritization reflects the system's multifaceted requirements, and it underscores the need for a balanced but well-considered approach to summarize:

- **PV, performance-based properties of the liquid: Mainly refraction index and transmittance**
- **PV, System reliability-based properties of the liquid: Liquid stability, and reactivity**
- **PVT, Flow, and thermal-based Characteristics: Mainly viscosity and thermal properties**
- **Toxicity and environment-based properties of the liquid**
- **Availability and cost efficiency of the proposed liquid**

4.2 | Ensuring Consistent Liquid Flow within the Panel

This section covers strategies for promoting uniform liquid fill and flow, with specific design features to enhance consistency. Finally, the Reynolds number will be introduced as a method for predicting laminar flow.

By strategically positioning inlets and outlets, the goal is to ensure a uniform fill and flow of the entire space while eliminating trapped air. Achieving this involves creating a vacuum on one side and applying controlled liquid injection pressure on the other, thereby facilitating even and complete system saturation. Additionally, incorporating systems for thermal expansion is necessary. This allows the system to accommodate temperature variations without compromising the integrity of the liquid interface. The inclusion of flow control mechanisms further enhances the precision of the process, ensuring that the liquid is distributed seamlessly and by the desired pressure and control.

To further optimize the flow, it could be worth investigating the adaptation of conventional rectangular solar panels by elongating their shapes. Although this configuration might be less practical, it presents potential advantages for both flow dynamics and structural integrity. As highlighted in Figure 8's elongated panel design, the elongation reduces the maximum distance between the sealants, which could enhance even pressure distribution. This approach may serve as an additional measure to consider in the overall design process.

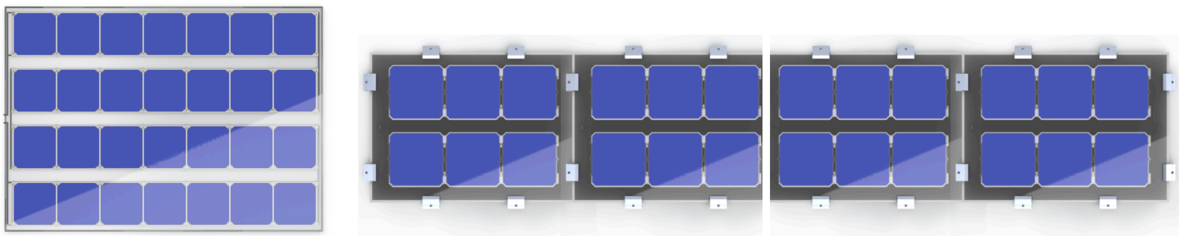


Figure 8, Elongated panel design

When a fluid flows through a closed channel, such as a pipe or between two flat plates, the flow can be characterized as either laminar or turbulent. The distinction between laminar and turbulent flow is primarily based on the fluid's velocity and viscosity. Laminar flow, characterized by smooth and predictable fluid motion, is an ideal state for ensuring consistent liquid distribution. Calculating the Reynolds number, a dimensionless quantity that relates fluid velocity, density, viscosity, and characteristic length, becomes crucial in assessing the flow within the flat plates. Maintaining a laminar flow, characterized by a low Reynolds number, enhances the predictability and stability of liquid flow (White, 1999). The formula to calculate the Reynolds number:

$Re = (\rho \cdot v \cdot L)/\mu$

μ= The dynamic viscosity of the fluid.
ρ= Density of the fluid
v= Velocity of the fluid relative to the object
L = L is a characteristic length

The Reynolds number at which the flow becomes turbulent is called the critical Reynolds number. The value of the critical Reynolds number is different for different geometries. For flow over a flat plate, the generally accepted value of the critical Reynolds number is $Re_x \approx 500000$. (Murad, 2022). Performing a calculation involving silicone oil with specific parameters, such as a panel thickness of 0.75mm, a width of 1m, and a velocity of 100ml per minute, gives a Reynolds number (Re) calculation: $Re = (960(\rho) \times 0.00222(V) \times 0.00075(L))/0.049(\mu) \approx 0.033$. This confirms that the flow is laminar, as this value is significantly lower than the critical Reynolds number for transitioning to turbulent flow. However, it's important to note that while laminar flow is a prerequisite, it is not the only factor to consider. Another aspect is the prevention of stagnant areas, especially in corners where fluid flow tends to be less dynamic. Stagnant areas can lead to inefficiencies in heat transfer and fluid dynamics, potentially impacting the overall effectiveness.

To address this, adapting the design to incorporate rounded sealants could be advantageous. This would minimize the likelihood of stagnant zones. Particularly, designing the top of the curve to serve as the inlet could enhance fluid distribution across the panel, ensuring a more uniform flow. This design modification not only complements the laminar flow conditions but also optimizes the fluid dynamics by reducing the chances of stagnation, thereby potentially improving the overall efficiency of the system (Figure 9, rounded seal).

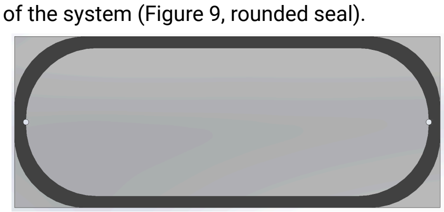
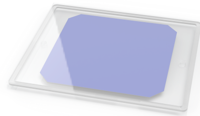


Figure 9, Rounded seal

Flow-conclusion for ideation: Opting for smart design decisions can promote consistent flow, placing the fittings in the upper and lower corners allows for easy total filling. Making use of syringes can create a controlled injection and suction promoting full saturation of the prototypes. To further validate a prototype's flow behavior, the Reynolds number can be calculated, confirming a laminar flow. In this project-specific scenario characterized by low velocity and a specific thin-gapped geometry, laminar flow is always evident.



Chapter 5 commences with an ideation process, integrating learnings from previous chapters to develop a comprehensive understanding of the necessary structural components and requirements. This chapter aims to synthesize these insights into a practical single-cell embodiment, with the benefits of the latter being its easy-to-build and easy-to-evaluate nature. The primary objective of these prototypes is to assess the efficacy of liquid encapsulation in enhancing thermal and optical performance, particularly in comparison to the Biosphere Solar EVA-Less panel design. Variations in the prototype will be introduced through differences in module thickness and various liquid coolants. These variants will undergo testing using a methodology outlined in section 5.2.1-2 with the results and conclusion being presented in section 5.2.3 & 5.2.4 respectively.

5.1 | Ideation

The first step of ideation was a graphical representation of complex concepts explored in earlier chapters, which is done by creating two figures. Figure 9, titled "PVT System Components/Requirements," encapsulates the components and requirements of Photovoltaic Thermal (PVT) systems, presenting complex ideas in a more digestible visual form. Similarly, Figure 10, "Liquid Flow Systems Components and Requirements," outlines the components and requirements for the liquid flow systems, offering a clear visual guide to these elements. Both categories outline crucial considerations that will shape the direction of ideation. Multiple brainstorming sessions and collaborative engagement with stakeholders and experts have been conducted to ensure the creation of functional prototypes and test setups.

Following the visualization, the focus shifts to developing a comprehensive list of requirements. To enrich the ideation process, multiple brainstorming sessions were conducted, involving collaboration with stakeholders and experts. This collaborative approach helps in refining the list of requirements and ensuring they are practical and comprehensive.

The final step involves moving from ideation to practical application. This includes the creation of functional prototypes and test setups that leverage the insights and requirements identified. A significant aspect of this phase is the creation and testing of a single-cell embodiment, which allows for focused testing of specific components or aspects of the system, ensuring detailed and precise evaluation.

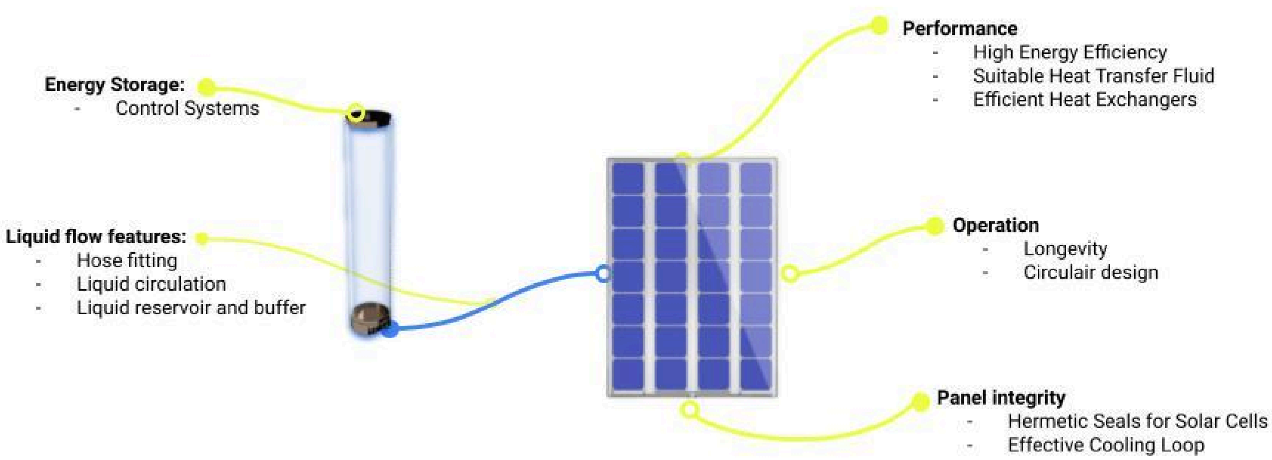


Figure 9, PVT system components and requirements

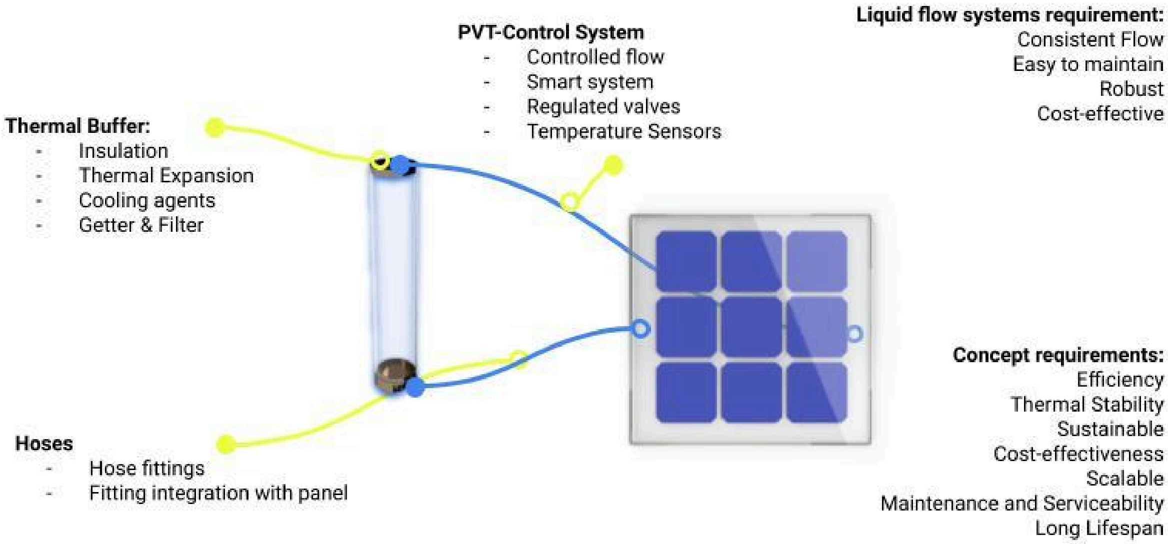


Figure 10, liquid flow system components and requirements

These figures provided a PVT framework, highlighting key components such as heat transfer fluid, heat exchangers, energy storage, control systems, and operational considerations. The product requirements have been outlined in Appendix D: “List of Requirements”.

The remainder of Chapter 5 covers the single-cell embodiment. Central to the investigation is the proof of concept concerning the thermal and optical advantages of liquid encapsulation, before advancing to more extensive applications, validating these benefits on a smaller scale is imperative, ensuring their viability for scaling up. The single-cell testing initiates the research methodology by addressing fixed aspects of the design, which involve materialization to maintain consistent parameters. Subsequently, specific test variations are introduced to evaluate the thermal and optical advantages of different liquid encapsulations.

Single-cell embodiment design choices:
In the development of the single-cell prototype, material selection plays an important role in achieving a desired setup. This section provides an overview of the materials chosen for the prototype, each selected for its specific advantages in the context of the design requirements. For a comprehensive description of the rationale behind these choices, please refer to Appendix E, "Single-Cell Embodiment." A Morphological Analysis was utilized as the guiding method. This approach involved breaking down the prototype into its key components - the front panel, backplate, cell type, and sealing material. For each component, a range of material options or features was considered, weighing their advantages in terms of efficiency, cost, and practicality for the prototype’s needs. This method allowed for a systematic exploration of alternatives, leading to the selection of the most suitable materials. These selections aim to test and validate different aspects of the prototype under varying conditions. The most important material selections are as follows:

- Front panel - 4 mm float glass: Primarily selected due to its accessibility and the ease with which it can be cut to the desired dimensions. This makes it a practical choice for the prototype.
- Backplate - 4 mm acrylic: This was chosen for the backplate due to its availability and the simplicity of sizing it to fit the prototype's dimensions. Moreover, its compatibility with easy mounting of threaded holes for couplings makes it suitable.
- Cell Type - Maxeon gen III cell: These were selected for their ease of soldering and practical form factor. These cells are known for their efficiency and reliability.
- Sealing - butyl rubber: This was the chosen sealing material, primarily because it offers good air sealing properties. Its use in biosphere solar's existing prototypes further validates its effectiveness. In the initial single-cell testing, butyl tape served as the primary sealant, and no additional clamps were used.

For a more extensive overview refer to Appendix E, “Single-Cell Embodiment”.

Single-cell embodiment design study:
After establishing the materials of the prototype, the next step involved introducing the different prototypes that had been subjected to testing. These variations were crucial for understanding the practicality and efficiency of specific design choices. They focus primarily on two key aspects:

- **Variations in encapsulant liquids**
  The encapsulant liquids chosen for this study were a glycol-water mixture and Fluorinert (produced by 3M), primarily for their known thermal and optical properties, as introduced in Chapter 4.2. The glycol-water mixture was selected to assess the effectiveness of corrosion inhibitors in protecting the metal components of the solar cell, while Fluorinert was chosen for its notably low viscosity. Additionally, these liquids had been selected for their refractive indices, which match the glass's. This match was expected to increase the efficiency of the solar cells due to the high light transmittance of the prototype. At this stage of the study, oil-based liquids were excluded due to their significantly higher viscosity, with the intention of exploring them in future iterations once successful application with lower-viscosity liquids is established.

- **Variations in sealing thickness**
  Two internal gap thicknesses, 0.5 mm, and 1 mm, were evaluated in this study. The purpose of testing these two thicknesses was to determine their effectiveness in the encapsulation process and to assess how well they contribute to the complete saturation of the solar cell by the liquid encapsulant. This analysis is focused on determining which thickness provides the most effective sealing while also considering factors like filling effectiveness, material use, and structural integrity.

5.2 | Single-cell Testing

5.2.1 - Methodological Approach

The testing objective is to design, construct, and analyze a novel PVT-panel architecture revolving around the usage of direct liquid PV encapsulation. The tests combine quantitative and qualitative data to address these aspects, focusing on experimental data gathered through controlled testing and observations. In this research, three fundamental methods were employed to analyze the novel PVT-panel: A) Investigating Cell Degradation through close-up photographic analysis to assess cell longevity and corrosion; B) Evaluating Panel Construction Rigidity by examining the liquid filling process, sealing effectiveness, and structural robustness; and C) Assessing Cell Performance by measuring key metrics like the IV curve and panel temperature, both with and without the liquid encapsulation.

The testing approach for evaluating solar cell prototypes involves the following steps:

- Thickness Control During Sealing: The thickness of the seals was accurately measured using a digital caliper.
- Initial Setup: The solar cell prototypes are placed in a leakage tray equipped with syringes to handle injection and prevent spills.
- Temperature Measurement: An infrared temperature meter is used to record the initial temperature of the prototypes, ensuring they are at or close to room temperature.
- The filling of the prototypes with liquids was done using two syringes. One syringe injected the liquid into the prototype, while the other syringe simultaneously drew air out from the opposite end. This process ensured a controlled and smooth filling, minimizing air bubbles.
- Testing Process: The tests are conducted on two types of modules – single-sealed 0.5 mm and double-sealed 1mm. Each module is tested with different liquids, glycol, and Fluorinert. The tests involve measuring various parameters before and after the liquid introduction, allowing comparisons with an air-insulated panel.
- Data Collection: All tests are conducted using a PVMD-Cell tester, which measures critical parameters such as voltage, current, and power output under controlled conditions of light intensity and temperature.

This approach ensures a thorough evaluation of the solar cell prototypes, focusing on sealing effectiveness and overall performance under simulated operational conditions. For detailed procedures, on the testing approach and reflection, please refer to Appendix G, Explain the testing approach for the single-cell prototypes. The next section will provide additional insight into the data collection step of the testing approach.

5.2.2 - Data Collection Methods

To ensure a clear image of the relevant data collected during the testing, this section will highlight the three main data aspects. Each of these data collection points are presented and elaborated below.

A) Cell degradation: By capturing photographs of the prototypes before, during, and after testing, it was possible to identify immediate signs of corrosion. For cell degradation analysis, data was collected through visual inspection. This included capturing close-up photographs and videos of the panel before, during, and after testing to identify corrosion and check the effectiveness of the liquid PV-encapsulation process. Post-testing observations were made once the liquid had evaporated to assess any deterioration, structural weaknesses, or irregularities.

B) Panel construction rigidity: This includes evaluating the liquid filling, the effectiveness of sealing mechanisms, and ensuring the panel's robust construction. Filming the filling sequence and inspecting for leaks or air gaps revealed if satisfactory construction of the prototype was established. The prototype was visually inspected during testing to identify any signs of immediate issues or vulnerabilities, with a particular focus on detecting signs of air or leakage. After testing, a second visual inspection was conducted to assess the panel for potential structural weaknesses, or irregularities.

C) Cell performance: This involves measuring key metrics such as the IV curve (efficiency), and the overall panel temperature. Measurements are taken twice; reference measurements without the liquid and with the liquid. The solar cells' current-voltage (IV) curve was measured using a PVMD-Cell tester with a 4-point probe method, capturing key performance indicators such as Voc, Isc, Pmax, and FF. This provided insights into the efficiency and electrical characteristics of the cells. Additionally, an Infrared (IR) temperature sensor was used to non-invasively measure the panel's surface temperature during different operational conditions, helping to understand the thermal effects of the encapsulant. Prior to analysis, the collected data was refined by excluding outliers. Efficiency comparisons were made between measurements taken with and without the liquid encapsulant, using the formula Gain = (Final Efficiency - Reference Efficiency) / Reference Efficiency. This comprehensive data collection approach enabled a detailed understanding of the panel's performance, structural integrity, and potential areas for improvement.

In summary, each method was selected based on its ability to effectively answer the research questions (see chapter 1 "general introduction"). It provided the rationale for focusing on specific aspects of the panel's design and performance while detailing the practical steps taken to gather relevant data and insights.

5.2.3 - Results and Discussion of Single-cell Testing

Using the testing criteria and relevant data points highlighted in the previous sections the first results of this study can be presented in this section. The results of the three main data points are addressed below.

A) Cell degradation: A clear sign of corrosion was observed on the cells after the evaporation of the glycol mixture, as shown in Table 5, Single-cell performance test results stationary Glycol-water mixture. In contrast, the cells tested with fluorinert displayed no signs of corrosion after liquid evaporation, detailed in Table 6, Single-cell performance test results stationary FC-72.

B) Panel construction rigidity: The filling sequence was satisfactory, ensuring the proper integration of the liquid encapsulant into the entire panel. During testing, both 0.5 mm thickness seals exhibited clear signs of air and liquid leakage. The 1 mm thickness seal displayed leakage specifically with the glycol water mixture. The butyl tape, utilized for sealing, demonstrated flexibility issues, revealing vulnerable points in the panel structure, especially for the glycol-mixture prototype.

C) Cell performance: The subsequent gain calculations, based on reference measurements, provide insights into the impact of direct liquid PV encapsulation on cell efficiency. This concise presentation offers a clear overview of the experimental outcomes, crucial for understanding the effectiveness of the novel PVT-panel architecture. For a complete overview, the single-cell test results are presented in Appendix F, "Single-cell test results".

Table 5, Single-cell performance test results stationary Glycol-water mixture

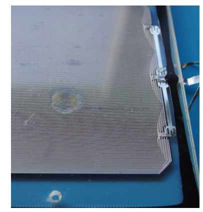
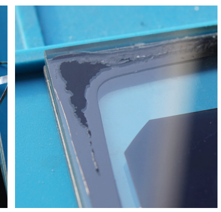
C) Cell Performance: test results	Panel 1 with air gap	Panel 1 glycol-mixture	Panel 2 with air gap	Panel 2 glycol-mixture	**A) Cell degradation & B) Panel construction rigidity**
Seal/gap thickness (mm)	0.5	0.5	1	1	**A)** Single-cell visual test results Glycol-mixture:
Efficiency (%)	19.3	21.3	19.5	20.6	Clear sign of corrosion after liquid evaporated
Post-test temperature (degrees)	25	24	25	25	 
Gain (%)	Reference measurement	+10.1%	Reference measurement	+5.8%	**B)** Sign of delamination and leakage

Table 6, Single-cell performance test results stationary FC-72

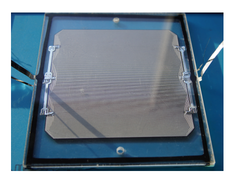
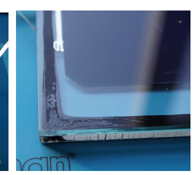
C) Cell Performance: test results	Panel 3 with air gap	Panel 3 FC-72	Panel 4 with air gap	Panel 4 FC-72	**A) Cell degradation & B) Panel construction rigidity**
Seal/gap thickness (mm)	0.5	0.5	1	1	**A)** Single-cell visual test results fluorinert:
Efficiency (%)	20.2	21.0	19.5	20.6	No signs of corrosion after liquid evaporated
Post-test temperature (degrees)	24	24	24	23	 
Gain (%)	Reference measurement	+4.0%	Reference measurement	+5.3%	**B)** Some signs of delamination and leakage

Table 5 and 6 reveal that replacing the intermediate air encapsulant with a specifically optically matched liquid enhances single-cell PV performance. The results align with expectations, supporting the hypothesis that the optically lower mismatched liquid improves panel performance.

While the study contributes valuable insights, certain limitations need acknowledgment. The presence of a leakage tray inhibited direct cell temperature measurements, necessitating the usage of IR measurements resulting in less accurate readings. Additionally, the absence of measurements without a glass front panel and a reference panel with a traditional laminated design limits the comprehensive comparison of performance. Time constraints hindered testing with other liquids like Silicone and Mineral oil. Further, conducting prolonged tests with the same prototype is necessary to gauge potential performance degradation resulting from observed corrosion. See Appendix G, "Explain the Testing Approach for the Single-cell Prototypes Test Setup" for a full overview of the setup.

Given the significant impact of temperature on solar panel performance, future tests should prioritize a thorough analysis of the thermal behavior of prototypes. This entails frequent and precise temperature monitoring in various locations during upscaled testing. Implementing thermistors and thermal imaging cameras can enhance thermal imaging accuracy. Additionally, incorporating a manometer to measure system pressure can provide valuable insights into the overall system dynamics. These recommendations aim to refine testing methodologies and contribute to a more comprehensive understanding of liquid-encapsulated panel performance.

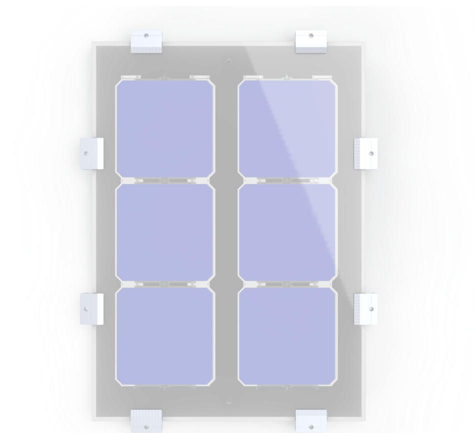
5.2.4 - Conclusion

The obtained results presented promising advancements, in the design and functionality of liquid-encapsulated PV panels. Increased efficiency was observed with the use of both glycol and fluorinert, indicating the viability of liquid encapsulation as a concept. The filling and subsequent testing of the prototypes proved to be generally successful. However, the experimentation process revealed critical areas for improvement and learning, particularly in the choice of materials and construction methods.

A key finding was the unsuitability of glycol due to its tendency to cause corrosion, leading to the elimination of water-based mixtures in future designs. Instead, the focus will shift to fluorinert or oil. The choice of oil is more substantiated by its superior insulation capabilities and lower cost. Additionally, the use of butyl tape as an adhesive was found to be inadequate, highlighting the need for a more effective sealing solution. Opting for a double-material seal, and potentially incorporating a stronger adhesive such as silicone, could address the identified sealing issues.

Looking forward, further tests are essential to refine the panel's adhesion, rigidity, and liquid flow. The limitations observed with butyl tape point towards exploring more robust adhesives. These findings form the basis for the next phase of development, where the focus will be on enhancing the panel design through material innovation and advanced construction techniques.

Chapter 6 | Small-scale Module Testing



Chapter 6 shifts focus to a new aspect of the research: scaling up to a multi-cell module. This expansion was a strategic move to combine and integrate the results from chapter 5 with a larger solar module design. The latter provided a more representative exploration of design opportunities for the novel liquid-encapsulated panel architecture outlined in the research question.

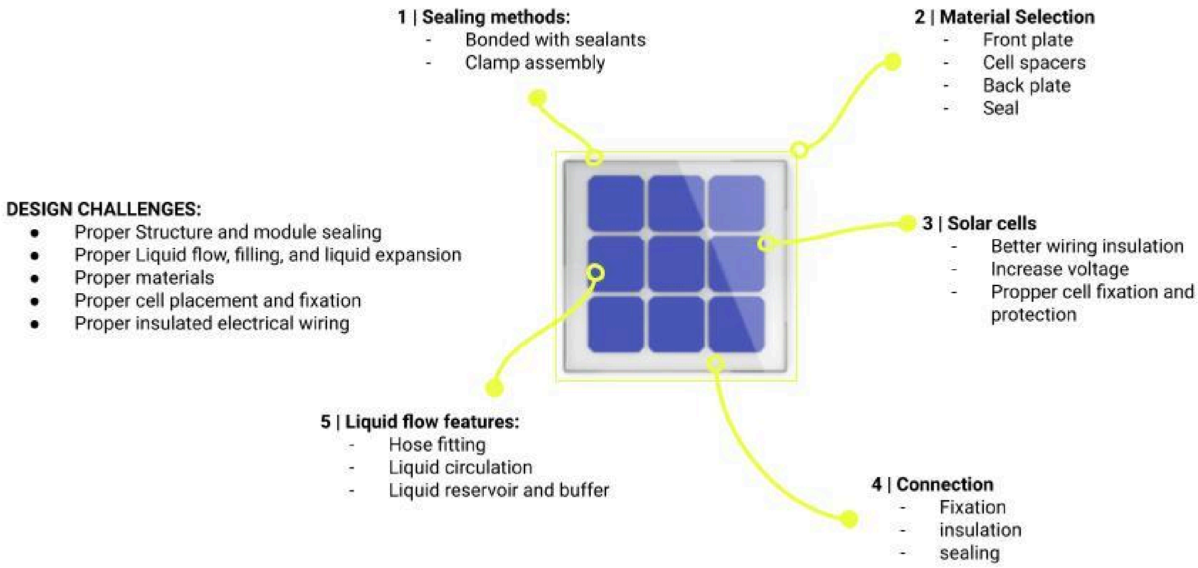
The expanded array of cells and larger module area also allowed for more extensive testing, especially in terms of thermal stability and heat exchange. (2. Identify opportunities for thermal exchange with liquid encapsulated PV module design.) By increasing the number of cells it became more prominent to identify the opportunities for thermal exchange, while similarly being able to be tested on the larger solar simulator.

For evaluating the performance of the small-scale module, with the assistance of a solar simulator to thoroughly analyze both the thermal and optical performance. The choice of a 6-cell module was strategic, meeting the minimum size requirement for using the solar simulator at the PVMD, better suited for thermal (stress) testing.

This involved assessing the stability and thermal distribution across the six-cell module under extreme heat exposure. The study will focus on the uniformity of thermal behavior and flow within the larger setup, providing insights into the scalability of the thermal management system. This includes a thorough evaluation of the liquid encapsulation process across multiple cells, the effectiveness of sealing mechanisms, and the overall robustness of the module.

6.1 | Concept Upscaling and Evolution

This chapter built upon earlier sections, with the shift towards scaling up to a larger module introducing new product challenges. Figure 11, Module overview played a role as a guiding map, systematically addressing every aspect of the new design. This comprehensive exploration of aspects is detailed in Appendix I, titled "Module Embodiment".



(Figure 11, Module overview)

Multi-cell module embodiment design choices:
The development of the multi-cell module involved careful consideration of material selection, as detailed in Appendix I, "Module Embodiment." While some material choices remained consistent with the single-cell prototype, key modifications were made to better align with the requirements of a larger module and with the learnings of previous tests.

Front Panel - 4 mm Tempered Glass: The transition from normal float glass to 4 mm tempered glass for the front panel was made to better resemble real solar panels using tempered glass. The thickness of the acrylic backplate was increased from 4 mm to 5 mm, providing additional strength and rigidity to support the larger module size. Additionally, with the thicker 5 mm backplate, the screw-in couplers can engage with more threads, providing a stronger and more reliable attachment. A dual-sealing approach was employed, using butyl tape on the outer side for its proven effectiveness and neutral white silicone inside for additional sealing and protection. This combination was expected to enhance the overall sealing integrity of the module, which had been proven successful on a dummy small-scale panel in Chapter 3.4.

Besides the use of a double seal, another extra feature was added to enhance the protection of the cells against shocks and to aid the manufacturing process. At the ends of each busbar, 10x5x1 mm (Blue)rubber pieces were attached with silicone glue, as referred to in Figure 12, Rubber cell strain relief. When the panel was sandwiched together, these rubber pieces became slightly squeezed, keeping the cells stationary and establishing strain relief on the output terminals. This approach was chosen over using plastic spacers, which, while functional, would have been more time-consuming to implement and could hinder the flow of the liquid encapsulant. The selected method offered a quicker and more efficient solution, allowing the focus to remain on liquid-encapsulated testing.

Figure 12, Rubber cell strain relief

Multi-cell embodiment design study:
In the multi-cell study, the variations from previous testing encompass the utilization of higher viscosity oil. The tests will be conducted both with and without(air reference) the presence of silicone oil (XIAMETER™ 561 Silicone Transformer Liquid). Additionally, the investigation involves the measurement of the IV curve across a range of temperatures as the panels heat up. Notably, during this testing phase, a dynamic approach will be employed whereby fresh cool oil is introduced to the panel after it heats up, allowing for an assessment of its effects on performance and thermal exchange.

6.2 | Module Testing

6.2.1 - Methodological Approach

Building upon the approach outlined in 5.2.1 - Methodological Approach, the methodology for the 6-cell model follows a similar pattern with some specific adaptations: A) Cell Degradation; B) Panel Construction Rigidity; and C) Module Performance.

A key adaptation in this test is the extended duration, designed to more rigorously assess the module's endurance. Therefore the use of a solar simulator, known for its high infrared output, is used. This simulator rapidly heats the module, enabling a quicker and more controlled approach to reaching the target temperature. The testing will continue until the panel reaches a temperature of 60 degrees Celsius. At every 10-degree increment in temperature, the current-voltage (IV) curve will be measured, providing detailed insights into the panel's performance under increased thermal stress.

6.2.2 - Data Collection Methods for Module Testing

Similar to section 5.2.2, to ensure a clear image of the relevant data obtained during the testing phase, the three main data collection aspects are depicted and elaborated below.

A) Cell degradation: By capturing photographs of the prototypes before, during, and after testing, it was possible to identify immediate signs of corrosion. For cell degradation analysis, data was collected through visual inspection. This included capturing close-up photographs and videos of the panel before, during, and after testing to identify signs of corrosion and check the effectiveness of the liquid PV-encapsulation process. Post-testing observations were made once the liquid had evaporated to assess any deterioration, structural weaknesses, or irregularities.

B) Panel construction rigidity: This includes evaluating the liquid filling, the effectiveness of sealing mechanisms, and ensuring the panel's robust construction. Filming the filling sequence and inspecting for leaks or air gaps revealed if satisfactory construction of the prototype was established. The prototype was visually inspected during testing to identify any signs of immediate issues or vulnerabilities, with a particular focus on detecting signs of air or leakage. After testing, a second visual inspection was conducted to assess the panel for potential structural weaknesses, or irregularities.

C) Module performance: The module's performance was analyzed using a two-point IV-curve tracer. The efficiency measurements were taken both with and without the liquid encapsulant, allowing for comparative analysis. The temperature of the module was monitored using a thermistor. For air reference measurements, the thermistor was placed underneath a solar cell. In contrast, for oil measurements, it was positioned at the center of the panel. The temperature data, collected before and after each test, provided important insights into the thermal behavior and influence on the power output of the module during experiments.

In summary, the methodology reinforces the validity of Multi-cell liquid encapsulation, focusing on oil-based liquids with higher viscosity. Tailored to assess performance under extensive thermal load. Tests across various temperatures and analysis of heat-up effects offer an evaluation of the module's (thermal) behavior.

6.2.3 - Results and Discussion

This section presents the testing outcomes of the newly developed six-cell prototype. The results of these tests, detailed in Appendix J, "Module Test Results," have provided crucial insights into the scalability and practicality of the proposed solar panel design.

A) Cell degradation: When utilizing silicone oil as the encapsulant, no immediate or subsequent signs of cell degradation were observed, indicating its effectiveness in preserving short-term cell integrity.

B) Panel construction rigidity: The filling sequence of the panel with the liquid encapsulant, in this case, silicone oil, was executed effectively. When the oil temperature reached 35 degrees Celsius, it became sufficiently less viscous to fully permeate the panel, ensuring complete coverage.The outcomes of the tests were promising, particularly in terms of efficiency. Refer to Table 7 for detailed module performance results using silicone oil. The table indicates a significant improvement in efficiency compared to the initial reference test with just an air gap encapsulant, as shown in Table 6 for single-cell performance. The sealants employed were unable to withstand temperatures exceeding 55 degrees Celsius, resulting in delamination of the sealants. These findings once more emphasize the critical need for optimizing sealant materials and composition to withstand higher temperatures.

C) Module performance: The efficiency of the panel varied with temperature, showing an initial increase and then a gradual decrease as temperatures rose. For instance, under air conditions at 20°C, the efficiency was recorded at 16.86%, which decreased to 14.50% at 60°C. In contrast, the module encapsulated with oil demonstrated higher efficiency levels, starting at 18.18% at 27.5°C and gradually reducing to 16.20% at 50°C.
The comparison with air conditions underscores the effectiveness of the liquid encapsulant in improving the overall performance of the solar cells.

Table 7, Module performance test results - silicone oil

Test 1 air reference	**Time / duration**	**Temperature (C)**	**Eta[%]**	**Test 2 silicone oil**	**Time / duration**	**Temperature (C)**	**Eta[%]**
	0	20	**16,9**		(Extra measurement)	30	**16,4**
	3 minutes and 30 seconds	30	**16,4**		0	27.5	**18,2**
	5 minutes and 33 seconds (2 minutes 3 seconds)	40	**15,7**		2 minutes 7 seconds	35	**17,3**
	8 minutes and 18 seconds (2 minutes 45 seconds)	50	**15,1**		3 minutes 43 seconds (1 minute 36 seconds)	40	**16,0**
	11 minutes and 57 sec (3 minutes 39 seconds)	60	**14,5**		6 minutes 23 seconds (2 minutes 40 seconds)	50	**16,2**

Table 7 presents the module performance test results of silicone oil. It's important to note that compared to the single-cell testing, the efficiency observed in the multi-cell setup is significantly lower. This discrepancy is attributed to the positioning of the module during single-cell measurements, where a leakage tray elevated the panel, inadvertently enhancing its efficiency. The key metric is the efficiency difference between air and liquid measurements, not absolute values, which again showed promising elevated results. Unfortunately, thermal liquid flow behavior couldn't be assessed as the panel delaminated before conducting liquid loop assessments.

6.2.5 - Conclusion: The application of liquid encapsulation, particularly using silicone oil, has demonstrated a notable increase in the solar cells' light absorption capabilities, leading to an enhanced output. The use of silicone oil as an encapsulant improves the efficiency of solar panels by altering the path of sunlight. Due to its higher refractive index compared to air, the oil changes the angle at which light enters the solar cells. This effect minimizes the amount of light that is reflected away and maximizes the light penetration into the solar cells.

Both the liquid-encapsulated and non-encapsulated panels exhibited similar thermal characteristics, heating up at comparable high rates. This is due to the high infrared output from the solar simulator used in the tests, combined with the absence of wind or any additional cooling mechanisms in the setup. Therefore, while the static presence of the oil shows promise in theory due to silicone oil having a higher thermal conductivity (0.151 W/m·K, chapter 4.1 Liquid Selection) compared to air (0.025 W/m·K), its effectiveness in transferring heat from the cells to both the front and back panels, and subsequently facilitating heat dissipation, remains unvalidated under these test conditions without additional actual wind.

In terms of the structural integrity of the module, specific strategies need to be explored and employed to enhance rigidity, such as elongating the panel and applying additional adhesive or fasteners at weak points. These considerations become more prominent due to the complexity introduced by scaling up the concept emphasizing the importance of resolving sealing and rigidity issues for the successful implementation of larger-scale modules.

Moreover, the larger module configuration introduced new electrical challenges, notably the elevation in voltage due to more cells connected in series. With the increase in the number of free-floating cells, additional measures to secure and protect these cells from shocks and vibrations were necessary, necessitating careful attention to the mechanical aspects of the design.

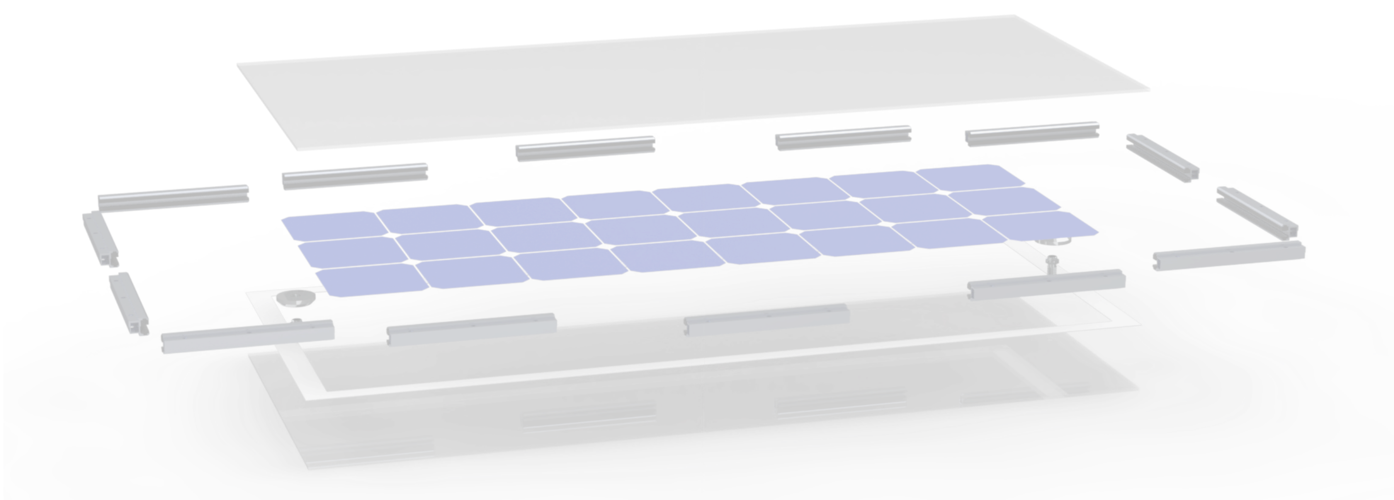
Chapter 7 Full-scale Product Development

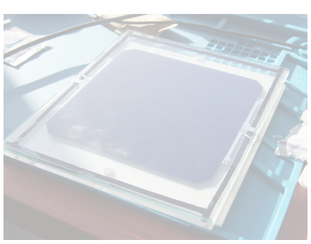
Chapter 7 presents a broad overview of how the novel PVT-panel concept transitions from an initial idea to a larger-scale model. This chapter focuses on general predictions regarding pricing, market appeal, and potential differences in design and function. Additionally, chapter 7 revisits the initial research questions, building upon earlier chapters that have highlighted the effectiveness of silicone oil and methods for promoting thermal exchange. Based on these insights, the chapter outlines the development of a more complete module design. It includes the introduction of a visual prototype section, emphasizing specific features that demonstrate the next design.

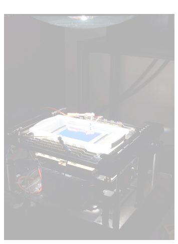
Section 7.1 is dedicated to the transition from a PV module to the conceptualization of a large-scale panel. The technical specifications and design elements necessary for upscaling the concept were explored and documented. Additionally, the section provided an economic analysis, highlighting the financial implications and cost estimation. This examination aimed to present an objective and detailed overview of the process, from a prototype to a commercial product, emphasizing both technical feasibility and economic viability. The embodiment of the final design, encompasses the final geometry, material selection, and technical details. The concept is further enriched with CAD models and renders.

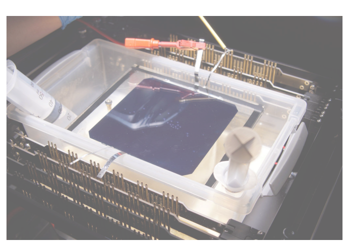
Section 7.2, titled "Concept Reflection," evaluates the final concept of a liquid-encapsulated PV module, concentrating on its technical feasibility, economic viability, and desirability. The desirability assessment encompasses not only the market appeal and consumer interest but also includes environmental impact.

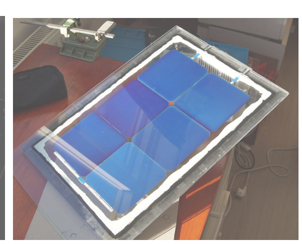
Section 7.3, 'Recommendations', summarized the key insights and experiences from the development of liquid-encapsulated PV modules. This chapter offers a set of recommendations based on the lessons learned during the project, aimed at guiding future research and development in this field

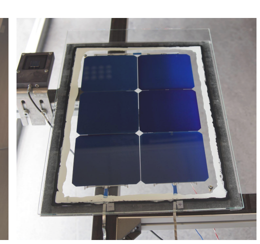












7.1 | From PV module to Large-size Module

During the research, a series of tests were carried out, initially on single-cell prototypes and later on multi-cell modules. The objective of these tests was to develop a configuration for liquid PV encapsulation. This involved creating a robust system specifically tailored for the integration of liquids within a PV-panel architecture. The secondary objective was to validate the hypothesized benefits of liquid encapsulation, particularly in terms of efficiency and thermal advantages. The following section elaborates on the technical aspects of the final concept, building on the research and activities undertaken. It aims to provide a detailed overview of the design, functionality, and technical specifications, presenting a clear understanding of the newly envisioned system.

7.1.1 - Geometry

The final design of the full-scale module features a stretched configuration of 3x8 Interdigitated Back Contact (IBC) cell arrays. This layout was chosen to optimize both the functional and aesthetic aspects of the panel. The dimensions of the front and back panels were set at 1100x475 mm, a size carefully calculated to ensure optimal spacing for the cells. The chosen dimensions allowed for sufficient space around the edges of the panel, accommodating options for thicker seal variations. The elongated design was strategically chosen to increase its rigidity. By extending the panel's length, the distance between the sealed edges is reduced. This reduction in distance plays a role in distributing pressure more evenly across the panel. The geometry also played a role in optimizing the liquid encapsulant flow. The elongated shape streamlined the flow path, promoting liquid circulation within the panel. Beyond the technical advantages, the unique shape of the panel contributed to its aesthetic value. The design distinguished the panel visually, creating a unique look, refer to Figure 13, Final geometry. Although this was not the primary focus of the assignment, the aesthetic appeal emerged as a pleasant, unintended side feature, potentially adding meaning beyond its functional design.

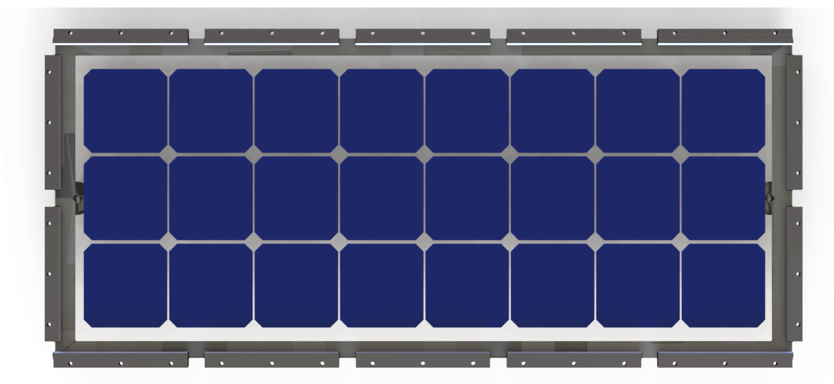


Figure 13, Final geometry

The decision to adopt a larger panel size in the final design is based on specific considerations aligning with the design goals and research objectives. Primarily, the challenge of maintaining rigidity, the selected dimensions for the 3x8 IBC cell array, with a focus on elongation, effectively reduces the distance between the seals. This reduction could potentially enhance rigidity, compared to a more traditional rectangular-shaped panel.

Furthermore, the larger panel size more easily facilitates outdoor testing with a Smart MPPT (Maximum Power Point Tracking) solar charger. These chargers are adept at measuring performance over extended periods but often require a minimum voltage of around 12 volts, a threshold more easily met by the larger panel. The increased size not only meets the voltage requirements for low-cost outdoor testing but also provides a broader canvas to observe and measure the panel's thermal exchange capabilities. The larger cell module, by its size, generates more heat, allowing for a more sizable and comprehensive assessment of thermal yield. This is crucial for comparing its performance with other systems, a task that would be more challenging with a smaller, uncommon 6-cell module.

7.1.2 - Cooling

In the final design, the integration of the cooling loop was more established. A significant modification was made to the back panel of the solar module, which involved drilling an 8 mm hole in the glass before its tempering. On this side of the panel, a 7,5 mm thick aluminum disk, with a 40 mm diameter, was secured using a high-strength epoxy adhesive. The aluminum disk, characterized by its chamfered design, featured a machined hole with a G1/4 thread, conforming to the British Standard Pipe dimensions. The aluminum disk facilitated the attachment of hose fitting (or end plugs), which was compatible with a 10 mm inner diameter hose. This setup provided the flexibility to attach end caps or various adapters, enhancing the panel's adaptability and future-proofing the design. For a detailed understanding of the components and their assembly within the solar panel, refer to Figure 14 titled "Hose fitting connection."

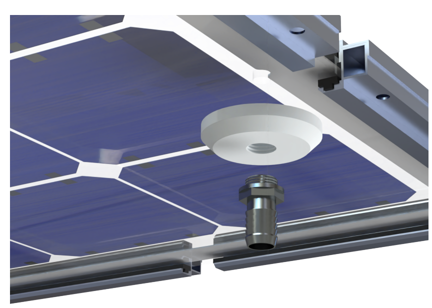


Figure 14, Hose fitting connection

The G1/4 thread was selected for its standardization in hose adapter couplings, ensuring wide compatibility. While alternatives like polycarbonate and plexiglass were tested, aluminum was ultimately chosen for the disk adapter. These were tested for suitability, as presented in the accompanying Figure 15, Hose fitting options, and final design. This decision was driven by two key factors: aluminum's superior UV resistance and its stronger adhesion with epoxy compared to polycarbonate and plexiglass.

Figure 15, Hose fitting options and final design

7.1.3 - Sealing

In response to the specific needs presented, a sealant manufacturer recommended using HelioSeal™ PVS 101 (ADCO), a commercially available sealant known for its thermal stability and durability. This suggestion was made considering the product's suitability for the solar industry. HelioSeal PVS 101 is compatible with various materials and stands out for its strong chemical bonding and ability to withstand heavy loads. These qualities ensure that it can maintain a tight seal over a long period, improving the durability of the final product.

For the inner seal, it's crucial to use a neutral-curing silicone sealant. Unlike acetone cure silicone, which releases acetic acid and can corrode metals and damage electronics, neutral cure silicone emits non-corrosive byproducts, possibly more compatible with solar cells and busbars. The specific shape of the final inner silicone seal, as illustrated in Figure 16, Final seal shape, has been selected to strike a balance between promoting flow guidance and creating sufficient space for solar cells.

figure 16, Final seal shape

7.1.4 - Buzzbar Connection

In the past, the busbar connection was made through the outer seal, applying sealant both underneath and on top of the busbar. This approach often leads to leaks and is considered too risky. Therefore, a new method has been developed. This approach is similar to how hose connections are made. The connection now uses a small aluminum disk, 5 mm thick with an outer diameter of 25 mm and an inner diameter threaded for an M5 screw. A flat-headed M5 screw with an O-ring is screwed into the disk. This screw, preferably made of copper for low resistance, extends into the panel to connect with the busbar, which has silicone underneath for providing pressure back into the screw and providing a reliable connection (refer to Figure 17, for Section view novel busbar panel connection system). Additionally, a silicone piece is glued at the end of each string where the busbars protrude to protect the solar cells from shocks and vibrations. This acts as strain relief and keeps the cells securely in place, similar to what is done in the smaller-scale module. This change improves the panel's durability making it more resistant to shocks and vibrations.

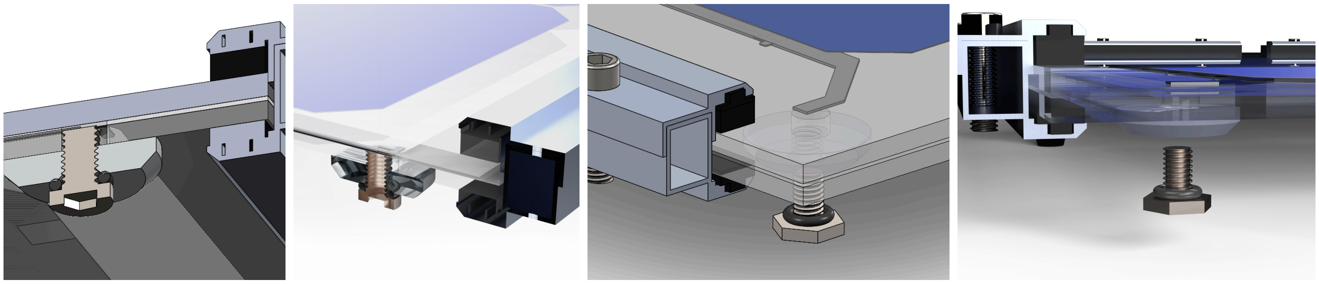


Figure 17, Section view novel busbar panel connection system

This feature, closely resembling the design of the hose adapters but in a smaller form and located in the corner, originated from the need for a more reliable busbar connection. With the potential of advanced solar-grade sealing, this particular design might become redundant in the future. However, its current implementation enhances the panel's modularity, as it relies on a mechanical seal using screws and O-rings, making it able to connect and disconnect the busbars without altering the outer seal.

7.1.5 - Panel Rigidity

The panel's design includes an optional two-section aluminum clamp extrusion frame along its edges. While these clamps are optional, they enhance the panel by providing additional physical protection and maintaining continuous pressure on the seals. Advanced industry-grade solar seals might eliminate the necessity for these clamps, yet they offer several benefits. They ensure better corner protection and, when used with (non-stick) pressure seals, significantly improve the panel's ease of assembly and disassembly, thereby increasing its repairability (refer to Figure 18, for Clamp design). Future testing, focusing on more advanced and broader seals along with a deeper emphasis on disassembly ease, will determine whether the clamps are advantageous or if they represent an overly resource-intensive and excessive solution.

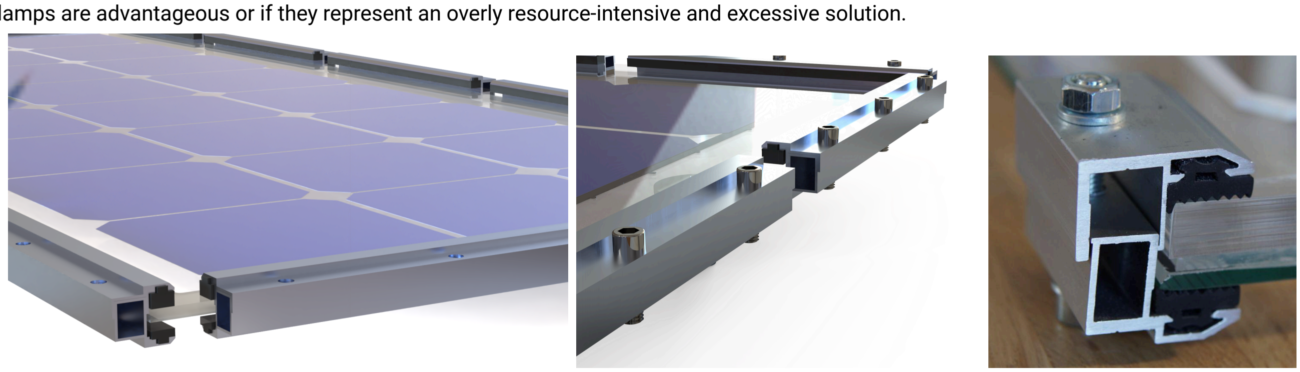


Figure 18, clamp design

To secure the cell array and provide shock protection, soft-cured silicone flat strips are strategically placed at the end of each string. When the panel is assembled, these strips ensure that the busbars and cells are held firmly in place, maintaining connections and offering shock protection. This approach was chosen over alternatives like mounting spacers on the glass, as it avoids the time-consuming and labor-intensive process of fixing spacers. Additionally, the flexibility of silicone offers a more forgiving solution compared to a rigid spacer, adapting better to various conditions and reducing the risk of damage refer to Figure 19, Silicone busbar-cell fixation.

Figure 19, Silicone busbar-cell fixation

The utilization of silicone busbar fixation not only serves its fixation purpose but also presents a promising feature for enhancing the modularity of larger modules. Unlike the conventional method of soldering each cell string together, the silicone pads allow for the overlapping and compression of busbars. This new approach facilitates easier solder-free replacement of a cell string within the module. This concept draws inspiration from the design proposed by Majdi et al. in 2021. Refer to Figure 20, Silicone busbar-cell modularity, for an illustration of the modular pressure connection and fixation.

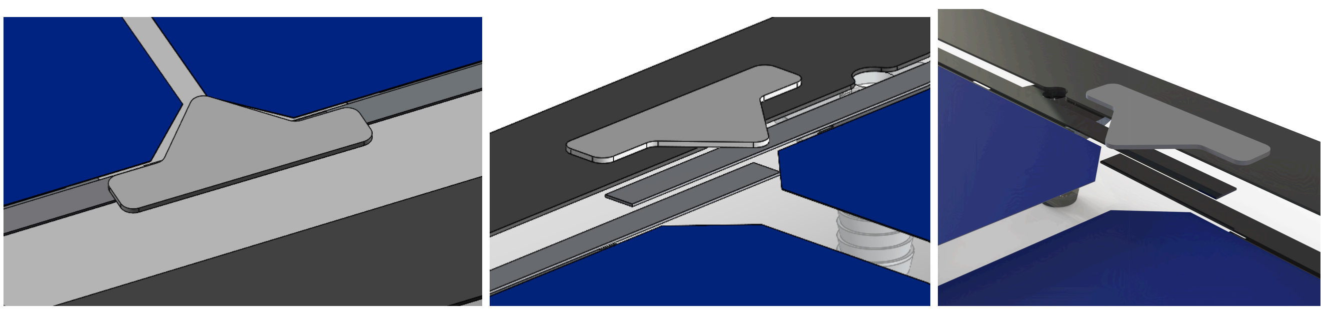


Figure 20, Silicone busbar-cell modular connection.

7.1.6 - Materialisation

Both the front and back panels were made of 4 mm tempered glass, chosen for its durability. The back panel was specially manufactured with pre-drilled holes to accommodate the liquid cooling loop and electronic connections. On the front glass panel, an anti-reflection coating was applied. The clamps are extruded from aluminum, a method well-suited for creating their elongated, uniform shapes. In contrast, the hose adapter disks are precisely machined out of aluminum. It's important to note that aluminum is a recyclable material, adding an element of sustainability to the choice of this material for both components.

7.1.7 - Economics

This section covers the economics starting with a rough estimate of the costs associated with the final concept. This estimate is based on prices that reflect bulk buying, where purchasing larger quantities results in lower per-unit costs. The breakdown includes both the core components of the solar panel and the additional elements of an integrated cooling system. These components enhance the panel's efficiency and incorporate the PVT functionality making it a potentially more cost-effective solution in the long term.

The power output of the final solar module, comprising 24 Maxeon Sunpower monocrystalline solar cells, produces approximately 80.16 watts (3.34 watts per cell). Increasing the cell count and size of the solar panel could potentially reduce the total cost per unit of power. However, the chosen size of chapter 7.1.1 Geometry, represents a strategic balance. This size inhibits increased power output while remaining manageable and practical for further testing purposes. Refer to Tables 8 and 9 for the panel material and cooling system cost predictions.

Table 8 Panel material costs

Panel component	Price (€)	Description
Tempered glass panels	20	Front and back panel
IBC Cells	12 (24 cells at 50 cents each)	Photovoltaic cell
Butyl and Silicone Sealant	5	Sealing
Aluminum Clamp Frame: 25 euros	25	Offers structural protection and additional seal pressure
Total	**62**	

N.B. The cost is 2023 euros.

Table 9 Cooling system costs

Cooling system component	Price (€)	Description
Silicone Oil	10	Improves thermal management, enhancing the panel's efficiency
Silicone Hoses	5	Connecting the cooling loop
Thermal Buffer Reservoir	200	Thermal buffer and expansion vessel
Hose Adapter, Connection Disk, and Epoxy	10	Necessary for connecting and securing the cooling system
Heat Exchange	100	Allows the panel to link with a heat pump system to utilize the absorbed heat
24V Pump	50	Circulates the coolant in the system
Controller Unit	50	Manages and controls the flow/cooling
Total	**425**	**Total panel + Cooling system =487**

N.B. The cost is 2023 euros.

The retail price for a traditional EVA-solar panel with similar cells and a power output of 200 watts, such as the SunPower 200Wp (*SunPower 200Wp*, z.d.), is approximately 220 euros. This suggests that the retail cost for such a panel with 80 watts of power output would be roughly around 88 euros. However, it's essential to recognize that this figure represents the retail price, which is distinct from the actual production costs. The material costs would likely be considerably lower. When considering only the panel costs, the precise difference is not substantial; the new concept probably is moderately higher. This increase can be attributed to additional sealing and clamps, the use of oil, and the incorporation of both front and back glass instead of just a front glass and a plastic backsheet.

The new large-scale PVT module system, at 487 euros, is more expensive than a traditional EVA-laminate panel. However, this cost could be justified by the increased functionality, potentially longer lifetime, and circularity(repair and recycling). The cooling system, particularly the silicone oil, can reduce thermal stress, prolonging the panel's life. The system's ability to utilize the absorbed heat in other applications adds extra functionality not present in standard panels. When compared to existing PVT panel systems, the cost difference becomes less significant. Recent on-the-market PVT systems are known for their premium pricing and justify their cost through dual functionality. Although the new liquid encapsulated system is still at a low Technology Readiness Level (TRL), indicating early development stages, it could hold promising potential. Especially notable is the possibility of creating a repairable system without sacrificing reliability, which could be a significant economic factor in its favor.

Chapter 7.2 | Concept reflection

This chapter offers a reflective analysis of the final concept. It examines the methodologies and outcomes of the testing on this innovative design. The tests have demonstrated the feasibility of the concept, however, this reflection underscores the need for more comprehensive and diverse testing in future research. The next goals in the development of the novel concept can be summarized as follows:

1. Panel seal optimization (Durability)
2. Optimize liquid encapsulation (Electrical and thermal performance)
3. Long-term testing (Durability)
4. Analyse thermal yield (Thermal performance)
5. Cooling loop mechanism (Thermal utilization)
6. Optimize structural design (Durability, performance & repairability)

1. Panel Seal Optimization (Durability): Engaging chemistry experts to experiment with various solar industry-grade sealants, such as silicone combined with HelioSeal™, is vital. These experiments could focus on small-scale, cell-free models, testing multiple seal configurations possibly under additional pressure to ensure a robust, leak-proof system. This step is crucial for enhancing the long-term durability of the panels.

2. Optimize Liquid Encapsulation (Electrical Performance): The goal is to refine the liquid encapsulant through chemistry expertise, aiming to boost performance and longevity without negatively impacting the solar cells. Testing at the single-cell module level, using tools like the PVMD cell tester, will help in optimizing the liquid for enhanced and long-term electrical performance.

3. Long-term Testing (Durability): Conducting outdoor long-term testing using small-scale modules, additionally in damp heat chambers, will evaluate the system's durability under varied environmental conditions. These tests will assess if the cells and the system can withstand thermal stresses over time. Additionally, chemistry experts should analyze whether long-term isolation of the cells occurs without corrosion. Special attention should be given to ensure the preservation of the encapsulant, materials, and the cells themselves preventing any deterioration. Implementing measures like an oxygen getter could mitigate potential issues.

4. Analyse Thermal Yield (Thermal Performance): Using a larger-scale module outdoors, the thermal yield can be effectively measured. Incorporating small-scale heat exchangers, flow control, and precise temperature sensors, the system can convert the generated hot oil to water, compatible with traditional heat pump systems, to evaluate its effectiveness in real-life scenarios.

5. Cooling Loop Mechanism (Thermal Utilization): Developing a small-scale cooling loop involving a thermally insulated liquid loop, a small heat exchanger and a thermal expansion buffer is essential. This mechanism will convert the hot encapsulant into hot water, facilitating its integration into more traditional heating systems. Doing so will shed light on the thermal capabilities of the new system and its competitiveness with traditional PVT systems.

6. Optimize Structural Design (Durability, Performance & Repairability): Post-sealing experiments, the necessity of aluminum clamps will be clearer. Therefore decisions on retaining or removing them will be more informed. The improved panel should also incorporate an anti-reflective coating on glass for a more direct comparison with traditional EVA laminate panels.

The novel PVT liquid-encapsulated panel's success largely depends on its durability through long-term testing. The main challenge is to increase its rigidity without compromising efficiency or significantly raising production costs. This panel's appeal lies in its lasting performance and innovative liquid encapsulation, which could distinguish it in the market. Key to its acceptance would be its aesthetic appeal, ease of installation, and maintenance. The economic viability of the liquid-encapsulated PVT panel depends on cost-effective production and operation and its market success will also hinge on operating lifetime and possibly minimal degradation.

7.2.1 - Environmental Impact

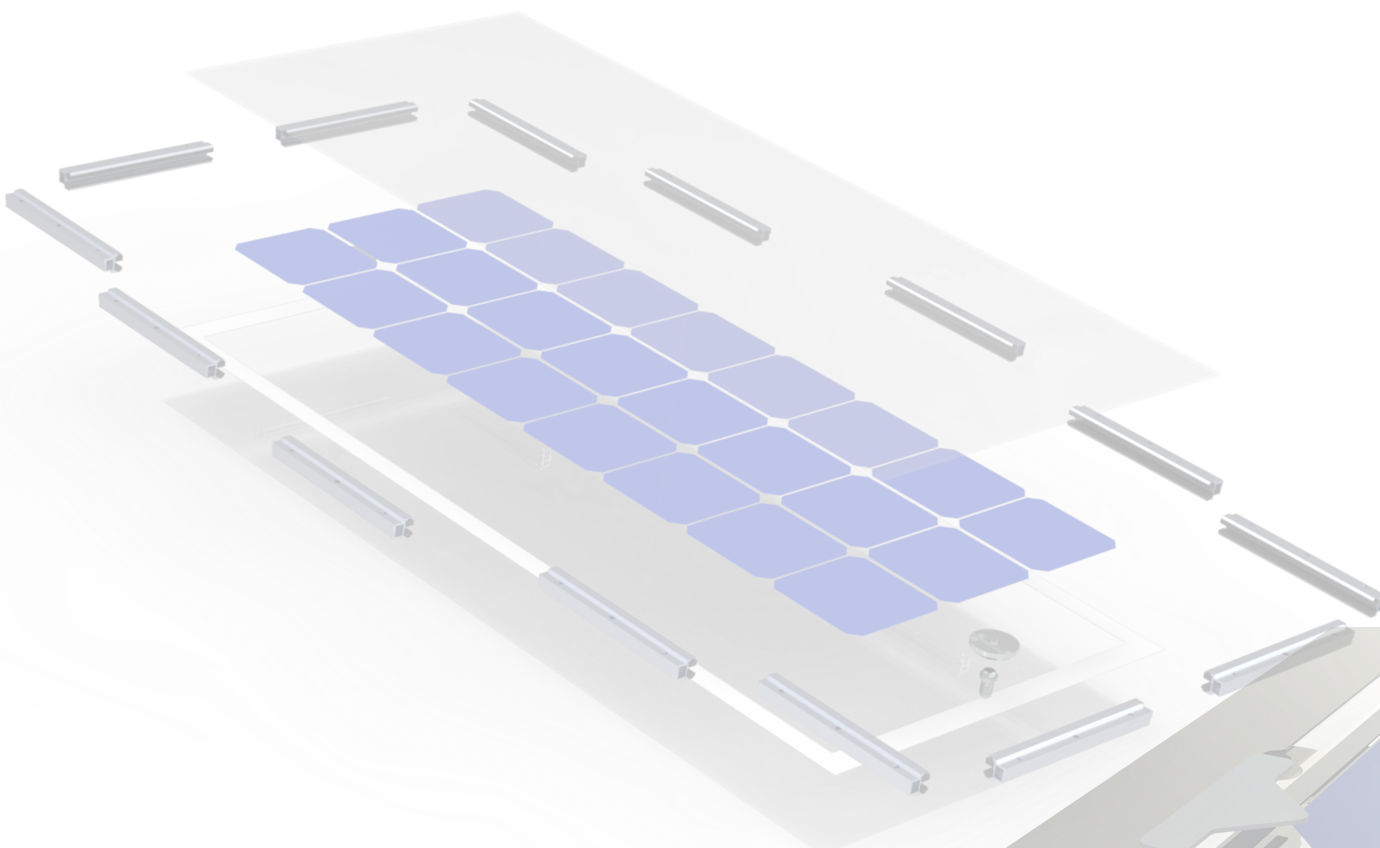
The environmental impact of the novel PVT liquid-encapsulated panel is multifaceted, presenting both potential benefits and challenges. One of the notable advantages is the enhanced recyclability stemming from the elimination of the EVA-laminate. This design choice simplifies disassembly and recycling processes, reducing the environmental footprint at the panel's life cycle end. Additionally, the absence of an EVA layer could mitigate delamination issues, potentially leading to a longer product lifespan. The primary challenge lies in determining whether the liquid encapsulation can protect the cells as effectively as EVA laminate, and ideally, even extend their lifespan.

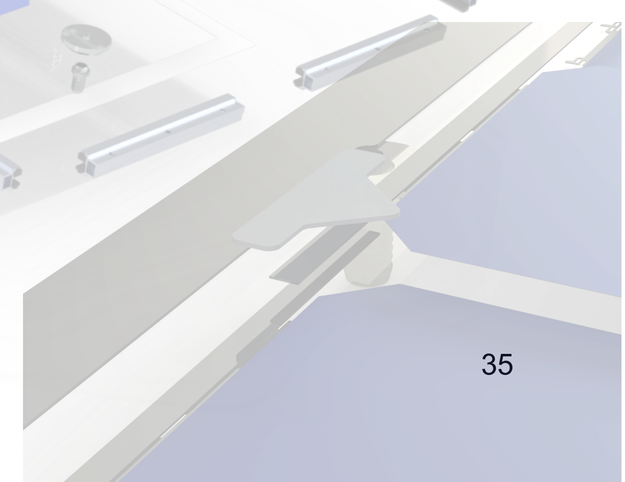
However, the overall construction of the panel could necessitate additional components or sealants for optimal functionality. These components, while essential for performance, might introduce complexities in manufacturing and recycling processes. It is important to carefully consider the final materials and design of these additional components to minimize any negative impacts.

The novel PVT liquid-encapsulated panel could present an environmental advantage when compared to current PVT panels, which typically utilize traditional PV modules(EVA)and metal radiators. These conventional components are expensive, and resource-intensive. To outperform current PVT systems, the new PVT liquid-encapsulated panels must meet precise design goals: Their efficiency should match with or exceed that of existing PVT systems, and their lifespan should be as long or longer. Achieving these benchmarks is crucial for these panels to stand as a superior alternative on the market.

In contrast to current PVT systems, the liquid-encapsulated panel design eliminates the need for metal radiators. By possibly minimizing metal usage, the new panel design contributes reduction of resources. An aspect for future research would be a comparative study of the thermal yield between the new liquid-encapsulated panels and traditional PVT panels. Such a study would provide valuable insights into the efficiency and sustainability of the new design, potentially highlighting its superiority in both performance and environmental impact.

Overall, while there are challenges to address, the integrated approach of electricity and heat generation, combined with improved recyclability, positions the liquid-encapsulated PVT panel as a potentially more sustainable option in the solar energy market.





Chapter 7.3 | Recommendations

If Biosphere Solar is committed to advancing the development of the liquid-encapsulated PV panels project, it is crucial to first engage experts in the relevant fields. These specialists should focus on optimizing sealing and encapsulation. With their expertise, the project can move into a phase of more testing and refinement. Biosphere Solar can proceed to evaluate the final concept features. This includes testing the features like the hose adapter connection and exploring additional structural enhancements like the clamp system. Referencing Chapter 7.2, Concept Reflection, it's recommended that Biosphere Solar initially prioritize a series of focused tests to refine the core aspects of the liquid-encapsulated PV panels:

- Panel seal optimization to enhance durability.
- Optimization of liquid encapsulation for better electrical performance.
- Long-term testing to assess durability under various conditions.
- Analysis of thermal yield for improved thermal performance.
- Development of the cooling loop mechanism for efficient thermal utilization.
- Optimization of structural design, balancing durability, performance, and repairability.

Once Biosphere Solar has effectively addressed the initial set of goals for the development of the liquid-encapsulated PV panels, the next step is to focus on validating the panels through industry-standard testing. This stage is crucial to ensure that the panels not only meet the functional and design objectives but also adhere to the standards of durability, reliability, and safety established in the solar panel industry. The first key certifications to consider are IEC 61215 and IEC 61730. IEC 61215 is the standard for crystalline silicon photovoltaic (PV) modules and encompasses a comprehensive range of tests, including thermal cycling, damp heat, mechanical load, and electrical performance. These tests are designed to assess the durability and reliability of solar panels, ensuring that they can withstand various environmental conditions and perform consistently over time. IEC 61730, on the other hand, focuses specifically on the safety aspects of PV modules. This standard includes critical tests for resistance to fire, electrical insulation, and protection against mechanical damage. By aligning with these industry standards and successfully passing the tests they require, Biosphere Solar can ensure that its liquid-encapsulated PV panels are ready for wider market acceptance, signifying a product that is more robust, reliable, and safe for consumers.

In the revised concept, the use of UV-resistant polycarbonate sheets as a replacement for the front and back glass panels in the solar module offers advantages, particularly in terms of thermal efficiency and cost. Polycarbonate's lower heat transfer coefficient is beneficial for retaining heat within the silicone oil encapsulant, potentially enhancing the thermal collector functionality of the solar module. This material choice could lead to an increase in the overall thermal yield of the system. Economically, polycarbonate is typically less expensive than tempered glass, which might reduce manufacturing costs. However, this substitution requires careful consideration of the material's properties. Polycarbonate has a higher refraction index than glass, affecting light transmittance. To mitigate this, the encapsulating liquid's refraction index should be closely matched with that of polycarbonate. Additionally, design adjustments might be necessary to account for polycarbonate's different expansion characteristics and flexibility compared to glass. While polycarbonate is durable, its susceptibility to scratching and UV degradation must be managed with appropriate coatings to ensure longevity. In essence, this approach can make solar panels more thermally efficient, lighter, and cost-effective, but it also demands thoughtful adaptation in design and material handling. The decision to utilize glass for the front and back material in this thesis was driven by a desire to streamline the process and concentrate on the research question. However, it remains worthwhile to explore alternative materials in future designs.

Design-Driven Materials Innovation (DDMI) offers a collaborative approach to the future development of this concept, blending the expertise of designers with scientists and engineers. This methodology, rooted in Erik Tempelman's insights, emphasizes integrating design aspects from the outset of material and product innovation. By applying DDMI, the development of liquid-encapsulated PV panels will benefit from a holistic view, incorporating aesthetics, functionality, and user needs alongside technical specifications. This approach will enhance the efficiency, appeal, and user-friendliness of the panels, considering factors like maintenance, installation, and visual impact (Tempelman, 2016). Additionally, DDMI ensures economic viability, balancing innovation with market feasibility and sustainability, making the panels more effective for real-world applications.

This methodology aligns with the multifaceted nature of this project, where disciplines like material science, chemistry, physics, and industrial design intersect. A practical and effective solution can only be achieved through the collaborative efforts of experts in these fields.

Closing statement:

This thesis lays the groundwork for further exploration of liquid PV encapsulation systems, demonstrating the viability of such structures through prototypes and tests. While it marks a significant step forward, it also highlights the need for extensive follow-up research to fully understand the long-term performance of these new systems.

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Appendix A | Project Brief

TUDelft

DESIGN FOR our future

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name	Kroon 6846
Initials	Y.K
Given name	Youp
Student number	4848934

IDE master(s)	IPD ✔ / DfI / SPD
2^{nd} non-IDE master	
Individual programme *(date of approval)*	
Medisign	
HPM	

SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2^{nd} mentor

Chair	Prof. dr. A.R. Balkenende	dept./section	SDE/DfS
mentor	Dr. M.R. Vogt	dept./section	EEMCS/PVMD
2^{nd} mentor			
client:	Biosphere Solar		
city:	Delft	country:	Netherlands
optional comments	Dr. M.R. Vogt is an excellent mentor for this project due to his extensive expertise in solar photovoltaic systems. As an integral member of the Photovoltaic Materials and Devices program at TU Delft(PVMD), Malte offers invaluable expertise in solar photovoltaic (PV) systems.		

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2^{nd} mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Digitally signed by Ruud Balkenende - IO
Date: 2023.10.21 09:27:50 +02'00'

Name Ruud Balkenende   Date 21 Oct 2023   Signature

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total ______ EC

Of which, taking conditional requirements into account, can be part of the exam programme ______ EC

★	**YES**	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

Robin den Braber
Digitaal ondertekend door Robin den Braber
Datum: 2023.11.07 09:44:57 +01'00'

Name Robin den Braber Date 7 nov 2023 Signature

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	★	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

EWI mentor approved

Based on study progress, students is ...

★	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Monique von Morgen
Digitally signed by Monique von Morgen
Date: 2023.11.07 10:18:32 +01'00'

Name Monique von Morgen Date 7 Nov 2023 Signature

Personal Project Brief – IDE Master Graduation Project

Name student Youp Kroon **Student number** 4,848,934

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title PV solar exploration: The Circular PVT panel of the future

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

As the world shifts towards more sustainable energy sources, solar energy has been and will be a vital contributor to this change. Nonetheless, ongoing concern remains when it comes to the repairability and recyclability of conventional solar panels.

Traditional solar panels rely on an intermediary material known as ethylene-vinyl acetate laminate (EVA), which plays an essential role in their functionality. Solar EVA sheets enhance the durability and **performance** of solar modules. They enable the solar cells to 'float' between the glass and the back sheet, **soften shocks and vibrations**, and **protect the fragile cells and their circuits.** At first glance, the use of EVA in solar panels offers significant benefits. However, over time, the EVA can experience degradation and have a negative impact on overall performance and longevity. The four primary factors contributing to degradation are thermal cycling, damp heat, humidity freeze, and UV exposure. These factors, over time, eventually result in a critical issue known as delamination. Delamination occurs when the laminate layer, which bonds the various components of the solar panel together, starts to weaken or separate. Another drawback of the laminate is that solar cell **repair is challenging,** often necessitating the replacement of entire panels. Additionally, the presence of EVA can **complicate** the **recycling** process of solar panels, increasing the difficulty of reusing valuable materials.

Biosphere Solar is a global collective start-up that aims to revolutionize solar energy by creating a repairable and recyclable photovoltaic module. They are developing a **modular, circular, and transparent solar panel** with an open-source approach and sustainable production practices to make clean energy available. Last year Biosphere Solar made many innovative breakthroughs and currently, they are working on the next tier of solar panels and production lines. Yet, for the panel to compete with more traditional panels, specific improvements need to be designed and industrialized. Their current design contains an intermediate layer of air, instead of EVA. Due to this layer **less light is transmitted** through to the solar cells. Additionally, the air acts as thermal insulation, causing the system to **overheat** and degrade performance. This IDE master graduation project involves experimental prototyping aimed at addressing these issues.

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introduction (continued): space for images

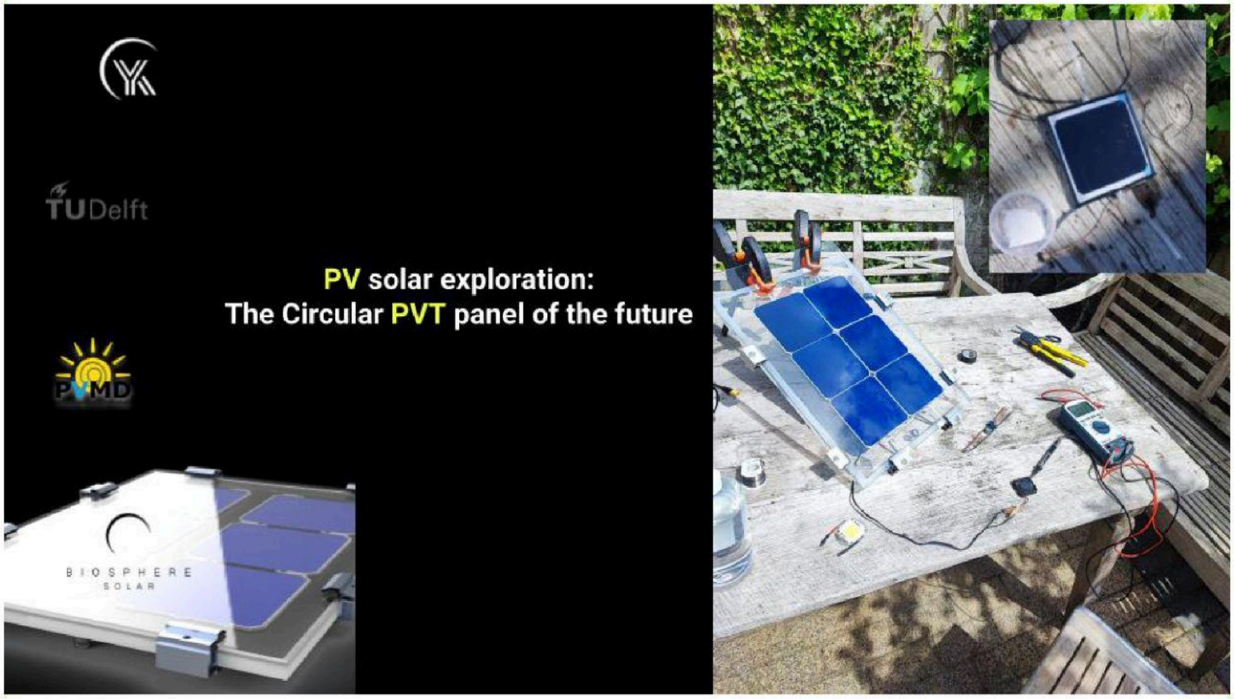


image / figure 1 PV solar exploration: The Circular PVT panel of the future

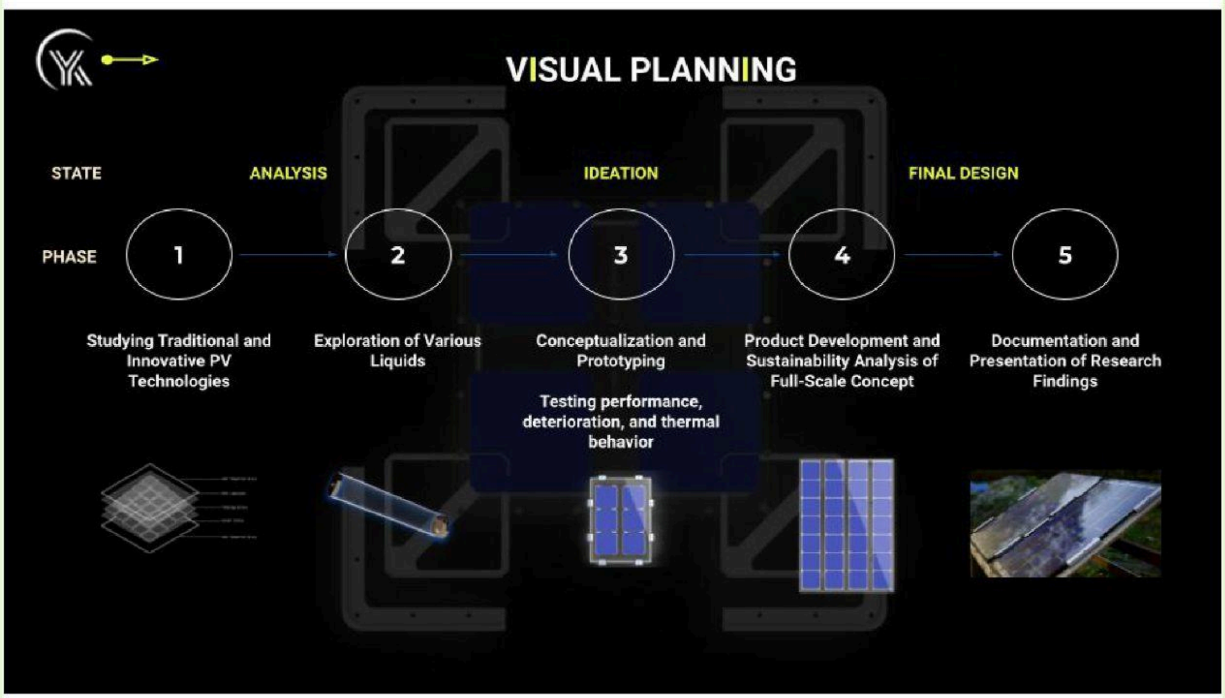


image / figure 2 Visual project planning

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

How can we design a (circular) solar panel **without a polymer laminate**, yet with thermal stability and acceptable light transmittance? The challenge lies in creating a new PV module architecture that is not only durable but also matches the **performance** of traditional solar panels.

The PV panel **construction design challenge** is to ensure that the new panel maintains its structural integrity, remains properly sealed, and functions effectively all while **minimizing the complexity and resources** within the system. Additionally, the new design must also accommodate for (liquid) cooling features.

Circularity design challenge, to make the panel more **circular,** it should be easily repairable and recyclable. However, achieving high repairability often involves designing products to be easily disassembled, which can introduce vulnerabilities. These vulnerabilities, if not properly managed, could potentially reduce the panel's life expectancy. Given that **longevity** is a crucial consideration, addressing these conflicting requirements presents a major design challenge.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

The goal of this research is to design and build functional prototypes that explore ways to effectively transmit light to the solar cells and reduce the thermal load on the module while enabling repair and recycling.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

1. Identify liquid agents with suitable thermal, optical, and non-corrosive properties for PV liquid encapsulation.
2. Identify opportunities for thermal exchange with liquid encapsulated PV module design.
3. Identify design opportunities for novel liquid-encapsulated panel architecture.

Phases 1 and 2 encompass the project's analysis stage, during which a multitude of (sub)research questions will be addressed. In Phase 3, during ideation, **small-scale modular prototypes** will be conceptualized and developed for experimentation. The objective of this initial prototype is to investigate and identify effective construction techniques for PV liquid encapsulation. Findings from these small-scale prototypes will be translated into the full-scale model improving its chance of success. The last two phases will result in the development of a refined **full-scale concept** that prioritizes, manufacturability, and circularity. This phase will also cover maintenance and regulations concerning the final concept.
If during the remaining phases, time allows, Biosphere Solar and I will collaborate to build and assess a full-scale prototype. Additionally, these phases will produce a comprehensive **report,** documenting research findings, novel concepts, test results, and conclusions, and offering recommendations for system design and engineering aspects to guide future projects.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting****,* ***mid-term evaluation meeting****,* ***green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	14 Sep 2023
Mid-term evaluation	9 Nov 2023
Green light meeting	4 Jan 2023
Graduation ceremony	18 Jan 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

The motivation behind initiating this project comes from my interest in the **energy transition**, specifically in the realm of harnessing the full potential of the sun. Through this project, I aim to:

Acquire In-Depth Knowledge: I seek to deepen my understanding of the energy transition, focusing on PVT panels and heat pump technology. This includes gaining insights into the intricate material properties of solar cells and cooling fluids, with a strong desire to become more affiliated with the chemical and physical background behind these systems.
Create Robust and meaningful novel concepts: My aspiration is to develop meaningful proof-of-concept prototypes that not only perform efficiently but also provide valuable results for the project.
Testing Proficiency: I want to expand my expertise in testing solar panels in a professional environment like the PVMD, honing my practical skills and understanding of real-world applications.
Contribute to Sustainable Solar Panel Design: Ultimately, I envision contributing to the design of cost-effective and robust solar panels that play a crucial role in sustainable energy.

Lastly, I aim to improve the arrangement and execution of team meetings, creating productive discussions and ensuring that the project progresses smoothly and with a clear direction. Throughout the entire graduation period, I aim to maintain a proactive stance, anticipating steps in advance to ensure the project's progression and success.

Appendix B | Initial Concepts

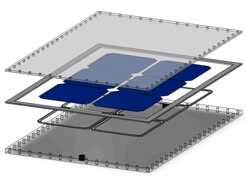
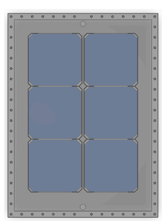
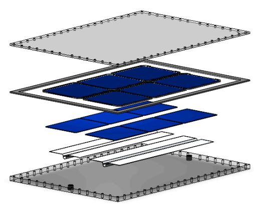
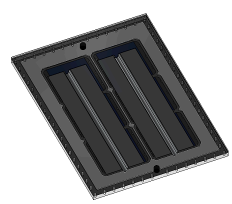
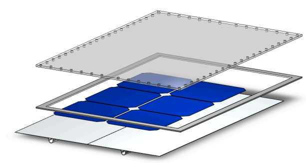
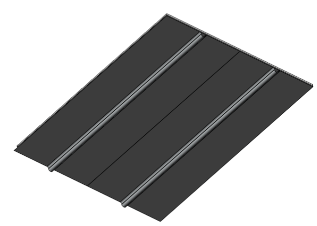
Introduction:
Before the final project brief multiple concepts on altering the panel architecture were considered but direct liquid encapsulation was deemed to be the most promising and interesting for the design project. (Table 10, Initial Concepts)

Concept 1: Liquid PV encapsulation
Rather than relying on air as the medium for heat dissipation, the concept suggests replacing it with a liquid coolant. This innovative approach aims to improve both the thermal and optical performance of the panel.

Concept 2: Thermal coupling glass and aluminium extrusion heat exchanger
The second concept modifies the back-end design of Biosphere Solar panels. It proposes incorporating silicone heat pads or a similar heat-conducting material to transfer accumulated heat to the back of the panel. To further optimize heat dissipation, a radiator is applied on the back panel.

Concept 3: Direct Aluminum Extrusion Heat Exchange
The third concept explores an innovative structural redesign of Biosphere solar panels by mounting solar cells directly on an aluminum extrusion. This extrusion, designed with a hollow interior, facilitates the flow of liquid, such as a coolant. The integration of thermal paste or adhesive enhances the direct transfer of heat. This concept aims to surpass the limitations of traditional designs by minimizing insulation layers, as seen in the second concept, and maximizing the efficiency of heat dissipation:

Table 10 Initial Concepts

Thesis concept direction	**Concept 1 Liquid PV encapsulation**	**Concept 2: Thermal coupling glass and aluminum extrusion heat exchanger**	**Concept 3 Direct Aluminium Extrusion heat exchanger**
Exploded View **Frond/Back View**	 	 	 
Optical Performance	This could increase if the liquids reduce good optical properties	Medium due to the air inside the panel	Medium due to the air inside the panel
Thermal performance	Optimal, heat can be directly dissipated with the coolant	Medium, Heat transfer potential is increased due to the multiple layers	Excellent, heat can quickly flow from cell to coolant inside the extrusion
Structural Performance	Liquid could affect PV cell Requires different panel architecture	Easy to implement on a biosphere's panel, however, it would require a significant amount of additional materials.	Challenges were identified in implementing the third concept due to the necessity of connecting the intertwining extrusions. The thermal expansion of these extrusions posed potential issues with the front panel. Additional insulation between the aluminum extrusion and solar cell bus bars is necessary to prevent short circuits.

Concept selection:
Following a thorough evaluation of the three proposed concepts, Concept 1, involving direct liquid encapsulation of the PV cells, emerged as the most promising for further experimentation and development. The decision to select this concept was reinforced during a meeting with the supervisory team. By eliminating air and introducing a coolant, Concept 1 is expected to bring about significant improvements in both thermal and optical performance. This strategic modification directly addresses the major shortcomings observed in the current architecture of Biosphere Solar panels.

Appendix C | Working Principles of Photovoltaic Systems

PV systems convert sunlight directly into current using semiconductor materials.
The key working principles of PV systems involve the following steps/principles:

Absorption of Sunlight: PV modules consist of numerous solar cells made from semiconductor materials, typically silicon. A semiconductor is a type of material that has electrical conductivity characteristics between that of a conductor and an insulator. It can conduct electricity under certain conditions and block it under others. Semiconductors are crucial components in electronic devices, enabling the control of electrical currents and information processing. They play a fundamental role in technologies like transistors, diodes, microchips, and PV. When sunlight (photons) strikes the surface of the solar cells, it's absorbed by the semiconductor material. Solar cells need to absorb a range of energy, which corresponds to the solar spectrum to be efficient. The solar spectrum has a range of 100 nm to 1 mm, but most of the irradiance occurs between 250 nm- 2500 nm with the maximum in the visible region of light (400-700 nm), which means that the solar cells should strive to absorb as much of solar spectrum as possible, Ranabhat et al. (2016)

The bandgap of the semiconductor material determines the minimum energy required to move an electron from the valence band to the conduction band. In the context of solar cells, this means that the band gap must be carefully chosen to align with the energy levels of the photons in the solar spectrum. If the band gap is too small, some of the incoming sunlight's energy will be wasted, as the energy difference between the photons and the band gap is turned into heat and not electrical energy. Conversely, if the band gap is too large, some photons will pass through without being absorbed.

Generation of Electron-Hole Pairs: The process of generating electron-hole pairs begins with the absorption of photons (particles of light). When these photons strike the semiconductor material, they transfer their energy to electrons within the material. This causes the electrons to become "excited" and break free from their usual positions within the atoms of the semiconductor. As these excited electrons move away from their origin, they leave behind voids known as "holes." These holes represent the absence of electrons in their usual positions and carry a positive charge. Together, the free electrons and positive holes create what is called an "electron-hole pair." These pairs are crucial in semiconductor devices, as they can be manipulated to conduct or block electric current, forming the basis of various electronic technologies.

In the structure of silicon solar cells, where a p-n junction is formed (see figure X), there is a critical region known as the "depletion region." This region lies at the interface between the p-type and n-type layers. As mentioned earlier, the p-type layer contains excess positively charged "holes," while the n-type layer has surplus negatively charged electrons due to the doping process with boron and phosphorus, respectively.

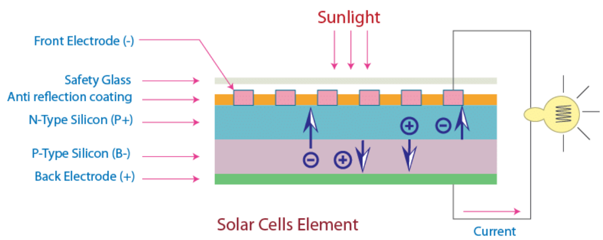


Figure 21, structure of silicon solar cells (Wikipedia contributors, 2014)

The depletion region is an area within the solar cell where a lack of charge carriers (both electrons and holes) prevails. This absence of free charge carriers results from the recombination of electrons from the n-type region and holes from the p-type region when they come into contact at the p-n junction.

Due to this recombination, the depletion region becomes electrically neutral, as the positive and negative charges effectively cancel each other out. Importantly, the depletion region sets up an electric field within the solar cell. This electric field creates a barrier that hinders the free movement of charge carriers across the junction.

When sunlight strikes the solar cell and generates electron-hole pairs, as previously explained, these pairs are affected by the electric field in the depletion region. The electric field acts as a force that separates the negatively charged electrons, driving them toward the n-type layer, and the positively charged holes, pushing them toward the p-type layer. This separation of charge carriers creates a potential difference, which is the basis for the generation of electric current within the solar cell. It's important to note that the depletion region plays a crucial role in ensuring the efficiency of the solar cell by maintaining this charge separation.

Generation of Direct Current: As the electrons move toward one surface of the solar cell and the holes move toward the other surface, they create an electric current. This current consists of negatively charged electrons flowing through an external circuit, forming a Direct Current (DC).

Collection and Conversion of Electricity: Conductive metal contacts (often silver, aluminum, or copper) on the front and back of the solar cell collect the electrons and holes, respectively. The front contact is usually made of a grid-like pattern to allow sunlight to reach the semiconductor material. The collected DC electricity can then be used for numerous applications. More advanced cells like Maxwell IBC have contacts only on the rear side, which enhances efficiency by eliminating shading from front contacts.

Power Utilization: A single solar cell typically generates an Open Circuit Voltage (VOC) of approximately 0.5 to 0.6 volts. To achieve a usable voltage, multiple solar cells are connected in series, forming a module. These modules are further combined to create a solar panel. The panels can be arranged in either series or parallel configurations, depending on the specific electrical load requirements. When several panels are connected in series, an inverter is often added. The inverter converts the DC generated by the panels into Alternating Current (AC), which is suitable for most household and grid-connected applications.

Appendix D | List of Requirments

PVT system components and requirements

- **High Energy Efficiency:**
  The PVT system should be designed for high energy conversion efficiency, both in terms of electricity generation from PV modules and thermal energy. (Higher or similar to that of traditional PVT-panels with EVA laminate)
- **Suitable Heat Transfer Fluid:**
  The right heat transfer fluid for the thermal component should be chosen, one that can operate efficiently at the desired temperature range and withstand environmental conditions.
- **Efficient Heat Exchangers:**
  Implement efficient heat exchangers to transfer thermal energy to the intended application (e.g., space heating, water heating, or industrial processes).
- **Energy Storage:**
  Integrating thermal energy storage systems to store excess heat for use during cloudy periods or at night, improves system usability.
- **Control Systems:**
  Control systems and sensors to monitor and optimize the operation of the PVT system.
  These systems can adjust the tilt and orientation of collectors, manage heat transfer fluid circulation, and control other operational parameters.
- **Environmental Considerations:**
  Evaluate the environmental impact of the system and use sustainable materials and practices in its construction and operation.
- **Longevity:**
  Use quality components and materials to ensure the long-term durability of the PVT system.
  Investing in a reliable design that can extend the system's lifespan. (Higher or similar to that of traditional PVT-panels with EVA laminate)
- **Maintenance-Friendly Design:**
  Design the PVT system with maintenance in mind.
  Ensure that key components are easily accessible for inspection and cleaning. Proper accessibility simplifies maintenance tasks.
- **Hermetic Seals for Solar Cells:**
  To protect delicate solar cells from moisture and air exposure, hermetic sealing is essential.
  Solar cells are highly sensitive to external moisture and air contamination, which can compromise their performance.
- **Effective Cooling Loop Sealing:**
  The cooling loop must be sealed effectively to prevent contamination of the cooling agent.
  Proper sealing ensures that the cooling system remains free from unwanted substances.
- **High-Quality and Durable Seals:**
  Seals should be of high quality and designed for long-term use.
- **Accessible for Inspection and Replacement:**
  Easy access for seal inspection and replacement is necessary for efficient system maintenance.
  Ensuring straightforward seal maintenance procedures contributes to the system's longevity and reliability.
- **Seal material:**
  Non-toxic, environmentally friendly materials should be selected, ensuring both safety and minimal environmental impact.

Liquid flow systems components:

- **Hoses:** The components of the system are connected with hoses. Applications primarily use nylon, polyurethane, polyethylene, PVC, or synthetic or natural rubbers based on environmental conditions and required pressure ratings.
- **Hose Fittings:** One end of the hose connects to a tapered, multi-stage shape, while the other end often features threading, enabling easy connections to various system components. Metal tubes like aluminum and copper can also be welded to other metal parts.
- **Regulated valves and Temperature Sensors:** These essential components help control the flow and monitor temperature within the system.
- **Thermal Buffer:** An insulated tank serves as a storage vessel for hot water, allowing it to be used when needed.
- **Control System:** A smart control system regulates the flow rate, a critical factor that significantly impacts the efficiency of the liquid cooling system. Excessive flow may result in inadequate temperature differences, while insufficient flow can lead to overheating (for PVT systems).
- **Thermal Expansion Buffer:** Due to thermal expansion, the cooling liquid can change in volume, causing system compression. To accommodate these volume changes, an expansion buffer needs to be incorporated into the system.
- **Cooling agents:** Cooling agents, also known as coolants, are substances used to dissipate heat from various systems and components to maintain their operating temperatures within safe and efficient ranges.

Liquid flow systems requirements:

- **Controlled Flow:** Flow should be continuously monitored and automatically adjusted to maintain the desired rate, ensuring optimal cooling performance and system stability.
- **Consistent Flow:** The coolant used in the system should have low viscosity to ensure consistent flow.
  Therefore It should prevent blockages and increase efficient heat transfer.
- **Homogeneous flow between plates:** To achieve homogeneous flow between plates, factors such as the viscosity of the fluid, the distance between the plates, the surface tension of the plate material, and the applied force or pressure are important. Controlling these parameters can help ensure that the flow remains uniform across the entire space between the plates.
- **Easy to set up and connect:** The system should be designed for straightforward setup and connection, minimizing installation complexities and reducing the risk of errors during assembly. Clear instructions and user-friendly components are essential for ease of use. User-friendly components that have the same characteristics as garden hosing or pneumatic quick-lock connections. In this context, there is no necessity for specialized tools, and installation is effortless.
- **Easy to maintain:** The system should be easy to maintain and allow for straightforward execution of repairs when necessary, reducing downtime and ensuring continuous operation.
- **Robust:** It should be weather-resistant and long-lasting, capable of withstanding environmental conditions
- **Cost-effective:** The additional integration of the cooling loop within the PV system should be cost-effective, considering both initial installation costs and long-term operational efficiency.

Concept requirements

- **Efficiency:** The system should be efficient in converting solar energy into both electricity and heat.
- **Thermal Stability:** It should maintain stable thermal performance over a wide range of environmental conditions.
- **Robustness:** The system should be durable and withstand various operational challenges and environmental factors.
- **Sustainability:** Design the system with materials and components that are environmentally friendly and sustainable, considering the entire life cycle of the system.
- **Cost-effectiveness:** Strive to balance performance and cost to make the system accessible and economically viable.
- A potential 50% cost increase may be incurred due to enhancements in sustainability, functionality, and performance
- **Scalability:** Ensure that the system can be scaled up or down to accommodate different applications and energy needs.
- **Integration:** The system should be easily integrated into existing energy systems or building structures, promoting versatility and widespread adoption.
- **Maintenance and Serviceability:** Design the system with ease of maintenance and repair in mind to minimize downtime and ensure long-term functionality.
- **Long Lifespan:** The system should be designed to have a long operational lifespan, fulfilling industry standards.

Appendix E | Single-Cell Embodiment

This appendix provides an examination of the materialization and development process of the single-cell prototype. It commences with the presentation of "Figure 22: Conceptualization Overview," offering a comprehensive visualization of each component, with a focus on highlighting their interplay and functionality. The discussion in this section centers around the selection of specific materials for the initial design, chosen for their distinct advantages in meeting the design criteria.

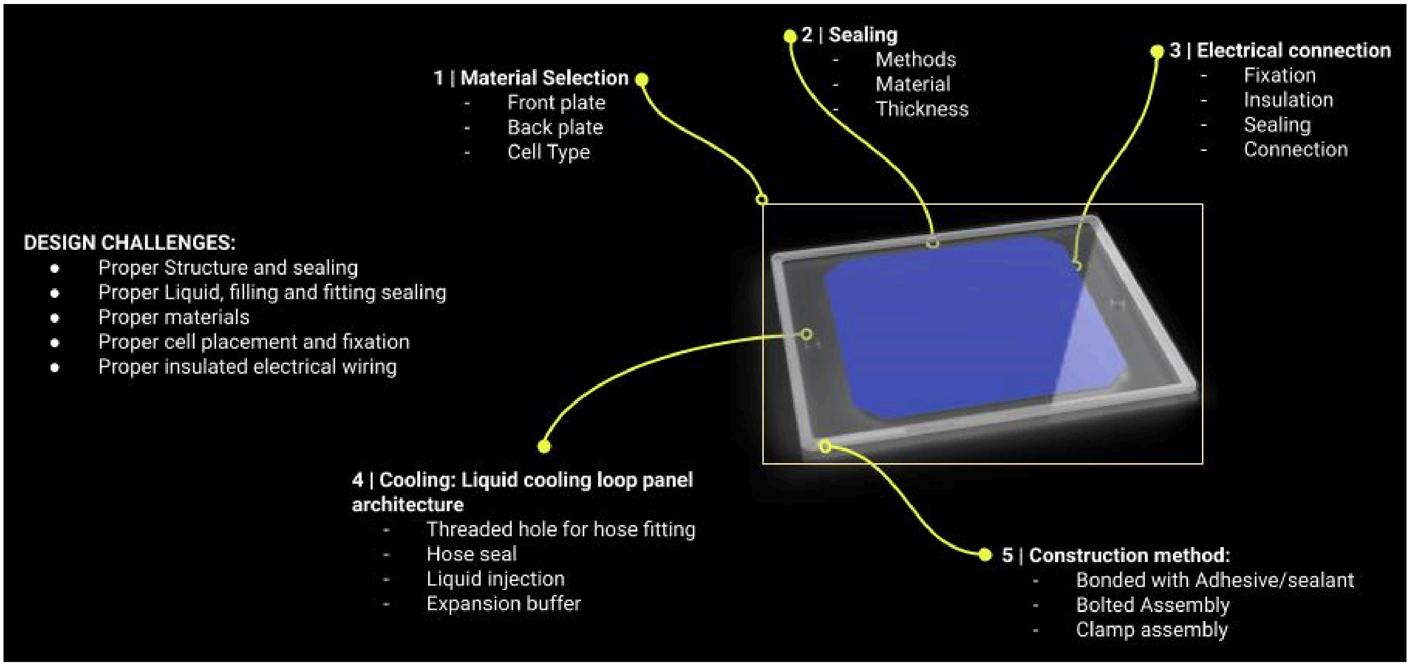
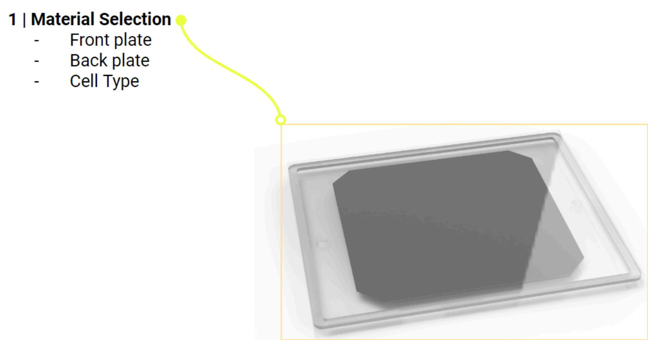


Figure 22, Conceptualization Overview

1| Materials selection

The initial step in the design process is the material selection, a critical factor for ensuring the robustness of the solar panel. The choice of materials for both the front and backplate is an essential start, as it significantly influences various subsequent steps in the design process. This selection is particularly crucial in light of its impact on the overall performance of the solar panel and the seamless integration of a liquid loop within the panel cavity. The subsequent chapter will address the determination of the seal material in detail.



- **Front plate:** Ideally, the front plate would be made of commonly used 3.2 mm tempered glass with an anti-reflective coating. This type of glass offers high transmittance, but it can be challenging to source in small sizes and quantities.

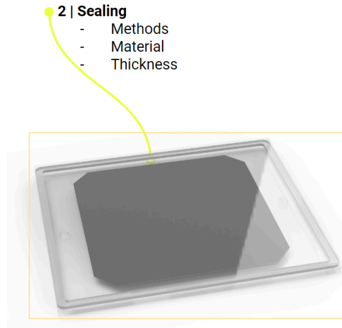
  For initial testing, 4 mm float glass was selected for its widespread availability and ease of resizing. However, it has a slightly lower transmittance than more common PV glass due to its higher iron content. Yet, this glass proves ideal for gradual testing of cooling efficiency, panel integrity, and thermal distribution. Additionally, the consistent use of similar float glass for each prototype ensures the reliability and comparability of the results across different cooling agents, and air-encapsulated cells. The refractive index of 4 mm soda-lime glass is approximately 1.5 (Vogt., 2015).

- **Back Plate:** The backplates were crafted using Acrylic. This material was selected for its ease of shaping into the desired form and its suitability for creating threaded holes. These threaded holes facilitated easy compatibility with threaded hose fittings.

- **Cell Type:** The chosen cell type is the Maxeon Gen III Cell, known for its exceptional performance with an efficiency of 24.3%. Additionally, the integrated back contacts, on which dog bones are soldered, allow for the convenient attachment of busbars for testing. This feature makes them the ideal choice for these prototypes.

2 | Sealing: Prototype sealing methods

The subsequent part of the design process focuses on determining the seal material, a critical element with specific requirements. The seal must exhibit robust moisture resistance and exceptionally low gas permeability. Two commonly employed and promising seal materials, silicone, and butyl, will be subjected to an analysis based on their characteristics:



- **Silicone:**
  Moisture Resistance: Excellent
  Low Gas Permeability: Good to Excellent
  Abundant and Non-Toxic: Silicones are derived from abundant materials, and they are generally considered non-toxic once cured.
  However, some curing agents may have toxicity concerns during the curing process.

- **Butyl Rubber:**
  Moisture Resistance: Excellent
  Low Gas Permeability: Excellent
  Abundant and Non-Toxic: Butyl rubber is derived from petroleum, which is relatively abundant.
  It is generally considered non-toxic and safe for many applications.

For the primary testing, butyl rubber was selected as it offers the best properties, including superior gas resistance when compared to silicone. Notably, Butyl rubber aligns closely with the properties of the commonly used PIB (Polyisobutylene) used in double-sided glass and Biosphere Solar panels. Biosphere Solar has successfully utilized butyl rubber in the past for numerous prototype applications.

3 | Connection: Insulated Circuitry methods for the prototype

To establish a connection with the cell for testing the prototype's electrical performance, it is necessary to solder connections onto the cell and extend them outside of the panel while ensuring a maintained seal. **Connection:** Dog bones are soldered to the back contacts, and on these, both horizontal and vertical busbars are soldered (refer to Figure 23). In addition to the vertical busbar, a thin busbar is included for voltage measurement, separate from the amperage measurement.
Connection Sealing: To ensure a proper seal, the busbars are enclosed between two layers of butyl tape. This sealing method should effectively secure and insulate the electrical wiring.

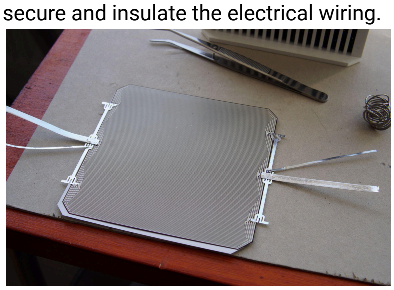
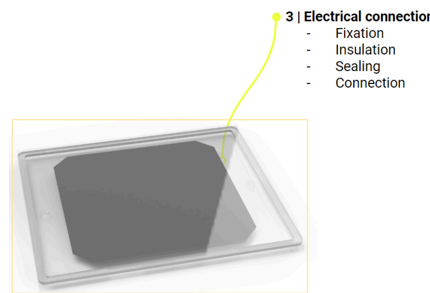
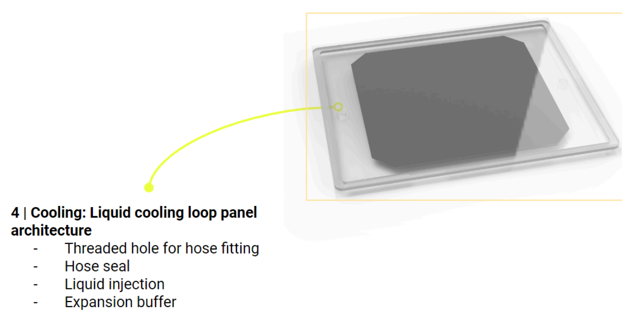


Figure 23, Wire soldering



4 | Cooling: Liquid cooling loop panel architecture

In this section, the liquid cooling loop panel architecture is outlined, explaining the steps for creating an effective and secure cooling system testing environment.



- **Liquid connection:** Threaded hose fittings are installed, and O-rings are added to ensure a proper seal. The fitting is then connected to a small hose, which is further protected with a 3D-printed hose sleeve.

- **Liquid injection:** With the assistance of a syringe and hoses, the liquid agent is collected and injected into the prototype from one side. On the opposite end, an empty syringe is positioned, and it is gently pulled back to create a small vacuum. This process effectively evacuates the air as the coolant is injected, preventing any coolant from leaking out of the prototype and facilitating a controlled injection.

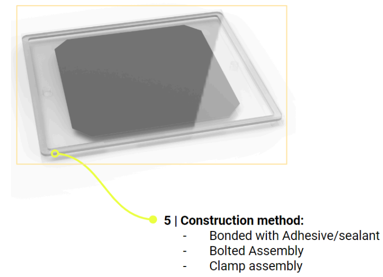
- **Liquid thermal expansion Buffer:** During testing, the syringe can move up and down, accommodating changes in coolant volume caused by thermal expansion.

- **Liquid sealing:** After the prototype is fully injected with the cooling agent, and all the air has been emptied from the void, the syringe and hose can be disconnected. An end cap can then be securely installed, enabling long-term sealing and deterioration testing.

By incorporating additional O-rings and employing double inlet syringes, an approach was adopted to establish a secure testing environment, effectively safeguarding against any potential issues of leakage or spilling during the system evaluation.

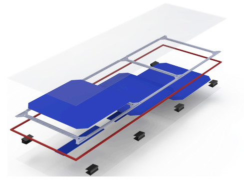
5 | Construction method: Assembly and Structural Cohesion of the Prototype

This section provides an overview of the construction methods illustrated for the assembly and structural cohesion of the prototype. Various approaches, including sealant application, clamp assemblies, clamp extrusion, and bolted assemblies, are examined, each presenting distinct advantages and considerations.

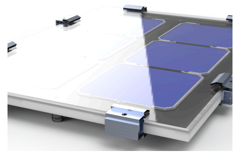


Sealant
+ Solid Seal
+ Requires no additional Components
- Challenging to disassemble

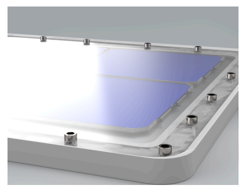
Spring clamp Assembly + seal
+ Modular approach
+ Flexibility: accommodate slight movement
- Resourceful: Require additional (Spring)clamps
- Weak pressure



Clamp aluminum Extrusion + seal
+ Modular approach
+ Flexibility: accommodate slight movement
+ Flexibility: accommodate some movement
- Less modular therefore harder to repair



Bolted Assembly + seal
+ Modular approach
+/-. Flexibility: accommodate minor movement
- Requires additional bolts, holes, Nuts, or tapped backplates



Construction conclusion

For the primary performance testing, the **sealant** method has been selected as it offers numerous advantages with only minor setbacks. Additionally, a quick **clamp design** will be evaluated to determine its effectiveness in sealing the panel compared to the sealant method. Refer to Appendix F Seal testing, for the results of the clamp design sealing tests.

Single-cell Prototype Development

In this appendix, the development process of the single-cell prototypes is addressed. Before delving into technical details, the groundwork was laid by outlining specific goals, involving design challenges, and establishing prototype requirements. Afterward, the development process will be explained, highlighting details in prototype deviations and repeating the liquids that will be utilized.

- **Prototype goals:**
    1. Design practical and innovative construction for a new liquid-loop panel.
    2. Validate the effectiveness of liquid encapsulation in maintaining PV performance.
    3. Analyze cell deterioration under liquid encapsulation conditions.

- **Design challenges:**
    1. Ensure a robust structure and effective module sealing.
    2. Establish proper filling features.
    3. Select suitable materials for the prototype components.
    4. Secure the placement and fixation of the solar cell within the system.
    5. Insulate electrical wiring and provide adequate solar cell insulation.

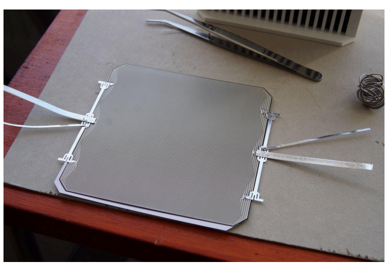
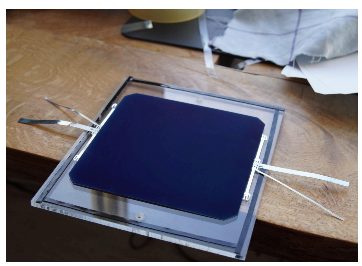
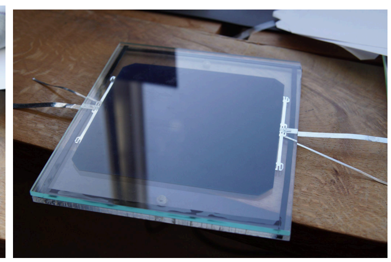
- **Single-cell prototype requirements:**
    1. Efficiency higher or similar to that of an air-encapsulated prototype (BioSphere solar 16/19%)
    2. Lower temperature to that of an air-encapsulated prototype (Temperature difference)
    3. Proper sealing, no leaking may occur (at atmospheric pressure)

Prototype development process:
In the fabrication process, the first step involves CNC-laser cutting acrylic back plates (thickness 4mm) to the required size and precision. Subsequently, holes with M5 threading are cut and threaded into the back plates. The glass is then cut to the specified dimensions of 175 mm x 150 mm, with extra care taken to remove any sharp edges.

The assembly of the solar cell involves soldering busbars as illustrated in the accompanying figure. To ensure a secure and sealed construction, butyl tape (0.5 mm thick) is applied to both the front and back plates. The solar cell is then sandwiched between these plates, and a pressure of 20kg is applied.

For the final stage of the assembly, threaded hose fittings with O rings (M5 thread) are installed. These fittings are attached and allow for easy mounting of 6 mm silicone tubing during the experiments.

***Table 11* | Prototype development process**

Prototype differences: The prototypes feature different sealing configurations. Two prototypes incorporate dual 0.5 mm butyl tape, totaling 1 mm in thickness. Another two prototypes utilize a single 0.5 mm butyl tape. Both prototypes share the common liquid connection features.

Prototype liquids: Two liquids will be employed for testing purposes. The first, a glycol-water mixture, specifically utilized the NALCO 460-TFS200 Treated Water Solution, complemented by the inclusion of CCLS (Corrosion Inhibitor/Biocide). This combination served multiple functions, contributing to both thermal conductivity and corrosion prevention. In a separate set of tests, Fluorinert™ Electronic Liquid FC-72 from 3M was employed. Known for their dielectric properties and low boiling point, these liquids were chosen for their suitability in assessing thermal cooling performance and sealing capabilities which was covered in previous chapter 9. (See Figure 24)

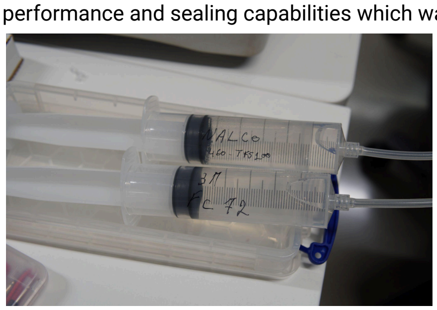


Figure 24, NALCO 460-TFS200 & Fluorinert™ Electronic Liquid FC-72

With the methodology and prototypes now firmly established, the forthcoming chapter, will unveil valuable insights that shaped the trajectory of this project.

Appendix F | Single-cell Test Results

Table 12 **| Single-cell Test Results**

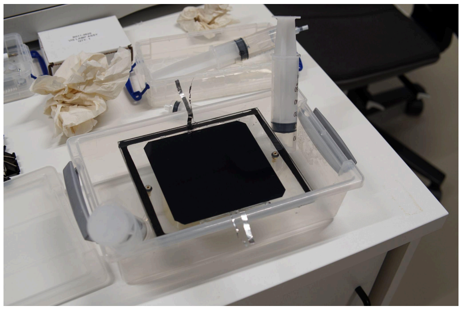
TEST 1 GLYCOL MODULE-TYPE 1 (SINGLE SEAL THK 0.5 MM) **Reference, no glycol mixture added** Efficiency: **19.33884** Temperature: (not measurable but close to room temperature 25 degrees) Liquid/encapsulant: air **Glycol mixture added** Efficiency: **21.3024** Temperature: glass surface approximately room temperature 24/25 degrees Liquid/encapsulant: glycol water mixture Result: gain =(final efficiency - reference efficiency) / reference efficiency Gain = (21.3024 - 19.33884) / 19.33884 Gain ≈ (1.96356) / 19.33884 Gain ≈ 0.1014 or **10.14%**	**TEST 2 FC72 MODULE-TYPE 1 (SINGLE SEAL THK 0.5 MM)** **Reference | No Fluorinert added** Efficiency: **20.17616** Temperature: (not measurable but close to room temperature 23 degrees) Liquid/encapsulant: air **Fluorinert added** Efficiency: **20.99166** Temperat
Test 3 Glycol Module-Type 2(double Seal THK1mm) **Reference, no glycol mixture added** Efficiency: **19.51385** Temperature: (not measurable but close to room temperature 25 degrees) Liquid/encapsulant: air **glycol mixture added** Efficiency: **20.63836** Temperature: glass surface approximately room temperature 25/26 degrees Liquid/encapsulant: glycol water mixture Result: gain = (final efficiency - reference efficiency) / reference efficiency Gain = (20.63836 - 19.51385) / 19.51385 Gain ≈ (1.12451) / 19.51385 Gain ≈ 0.0576 or **5.76%**	**Test 4 FC72 Module-Type 2(double Seal THK1mm)** **Reference | No Fluorinert added** Efficiency: **19.51385** Temperature: (not measurable but close to room temperature 23 degrees) Liquid/encapsulant: air **Fluorinert added** Efficiency: **20.55044** Temperature: glass surface approximately room temperature 24 degrees Liquid/encapsulant: fluorinert Result: gain = (final efficiency - reference efficiency) / reference efficiency Gain = (20.55044 - 19.51385) / 19.51385 Gain ≈ (1.03659) / 19.51385 Gain ≈ 0.0531 or **5.31%**

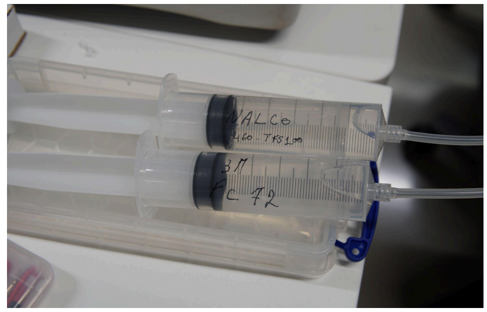
Appendix G | Explain the Testing Approach for the Single-cell Prototypes

During the initial set of tests, four single-cell prototypes will undergo injection with a selected pair of cooling liquids. Before the liquid injection, baseline tests will be conducted on the prototypes without any liquid inside to establish a comparative reference measurement.

Additionally, two extra prototypes will undergo quick testing specifically focused on assessing the effectiveness of their sealing methods. This evaluation aims to determine whether a nonstick modular seal with a moderate clamping construction is capable of effective sealing.

***Table 13* | Explain the Testing Approach for the Single-cell Prototypes**





Testing machine:
PVMD-Cell tester (see figure 24) (Need to add specific name and specs + software). For measuring individual solar cell prototypes, a cell tester was utilized. The cell tester operates by subjecting the solar cell to controlled conditions, including light intensity and temperature incline. This allows for the measurement of critical parameters such as voltage, current, and power output. The data obtained from the cell tester is essential in evaluating the solar cell's efficiency, and overall electrical characteristics.

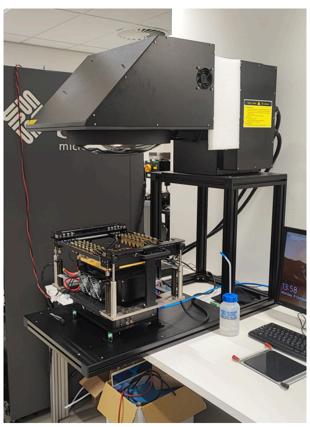


Figure 24, PVMD-Cell tester

Testing equipment:
The test begins by using an **infrared temperature meter** to measure the initial temperature of the prototypes. Next, 50ML **syringes** are employed to carefully extract and dispense specific liquids. **Silicone 6 mm tubing** is then utilized to facilitate controlled fluid transfer between components.

Tests:
Multiple tests were conducted on module type one (single sealed) using both glycol and Fluorinert. Measurements were taken twice—before and after the introduction of the liquid. This approach facilitated automatic comparisons with an air-insulated panel featuring the same performance cell. Before the test, the top plate's temperature was measured with an infrared sensor to ensure the prototype was close to room temperature or ideally at the official test temperature of 25 degrees (Or lower).

Subsequently, the same tests were repeated with module type two (Double sealed). The duration of this test spanned approximately 20 minutes, with continuous light exposure. Throughout this period, the module's temperature gradually increased, allowing for the observation of efficiency changes. (See figure 25, Single cell test setup)

Additionally, two tests with the remaining silicone and Thermoplastic polyurethane seal were conducted by injecting liquid to see the seal's performance.

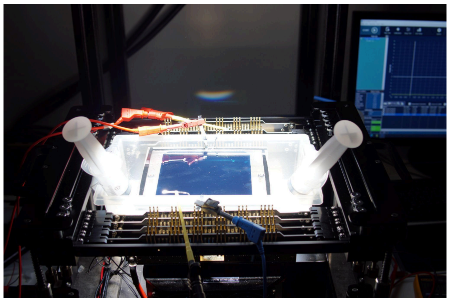
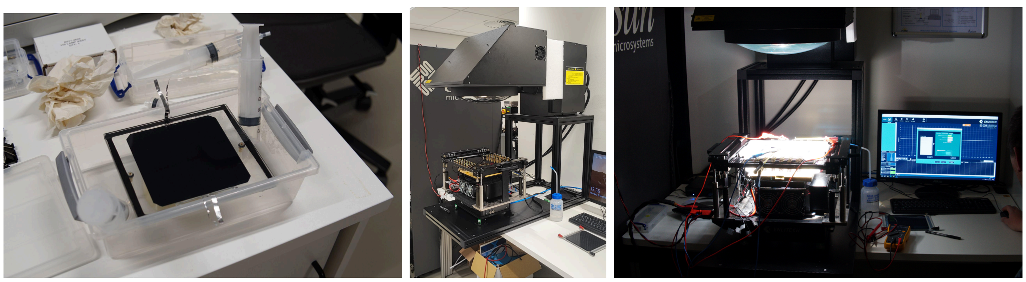


Figure 25, Single cell test setup

Test setup:
The prototypes are positioned in a leakage tray with attached syringes. In the event of any unintended spills, the liquid will be gathered within the tray, safeguarding the expensive and delicate machines.

The liquid is collected in a 50ml syringe, elongated with a short silicone tube. During the liquid injection, one syringe draws in air while the other introduces the cooling liquid. This method facilitates a smoother and more controlled filling process. It aids in removing all air and prevents undesired spills at the prototype's outlet. The tray is situated atop the machine, and four wires are connected accordingly.

***Table 13* | Single-cell Prototypes test setup**



Testing approach reflection:
Discuss the thermal behavior: Include heat mapping during testing.

- **Temperature Control is Crucial:** The precise control and monitoring of temperature is essential during testing, temperature highly impacts VOC and therefore efficiency
- **Temperature Stability:** Overall, temperature control remained more stable, contributing to the overall success of the added liquid.

Discuss the structural integrity: Include deterioration findings and sealing performance.

- **Sealing:** Butyl tape proved to be less effective for sealing. It is recommended to consider using silicone or a combination of silicone and butyl for improved sealing. Conducting small-scale sample tests on these alternatives is sensible.
- **Filling:** The filling process proceeded smoothly with no occurrence of bubbles. It's worth noting that glycol performed slightly better than Fluorinert, which aligns with expectations.
- **Syringes for Filling:** The use of syringes for filling demonstrated excellent results.
- **Inlet and Outlet Placement:** To facilitate the removal of air, consider placing the inlets and outlets closer to the edges or even better the corners.

Suggestions for Improvement/reflection:

- **Temperature Control is Crucial:** The precise control and monitoring of temperature is essential during testing, temperature highly impacts VOC and therefore efficiency

- **Reference Measurements with Air in the System:** Reference measurements conducted with air in the system could heat up rapidly, leading to reduced performance. The imprecise temperature measurement, which only indicated the top surface temperature, underscored the need for a more accurate method such as integrating a thermistor inside the module.

- **Inadequate Sealing in Initial Design:** The initial design suffered from inadequate sealing, highlighting the importance of addressing sealing issues for reliable testing.

- **Distance to the Cell Tester:** The distance between the module and the cell tester was too high due to the presence of a leakage container. This distance needs adjustment for improved testing conditions.

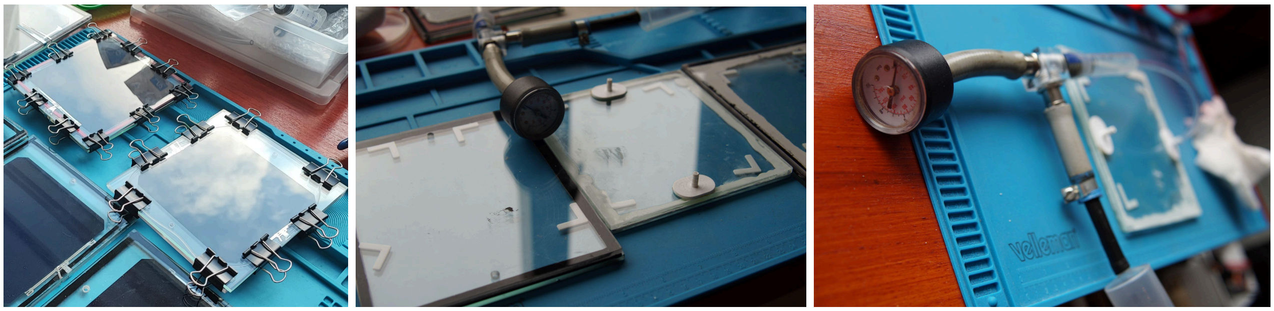
- **Unexplored Testing Scenarios:** Several important testing scenarios have not yet been explored:)
  Testing the panel without any glass to evaluate the effectiveness of 4 mm float glass and for an overall comparison. Note that soldering issues have hindered this testing.
  Testing a reference panel typically laminated with an EVA layer for comparison purposes.
  Testing with mineral oil has not been performed due to the absence of liquid access and issues with one prototype.
  Testing with silicone oil has not been conducted for similar reasons, including the absence of liquid access and a failed prototype.

Appendix H | Seal Testing

Compression Seal Tests:
The application of a solid non-stick silicone seal on one side revealed that the seal did not hold effectively, leading to leakage around the busbar. To enhance performance, it is recommended to consider applying more pressure and potentially explore the use of a flat double-sided silicone seal for improved sealing capabilities.

The utilization of 3D printed Thermoplastic Polyurethane resulted in insufficient sealing due to the coarse nature of the material. This outcome highlights the need for a finer resolution or alternative materials for 3D printing to achieve a more effective and reliable seal.

Table 14 | **Seal Testing**



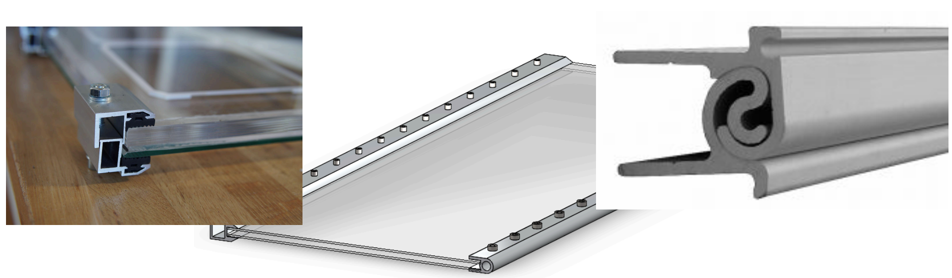
Appendix I | Module Embodiment

1 | Sealing methods: Assembly and Structural Cohesion of the Prototype

This section evaluated key sealing methods for the small-scale PV module: Sealant and Clamp Aluminum Extrusion + Seal. Balancing factors such as strength, modularity, and repairability, the goal was to determine the optimal approach. The chosen method played a significant role in shaping the assembly and structural cohesion of the prototype, impacting its reliability and long-term performance.

Sealant
+ Very strong Seal
+ Require no additional Components
+ Flexibility: accommodates some movement
- Less modular therefore harder to repair

Clamp aluminum Extrusion + seal
+ Modular approach
+ Flexibility: accommodates slight movement
+ Can be used as frame and surface mounting
+ Even and extensive pressure
- Seal not as good as adhesive sealings
- Resourceful: Require additional extrusion and bolts



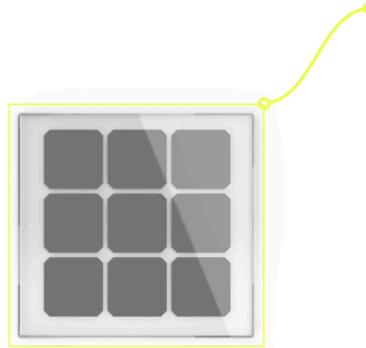
Construction conclusion
After a thorough evaluation of the sealing methods for our small-scale PV module, the analysis concludes that Sealant emerges as the optimal choice. The Sealant method exhibits a very strong seal without requiring additional components. While offering flexibility to accommodate some movement, it is less modular, making repairs more challenging.

On the other hand, the Clamp Aluminum Extrusion + Seal method provides a modular approach with flexibility to accommodate slight movement. It can be utilized as both a frame and for surface mounting, providing even and extensive pressure. However, its seal is not as robust as adhesive sealings, and the method requires additional extrusion and bolts.

In construction, the preference for Sealant is rooted in its balanced attributes. It strikes a harmony between repairability, as Sealant allows disassembly, and rigidity, benefiting from its robust nature without the need for extra parts. While the clamping system offers ease of repair, it is noted for its fragility, making it less suitable for our module's requirements. Thus, the Sealant method stands out as the most fitting choice for achieving the desired combination of repairability and rigidity in the assembly and structural cohesion of our small-scale PV module.

2 | Materials: Prototype material selection

In this part, we explore material choices for key components of the small-scale module prototype. The front plate features high-transmittance glass with AR coating, while the back plate selection depends on thermal properties and drilling needs. Cell spacers, made from 3D-printed Polyethylene terephthalate glycol, ensure proper cell alignment. The chosen Maxeon Gen III Cells, boasting 24.3% efficiency and integrated back contacts, are pivotal for testing, making them ideal for our prototypes.



Front plate:
Glass with high transmittance and AR coating

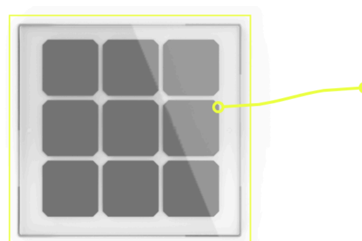
Back Plate:
Glass or Polymer depending on the thermal properties and necessity for drilling and tapping holes

Cell Spacers:
Not necessary anymore due to the rubber strain relief features

Cell Type:
The chosen cell type is the Maxeon Gen III Cell, known for its exceptional performance with an efficiency of 24.3%. Additionally, the integrated back contacts, on which dog bones are soldered, allow for the convenient attachment of busbars for testing. This feature makes them the ideal choice for these prototypes.

3 | Solar cells

To overcome the new module challenges, a thicker busbar has been used, and rubber pieces have been glued on. These rubber pieces will be squeezed when the panel is assembled, creating strain relief on the outputs and solar cells.



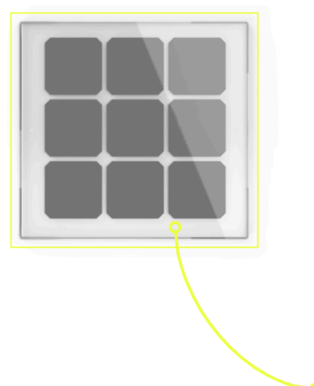
4 | Connection: Insulated Circuitry methods for the prototype,

Option 1: Double layer sealing and electrical wiring sandwiched in between

Option 2: Polymer backplate with threaded holes, in which connector bolts can be screwed in making the connection

Option 3: In the back panel glass slits can be applied for wiring to pass thru

Conclusion: Option 1 has been selected for the module test due to its simplicity, making it the most practical choice for our prototype's insulated circuitry methods.



5 | Liquid flow features

Sealing: Prototype sealing methods

A polymer backplate with threaded holes, similar to the single-cell prototypes, proved to be effective. However, it requires a polymer backplate to which threaded holes can be applied. Additionally, it increases the panel's thickness, making access difficult once the panels are installed. This may or may not pose an issue in full-scale scenarios. See Figure 26 for a full-size hose fitting.

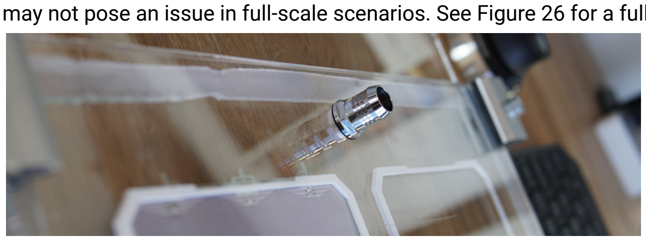
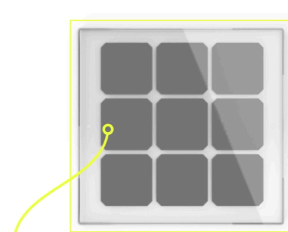


Figure 26, full-size fitting

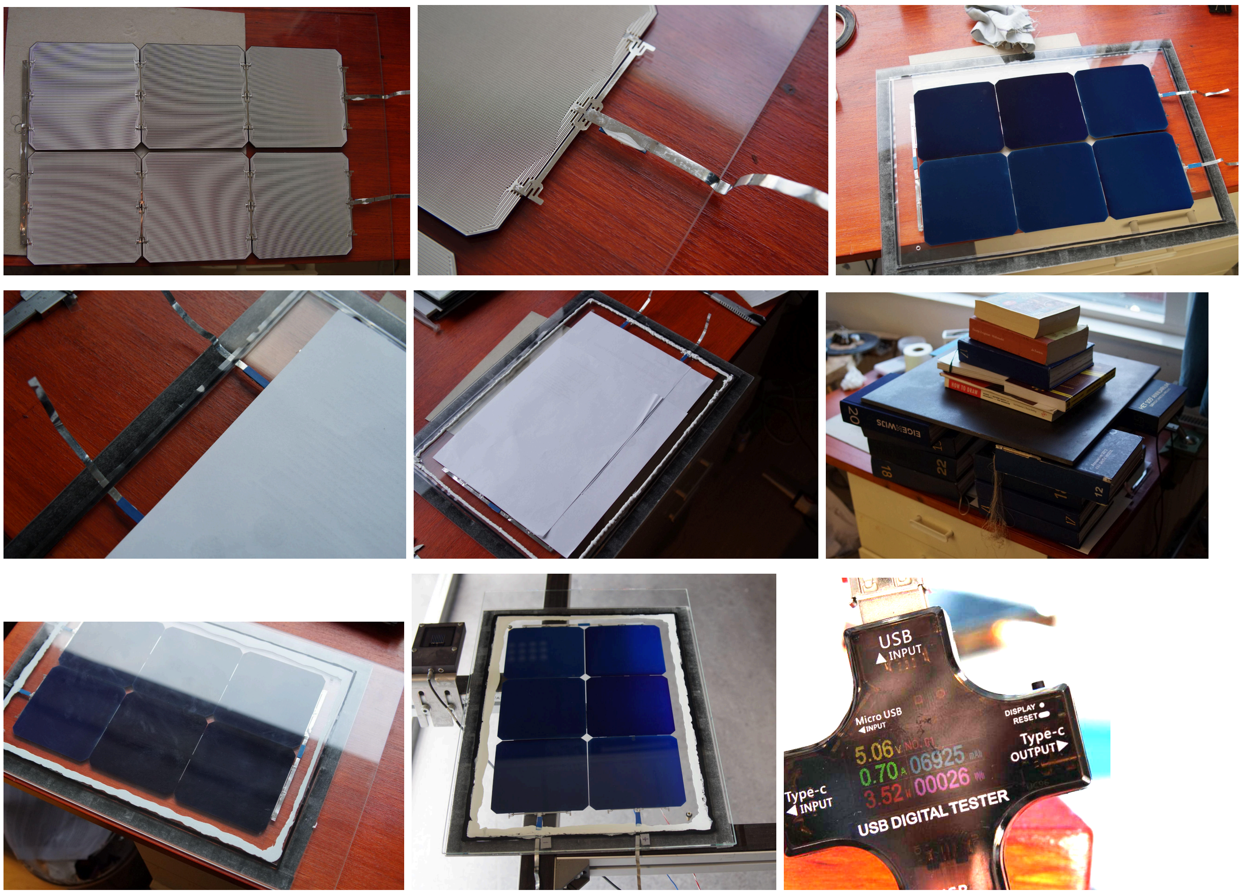


Module prototype development:

During the development process of the solar module, the acrylic back plate, measuring 350x500mm, was precisely cut using a CNC laser. Holes were then tapped into this back plate for future attachment of hose fittings. A silicone sealant was applied along the inner ring of the back plate, while butyl tape was placed on the outer ring to ensure a secure and leak-proof seal.

In the central area of the module, six series of soldered cells were positioned. The busbars were carefully positioned between the layers of silicone and butyl, enhancing the module’s resilience to leaks. For additional security and shock absorption, three rubber strain relief parts were adhered to the top side, and one to the bottom of the bussbars. This arrangement not only stabilized/secured the solar cells but also provided strain relief for the power output cables. Finally, the top tempered glass module was placed over the assembly. Significant pressure was applied to the entire module to ensure firm adhesion and seal integrity. After a few days, allowing sufficient time for all sealants to cure, the module was fully assembled and operational. This process is vividly depicted in the accompanying collage of photographs, showcasing each step of the module's creation:

Table 15 | **Module prototype development**



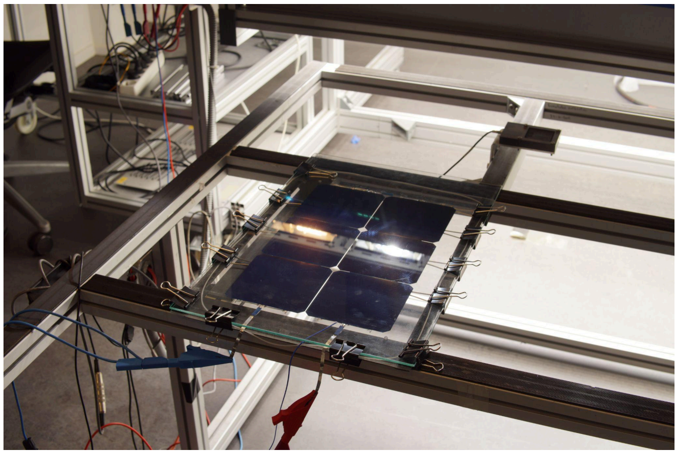
Appendix J Module test Results

Table 15 | Module prototype development

TEST 1 REFERENCE	Duration	Device	Size	Material	Date	Time	Temper	Irradiance	Irradiance	Jsc	Isc	Voc	Impp	Vmpp	Pmpp	FF	Eta	IscSlope
			[cm2]				[C]	[W/m2]		[mA/cm2]	[mA]	[mV]	[mA]	[mV]	[mW]	[%]	**[%]**	[Ohm.cm2]
Time	0 minutes and 0 seconds	**Test_Air_20C**	156,25	None	12/21/2023	**2:32:47 p.m.**	20,445	956,6427	yes	32,22678	5035,434	4298,929	4668,483	3385,754	15806,33	73,01867	**16,86009**	24,72707685
3minutes30seconds	3 minutes and 30 seconds	**Test_Air_30C**	156,25	None	12/21/2023	**2:36:17 p.m.**	21,7	947,4052	yes	32,29813	5046,583	4192,505	4684,306	3288,219	15403,02	72,80061	**16,42989**	34,95802618
2 minutes 3 seconds	5 minutes and 33 seconds	**Test_Air_40C**	156,25	None	12/21/2023	**2:38:20 p.m.**	22,155	948,6421	yes	32,36923	5057,692	4153,014	4639,472	3167,582	14695,91	69,96497	**15,67564**	177,5975758
2 minutes 45 seconds	8 minutes and 18 seconds	**Test_Air_50C**	156,25	None	12/21/2023	**2:41:05 p.m.**	22,415	953,4365	yes	32,59903	5093,599	3956,279	4676,895	3020,009	14124,26	70,08969	**15,06588**	41,40087522
3 minutes 39 seconds	11 minutes and 57 seconds	**Test_Air_60C**	156,25	None	12/21/2023	**2:44:44 p.m.**	22,585	958,7836	yes	32,83561	5130,565	3801,099	4690,804	2898,410	13595,87	69,71605	**14,50226**	23,5409876

TEST 2 OIL	Duration	Device	Size	Material	Date	Time	Temper	Irradiance	Irradiance	Jsc	Isc	Voc	Impp	Vmpp	Pmpp	FF	Eta	IscSlope
			[cm2]				[C]	[W/m2]		[mA/cm2]	[mA]	[mV]	[mA]	[mV]	[mW]	[%]	**[%]**	[Ohm.cm2]
		Air_Ref_21C	156,25	None	1/12/2024	**2:24:50 p.m.**	21,115	940,0527	yes	33,38098	5215,778	4316,723	4870,428	3394,946	16534,84	73,43899	**17,63716**	22,9622172
		Air_Ref_30C	156,25	None	1/12/2024	**2:27:43 p.m.**	30,6	951,5570	yes	33,63302	5255,159	4140,022	4845,589	3177,437	15396,55	70,76770	**16,42299**	22,13901023
Time	0 minutes and 0 seconds	**Oil_27.5C**	156,25	None	1/12/2024	**2:47:14 p.m.**	27,615	948,0563	yes	35,72292	5581,706	4292,710	5186,575	3286,609	17046,24	71,14267	**18,18266**	26,37169946
2minutes7seconds	2minutes7seconds	**Oil_35C**	156,25	None	1/12/2024	**2:49:21 p.m.**	35,66	956,4832	yes	35,89311	5608,298	4133,522	5188,608	3128,717	16233,69	70,02704	**17,31593**	100000000
1 minute 36 seconds	3minutes43seconds	**Oil_40C**	156,25	None	1/12/2024	**2:50:57 p.m.**	41,61	961,2632	yes	35,97421	5620,970	4038,503	5226,124	3022,087	15793,80	69,57528	**16,84672**	100000000
2 minutes 40 seconds	6minutes23seconds	**Oil_50C**	156,25	None	1/12/2024	**2:53:37 p.m.**	50,715	965,7458	yes	36,49747	5702,729	3947,640	5245,791	2896,156	15192,63	67,48584	**16,20547**	18,40658381

REFERENCE AIR TEST



SILICONE OIL TEST