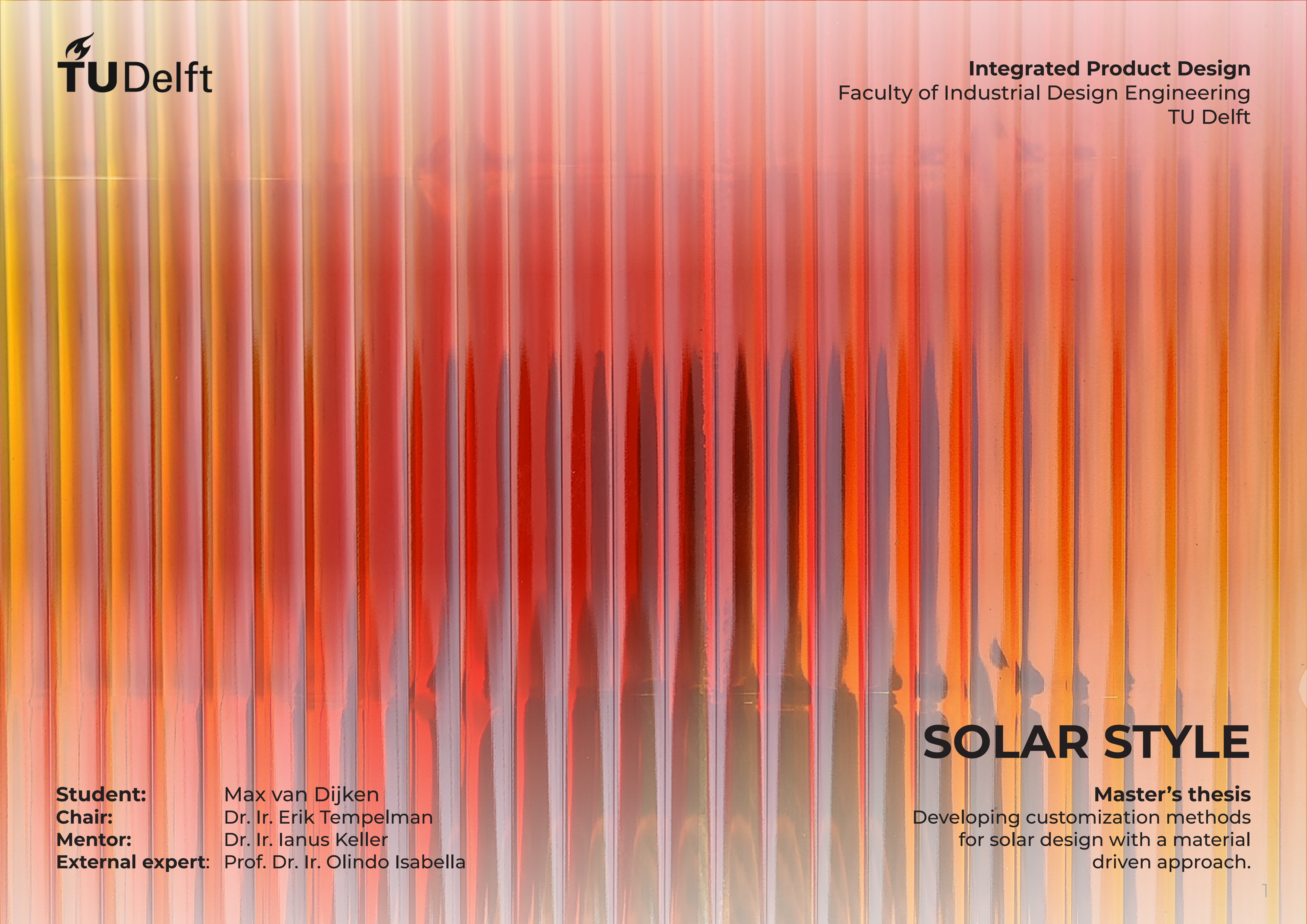
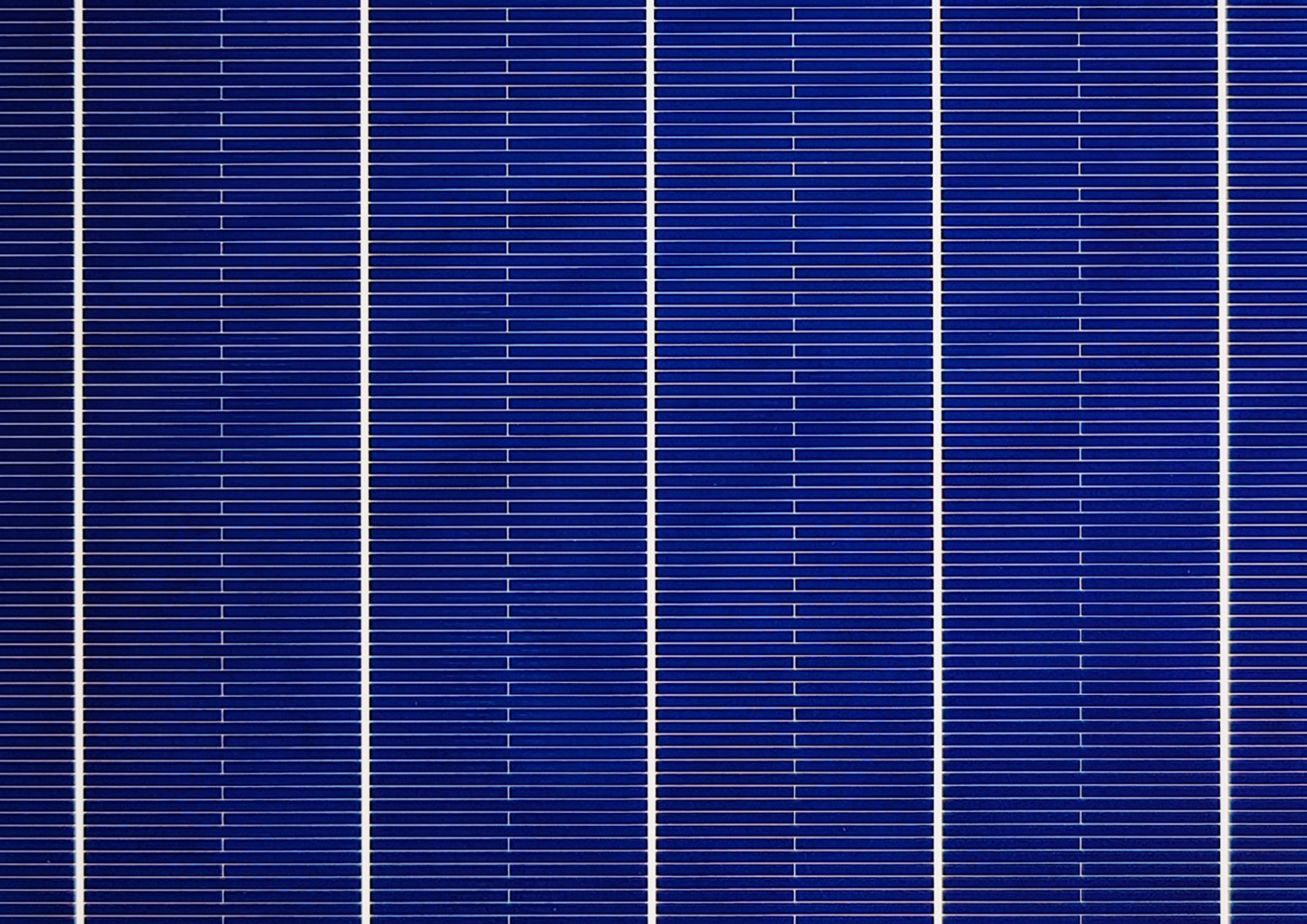


Integrated Product Design
Faculty of Industrial Design Engineering
TU Delft

SOLAR STYLE

Master's thesis
Developing customization methods for solar design with a material driven approach.

Student: Max van Dijken
Chair: Dr. Ir. Erik Tempelman
Mentor: Dr. Ir. Ianus Keller
External expert: Prof. Dr. Ir. Olindo Isabella



SOLAR STYLE

Developing customization methods for solar design with a material driven approach.

06-06-2023

Max van Dijken
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Delft University of Technology
Faculty of Industrial Design Engineering

Supervisory Team

Chair:	Dr. Ir. Erik Tempelman
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SUMMARY

This graduation report covers the process and outcome of developing and designing novel photovoltaic (PV) products for architectural and design applications. The project aimed to find innovative solutions for seamlessly integrating photovoltaics into architecture and design and thus contribute to sustainable building practices. With a hands-on, material-driven approach novel PV customization methods were developed and showcased with a demonstrator. Four concepts were proposed based on PV products made with customization methods that were developed during the project. One of these concepts was worked out into a working prototype. This demonstrated the aesthetic qualities of a novel PV coloring technology. The outcome of Solar Style formed the basis of the continued development and commercialization of PV products.

Figure 1. The prototype showing the outcomes of the project.

CONTENTS

INTRODUCTION

The project was initiated by IPD graduation student Max van Dijken from an interest in Solar Design and an entrepreneurial ambition. Two parties were involved to support with expertise, prototyping, and material provision. These parties were the Photovoltaic Materials and Devices Group (PVMD) from the TU Delft and Van Dijken Glas Beleving B.V. The PVMD group is specialized in PV (manufacturing) technology, material development, modeling, and advanced measurements. Van Dijken Glas Beleving B.V. is a company that processes flat glass. They have a specialization in custom work and high-end (interior) design applications.

A hands-on approach was taken, heavily influenced by the methods of “Material Driven Design” and “Design Driven Material Innovation”. The first part of the report introduces the assignment and provides the context for the project. Secondly, an analysis is provided, looking at the topic from technological, historical, architectural, and design engineering perspectives. This is followed by an overview of ideation and conceptualization where the topics of the analysis phase were embodied in prototypes, sketches, and concepts. Afterwards, a concept was chosen that was developed into working prototypes. The results were incorporated into a demonstrator that was designed as a part of this project. Finally, the solar design concepts were validated on a technical level and a conceptual/design level.

The outcome of the project includes novel methods for customizing solar panels and a demonstration setup to showcase examples of solar panels made using these methods. This resulted in a continuation of the development of said innovations.

Back sheet
The protective layer on the back side of a solar module

BIPV (Building-Integrated Photovoltaics)
Integration of solar panels into building elements while maintaining architectural aesthetics.

Front Sheet
The protective outer layer on the front side of a solar module.

Insert (lamination)
Additional layers incorporated in the lamination stack.

NZEB (Nearly Zero Energy Building)
A building with very high energy efficiency, where the energy consumed is nearly balanced by the energy produced on-site, typically through renewable sources. Also see ZEB.

Optical loss
Reduction in the efficiency of a solar module due to factors like reflection, scattering, or absorption of light within the module.

Photovoltaics
The technology that converts sunlight into electricity using semiconducting materials. Used interchangably with “solar”.

Solar cell
The basic unit of a photovoltaic system that converts sunlight into electricity.

Solar Design
The process of incorporating solar energy systems into architectural and object design to optimize energy efficiency and harness renewable solar power.

Solar Efficiency
The ratio of electrical output power to the amount of solar energy input, typically expressed as a percentage.

Solar Generations
A categorization of solar technologies based on technological advancements and materials, including first generation, second generation, and third generation solar technologies.

Solar module / panel
A collection of interconnected solar cells, encapsulated to form a single unit, also known as a solar panel.

Substrate
The underlying material that supports the solar cells in a module.

Yield
The amount of electricity or energy produced by a solar system over a given period, typically measured in kilowatt-hours (kWh).

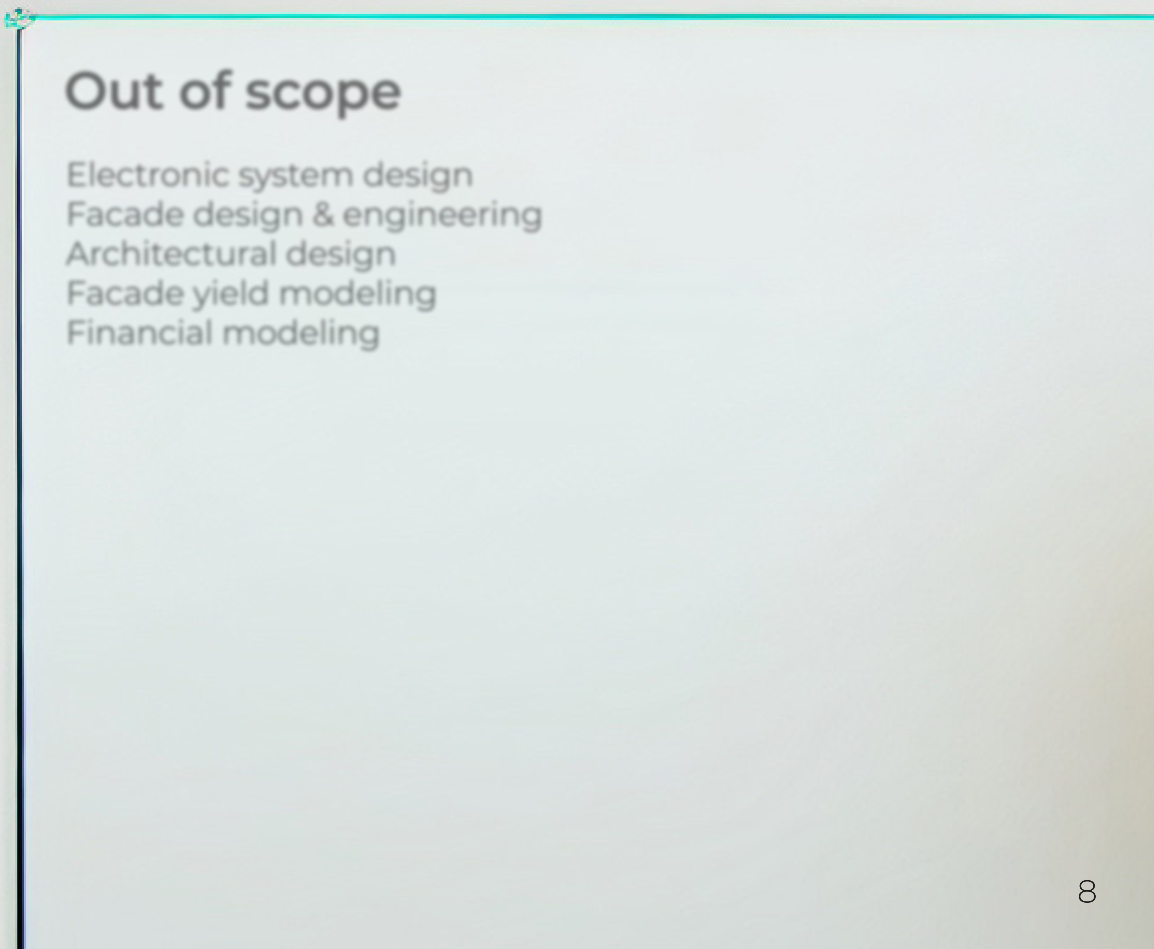
ZEB (Zero Energy Building)
A building that produces as much energy as it consumes on an annual basis, effectively reaching net-zero energy consumption.

ASSIGNMENT

“To design new photovoltaic (PV) products for architectural and design applications that are **visually appealing, provide design freedom, and are functional.**.” Focus on materialization and finding new and creative ways to make solar panels an aesthetic material to design with.

Within scope

Material compositions
Manufacturing
Design research
Design of PV product
Concept development
Market research
IP strategy



There was no assignment from a company since the project was self-initiated. Positive reactions from solar panel manufacturers, other designers, and architects on earlier PV-related work in combination with the experience of working with solar panels resulted in the realization that there were many more possibilities in the field of integrated PV. This formed the start of my motivation to develop novel PV design solutions. The idea behind the way the assignment was formulated was to use my graduation project as a runway to develop PV products that could be taken off as a startup company.

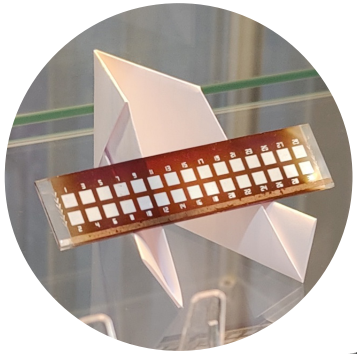
The objective was to design new PV products for architectural applications that are visually appealing and functional. The assignment required consideration of material development, PV product design, concept development, and finding business opportunities to create innovative and marketable products.

The scope of the project can be described in four main categories:

1. The technical aspect of material composition development.
2. The creative aspect of finding the qualities in said material compositions and translating them to aesthetic design solutions.
3. IP management to deal with the outcomes of the project in a manner that is suiting for my entrepreneurial ambitions.
4. A network aspect to map relevant stakeholders and see how my project fits into the ecosystem of the PV industry.

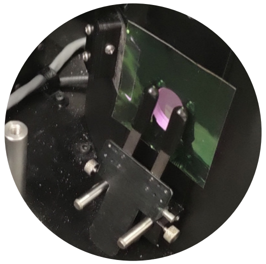
The priority of the project was in the first two topics. The latter two were taken into account but were given less attention. Finally, some topics were left out of scope such as PV-related electrical engineering, facade construction, and architectural facade design to name a few. It should be realized that these are part of the ecosystem of Building Integrated Photovoltaics (BIPV) and they are entire fields on their own.

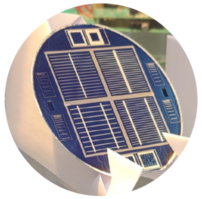
CONTEXT



PVMD
Delft University of Technology

TU Delft





van DIJKEN GLAS
-BELEVING B.V.

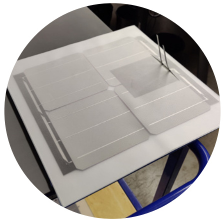
The origin of this graduation project was the result of various societal and personal developments, experiences, and qualities coming together. These include the energy transition, the techno-creative nature of the Integrated Product Design (IPD) track I followed, and my experience with glass as a main ingredient in design from my work at a family-owned glass processing company.

Before starting the IPD master program I was doing a gap year. During this time, I had been looking for opportunities in the glass industry for my job at Van Dijken Glas Beleving B.V. My search led me to solar design. In collaboration with a solar module manufacturer, we started developing colored PV modules. Working on this project was my introduction to the field of PV. Starting my master, I kept working on PV design on the side. The graduation project seemed the perfect opportunity to take this work to the next level.

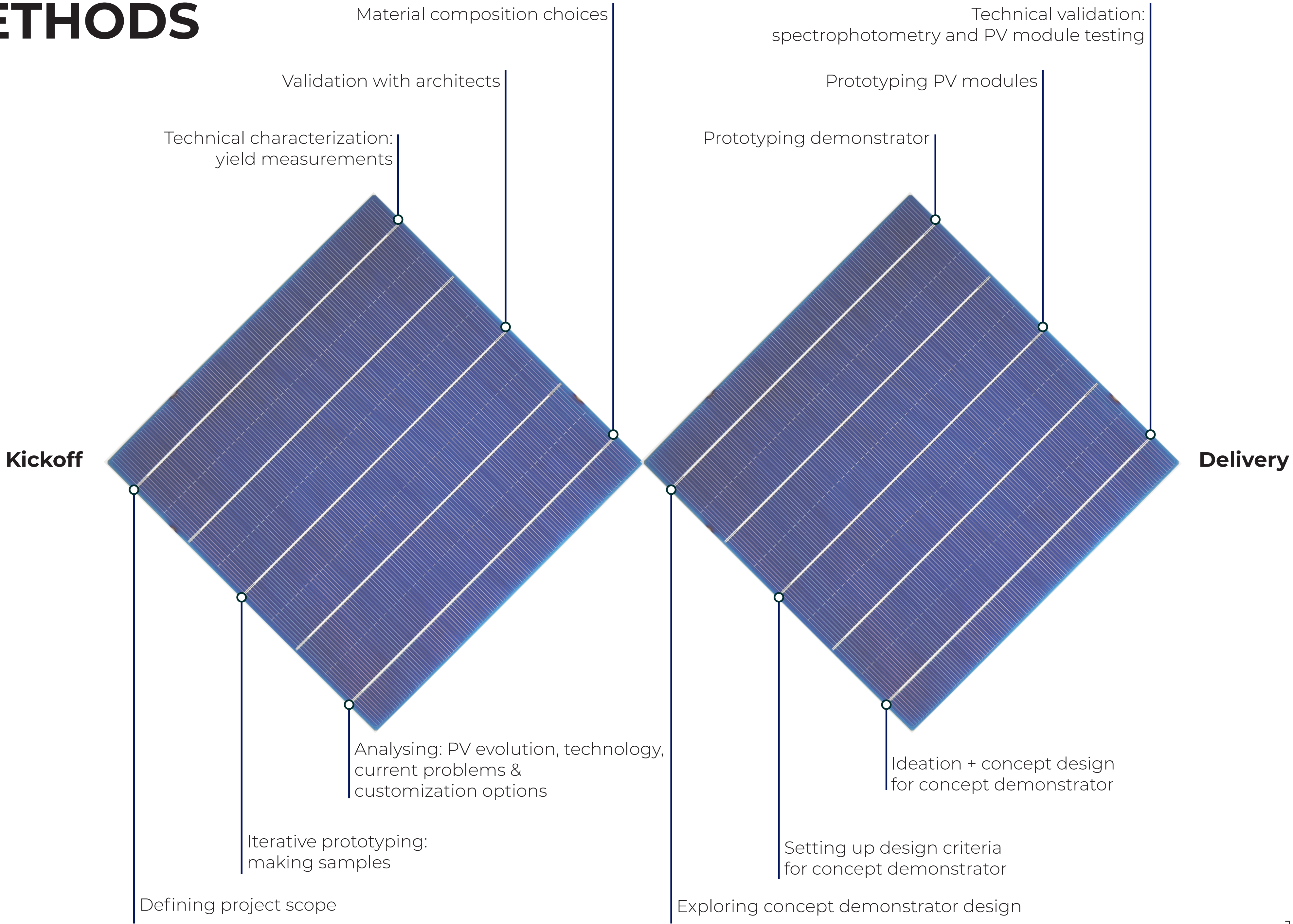
During the project, glass and access to manufacturing equipment were provided by Van Dijken Glas Beleving. B.V. They are a small-sized company specializing in high-end glass design projects.

The other stakeholders included TU Delft and its Photovoltaics Materials and Devices (PVMD) group. This group specializes in the design and fabrication technology of solar cells and other devices based on thin semiconductor films. They helped me with processing results and prototyping. The group is rather technical. With this project, I aimed to introduce a designer's perspective on their expertise.

Max van Dijken



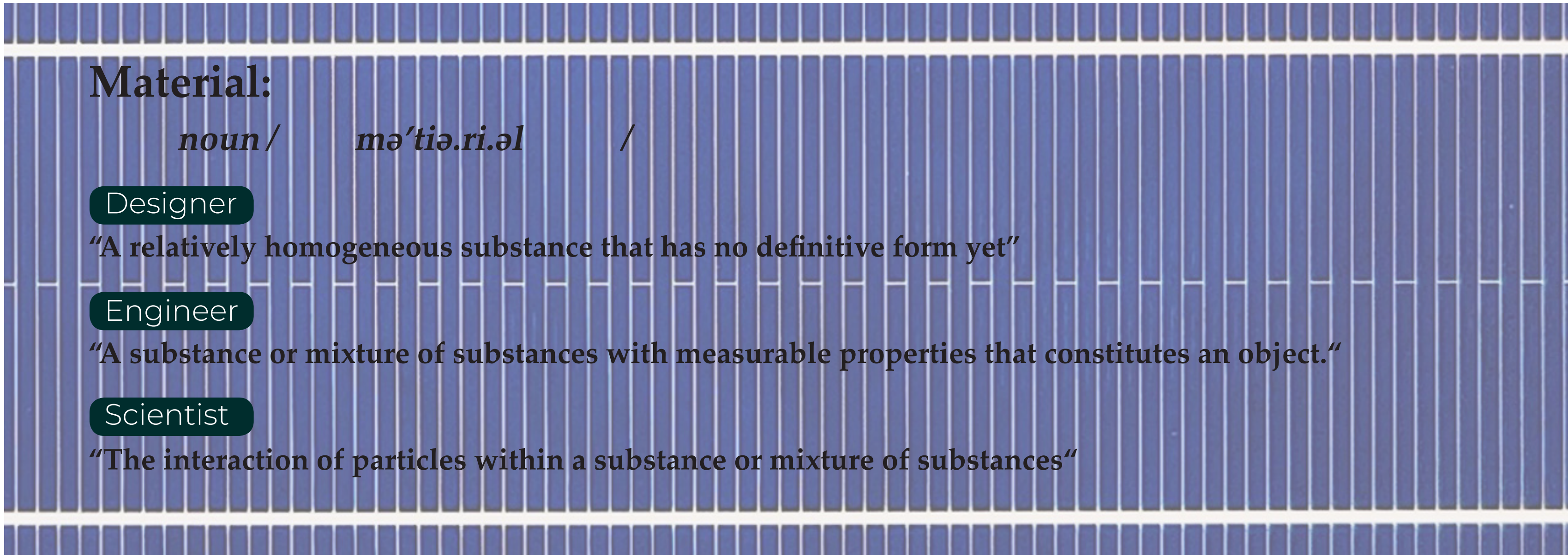
METHODS



Material composition choices
Validation with architects
Technical characterization: yield measurements
Technical validation: spectrophotometry and PV module testing
Prototyping PV modules
Prototyping demonstrator
Kickoff
Delivery
Analysing: PV evolution, technology, current problems & customization options
Iterative prototyping: making samples
Defining project scope
Ideation + concept design for concept demonstrator
Setting up design criteria for concept demonstrator
Exploring concept demonstrator design

Since the aim of the project was to design solutions for PV materials, an approach was taken where materials were central in the design process. Elements were taken from the methods “Design Driven Material Innovation” (DDMI) (Dell’Era et al., 2016) and “Material Driven Design” (MDD) (Karana et al., 2015). These methods were applied to a “standard” design process called the Double Diamond. The double diamond design process is a framework for approaching design problems that involve four phases: discover, define, develop, and deliver.

The starting point of this design project was “PV material”. In other words: materials that have the property to generate electricity when light reaches their surface. Strictly taken, PV is a property of a composition of material layers rather than a material itself. But for me as a designer, this is interpreted as a material. A fitting definition of the word material was “A relatively homogeneous substance that has no definite form yet” (Tempelman, 2022). This meaning could be different from the definition a material scientist or engineer might take. Using this definition of material allowed me to treat it as any other material in a design process and gave me the possibility of applying methods that allow for a more in-depth understanding of the material’s properties and how they can be utilized in a design.



Design Driven Materials Innovation (DDMI)
In DDMI, a back and forth between material science and product design result in a synergetic process that accelerates the speed in which new materials can enter the market in the form of new products and services. Material scientists use input from designers to determine what characteristics of a new material should be prioritized. Designers receive new materials of which their unique properties enable the design of innovative solutions.

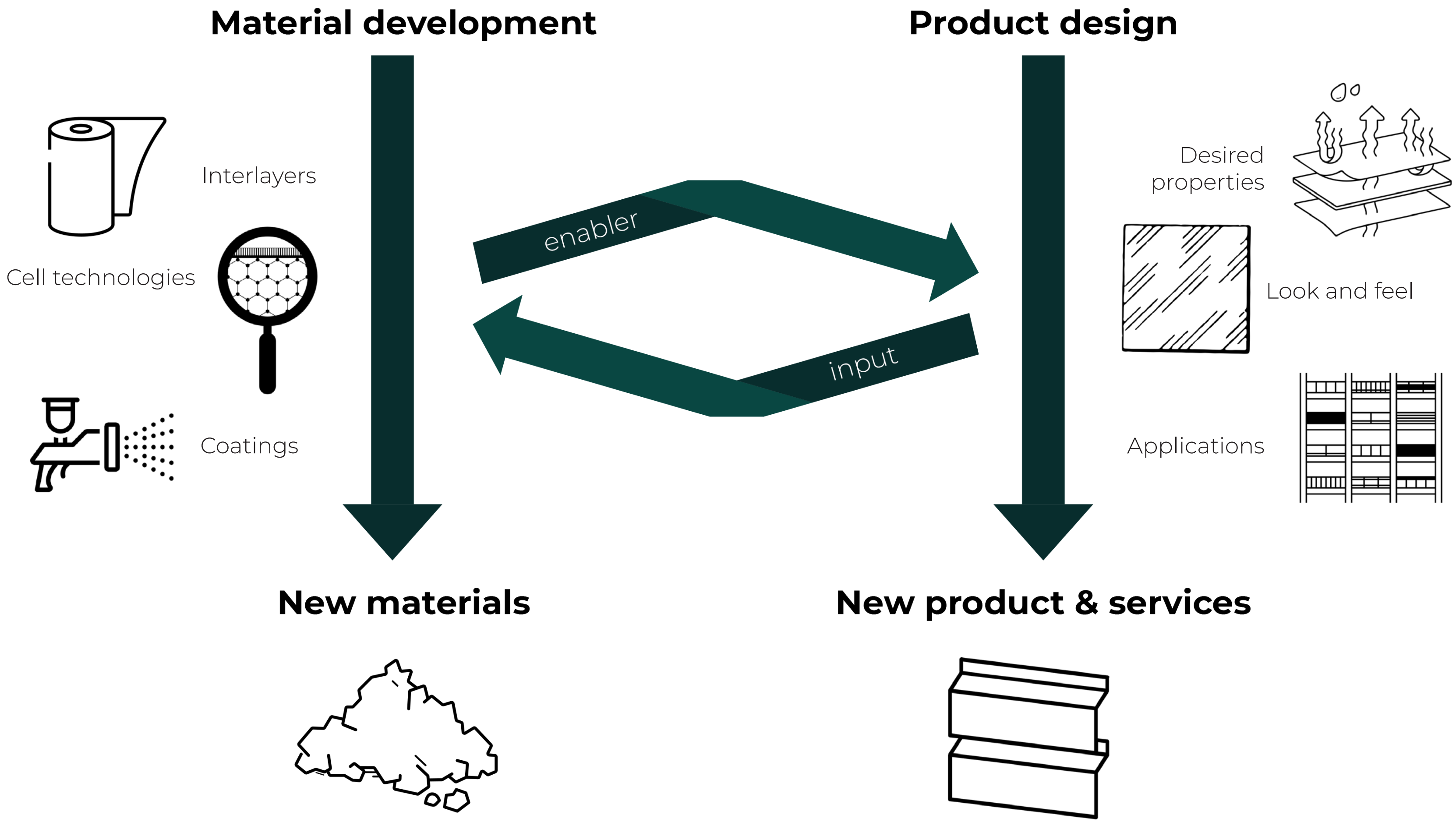


Figure 2. A visualization of the Design Driven Material Innovation process.

In this project, my role resembled that of the designer in a DDMI-like project. A recurring phenomenon was that during my research a certain material or production process enabled a design opportunity. The unique properties were translated into samples to study the effects. In the next iterations I looked for other forms of said material or production process to improve on the sample. Other elements from DDMI that were used were using substitute/dummy materials to imitate and communicate a desired look and feel to save time and costs.

Another design method that was applied to this project was Material Driven Design (MDD) (Karana et al., 2015). It is similar to DDMI because material properties are central in the process and there is a focus on fast, iterative, hands-on design cycles. The main difference between the two methods is the more holistic approach in DDMI whereas MDD is more design focused. My approach was somewhere in between the two. The elements taken from MDD were the use of a technical characterization, creating a material taxonomy, setting up a material vision, and translating this into a design concept.

To summarize: the project largely followed the order of a classical design project using the Double Diamond framework. In this framework elements from DDMI and MDD were applied to make it more hands-on and material oriented.

Working with PV cells hands-on and early on in the process provided a feeling for the material that would have been impossible to obtain with literature research only. Experimenting early ensured I had a minimal bias, which would not have been the case if prototyping/ideating started after a literature analysis.

ANALYSIS

This chapter covers the analysis phase of the project. The aim of this research was to gain insight in the context of the project from multiple perspectives. These perspectives included technical, historic, and architectural points of view. The findings served as the input to set up the main drivers for the project. The following topics are discussed on the following pages:

1. PV technology overview
The pros and cons of the available base materials.

2. Evolution of PV integration
Where do we come from? Where are we going?

3. PV and architecture
How does PV fit into architecture and why is PV adoption so low?

4. Customization options
What can we do to customize PV panels?

5. Product benchmark
What is already available?

PV tech overview

The aim of this research was to explore the available base PV technologies and materials for solar design. On a superficial level, their manufacturing processes were studied as well. The goal was to identify the opportunities and limitations of each technology and to consider the potential for future developments.

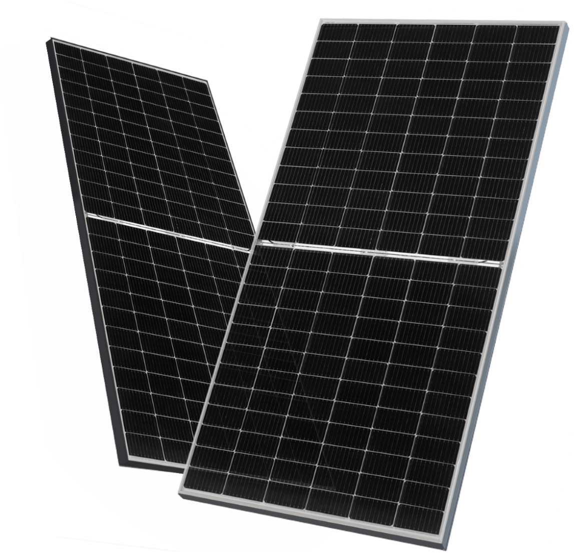
A combination of desk research and expert interviews was conducted. Desk research included reviewing reports from institutions such as, Fraunhofer, NREL, and TNO, as well as papers from the PV and build environment departments of TU Delft. Additionally, commercially available products and suppliers were evaluated, with their specifications being reviewed. Interviews were conducted with experts from Kameleon Solar, Solliance, and Biosphere Solar.

The results of the research provided an overview of the most relevant PV technologies, including their pros and cons. It is displayed on the next pages. Technical facts and information can be found in Appendix A. This figure contains an additional overview of technical characteristics and suppliers. Currently, mono-crystalline technology is the most applicable for most BIPV applications. This is due to the low cost and high energy yield of this technology. However, second and third-generation technologies are rapidly developing. This may change crystalline technology's dominance in the near future. Perovskite technology and the possibility of combining different technologies into tandems are particularly promising, which could make solar panels more efficient, customizable, and flexible.

It is important to note that the availability and accessibility of certain PV technologies are often underreported in reports about PV technologies. While there are many manufacturers that can make crystalline PV modules, this is not the case for other PV technologies, making crystalline technology more accessible for design experimentation.

Overall, this research provided valuable insights into the available base PV technologies and materials for solar design, highlighting the potential for future developments and the importance of considering accessibility and availability when designing PV material compositions and products.

PV tech overview



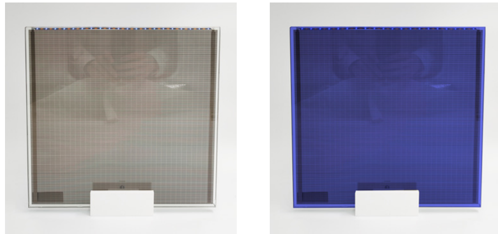
1st generation

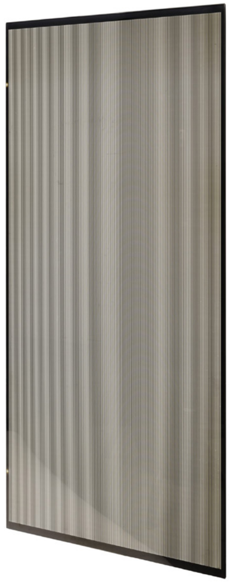
Crystalline Silicon (C-Si)
Largest market share out of all technologies.
Available as glass-glass or glass-backsheet.

Accessible due to many manufacturers.
Lowest module price.
Highest ROI due to relatively high efficiency.
Long life span (>25 years)

Sensitive to heat and partial shading (hot spots).
Low customizability due to wafer structure.

image credit: Jinko Solar





2nd generation (thin film)

Cadmium Telluride (CdTe)
PV layer is directly applied to glass substrate.

Lowest carbon footprint.
Lowest price per watt.
Variable transparencies + color options.
Functions well in low light.

Toxic materials, recycling programs exist.
Lower efficiency compared to C-Si.
Difficult to customize in shape

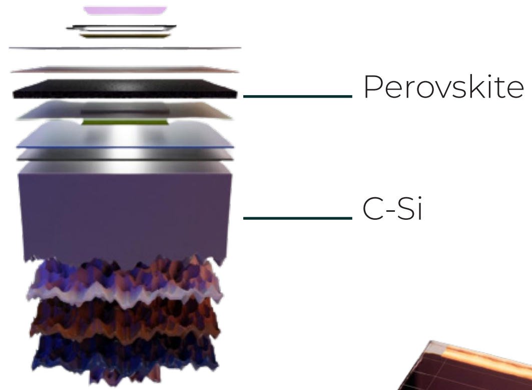
image credit: Toledo Solar

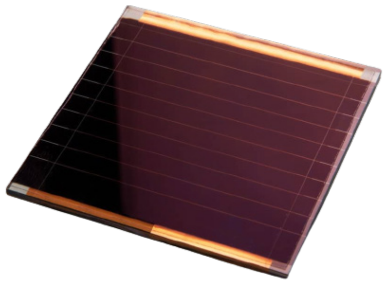
Amorphous silicon (A-Si)
PV layer is applied between polymer sheets

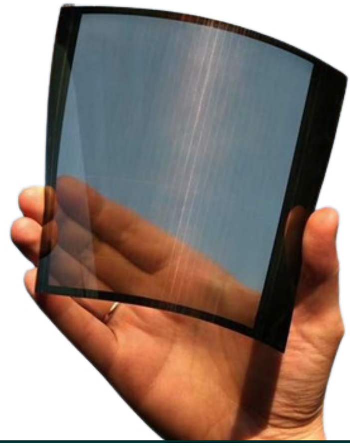
Flexible and light weight.
Easy to install and remove.
Non-toxic
Functions well in low light.

Short life span (10-25 years) vs. C-Si
Lower efficiency vs. C-Si.

image credit: HyEt Solar







2nd generation

CIGS
PV layer is applied between polymer sheets

Flexible and light weight.
Easy to install and remove.
High(er)-efficiency thin film
Non-toxic

Short life span (10-25 years)
Lower efficiency compared to C-Si.

image credit: Amazon

3rd generation

Organic
PV layer is applied between polymer sheets

Flexible and lightweight.
Highly customizable in shape and color.
Easy to install and remove.
Performs well in low light.

Low overall efficiency.
Cleanest technology
Shorter life span compared to other techs.

image credit: ASCA, Infinity PV

Perovskite and tandems.
Considered the future of PV.

Abundant and cheap materials.
Potential for high efficiencies.
Flexible and lightweight.
Highly customizable in shape and color.
Easy to install and remove.
Clean technology

Low TRL.
Less scalable due because less mature.

image credit: TNO, Eike Köhnen/HZB

Evolution of Photovoltaics

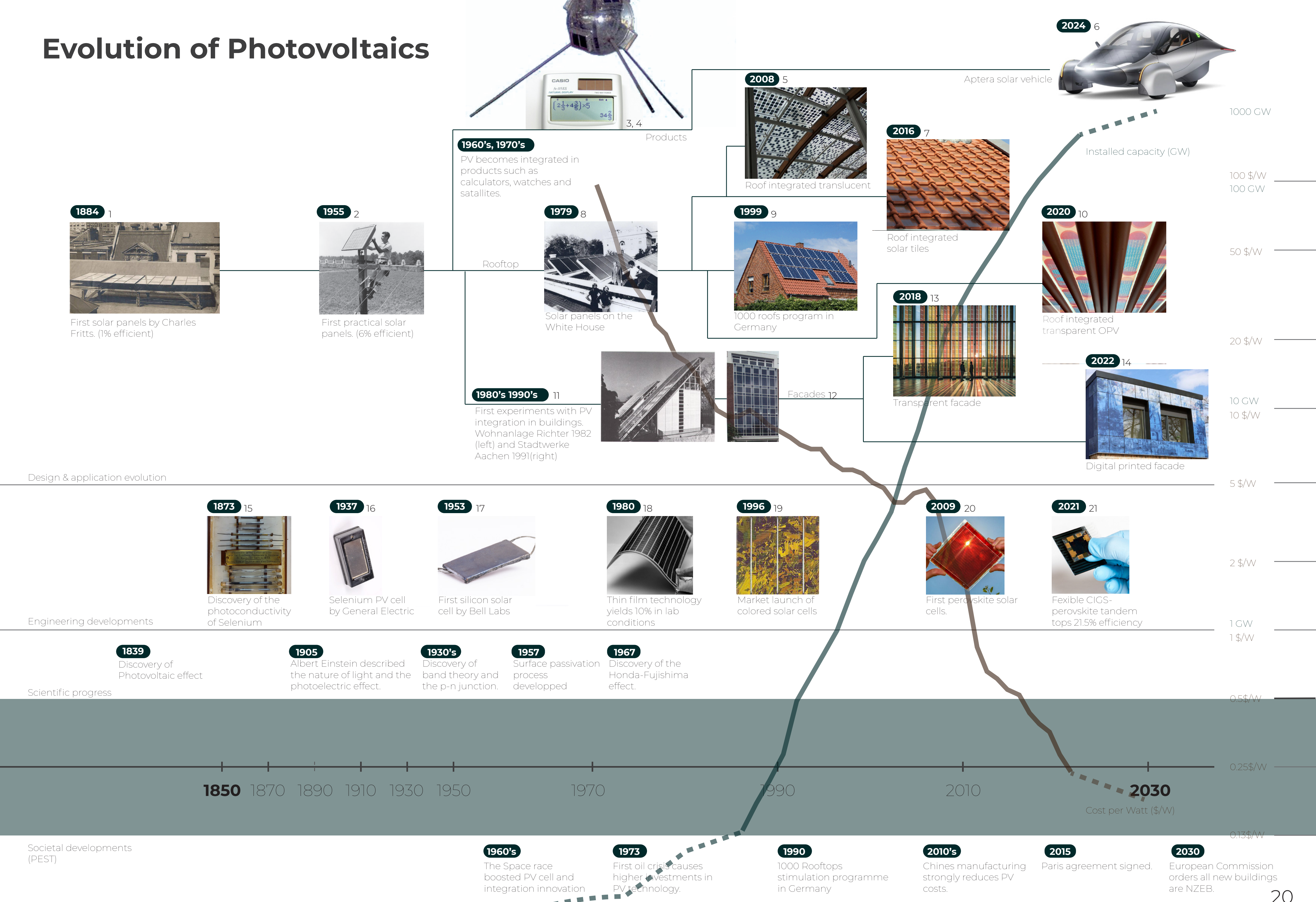


Image credits: 1, 15. John Perlin; - 2. Bell Labs. - 3. Casio - 4. NASA - 5. Solstice - 6. Aptera - 7. Ecoenergy - 8. The White House - 9. birgstockphoto.com - 10. V8 - 16, 17. Museum of Solar Energy, Karl Wagner; 13 SwissTech Convention Center; 14. Kameleon Solar. 19: LOF Solar - 20, 21: Solliance

A brief history of PV integration

This section explores a broader perspective on PV technology in general by displaying its evolution from discovery to the current state of the industry. Understanding the evolution of PV technology is important because it provided insight into the logical next steps in the industry. This knowledge also provided insight into how science, engineering, design, and societal developments will continue to influence the evolution of PV technology and its applications.

An Evolution in Design (Eger & Ehlhardt, 2017) inspired framework was used to analyze the evolution of PV technology on four levels: a scientific level, an engineering level, a design level, and a societal level. Information was found through desk research using reports (Corti et al., 2020), (Rode & Crassard, 2007), and books about solar design (Van Aubel, 2022). The price per Watt and total installed capacity were found in (Solar (photovoltaic) panel prices, z.d.) and (Installed solar energy capacity, z.d.) respectively.

The design of standard PV panels has almost stayed the same since the first one was made in 1854. This was because the design allows for the most efficient energy yield. However, integration happened from an early point, which can be seen in the solar gadgets from the 1960s and the first building-integrated photovoltaic (BIPV) applications in the 1980s. As the cost of PV technology dropped and its capacity increased, so did the variety of integration options. In the last decade, the cost per watt turned low enough to give in on energy yield efficiency to increase aesthetic value. PV manufacturing, especially with Si cells, has become more accessible, making experimentation easier.

As the installed capacity increased so did the public resistance against them. This included complaints about large fields full of solar panels (Geurts & Heeringa, 2023). Opposition pleaded for using solar panels on places where energy is being consumed as opposed to using agricultural land and transporting it (Hansen, 2021). As a response projects with smaller, more aesthetically pleasing PV panels have increased, and manufacturers have started producing panels in a variety of sizes, colors, and shapes.

All in all the evolution in solar design had a significant impact on solar design, particularly in the area of building-integrated photovoltaics (BIPV). BIPV systems integrate PV panels into building facades, roofs, and windows, creating a seamless and aesthetically pleasing design. The availability of smaller and more flexible PV panels has made it easier to integrate them into building designs without compromising on aesthetic appeal. If the other PV technologies make the same progress as crystalline technology in terms of price reduction and efficiency increase, more integration opportunities will emerge.

Despite all the criticism of solar panels and the recent developments in aesthetic solar design, BIPV only accounts for about 2-3% of all installed solar capacity. The next chapter report on why this is the case.

PV and architecture

BIPV currently makes up only 2-3% of the total installed PV capacity. Why is adoption in facades so low? And what can we do about it? This chapter covers the question of why the worlds of solar design and architectural design do not have the desired synergy that is necessary to make the zero-energy architecture ambition a reality. Firstly, the issue is covered by the current state of architects' attitudes towards BIPV. Secondly, facades and aesthetics in architecture are discussed in a more general manner. The chapter ends with a discussion of how these two topics come together and how solar design can bridge the gap between PV technology and architectural design.

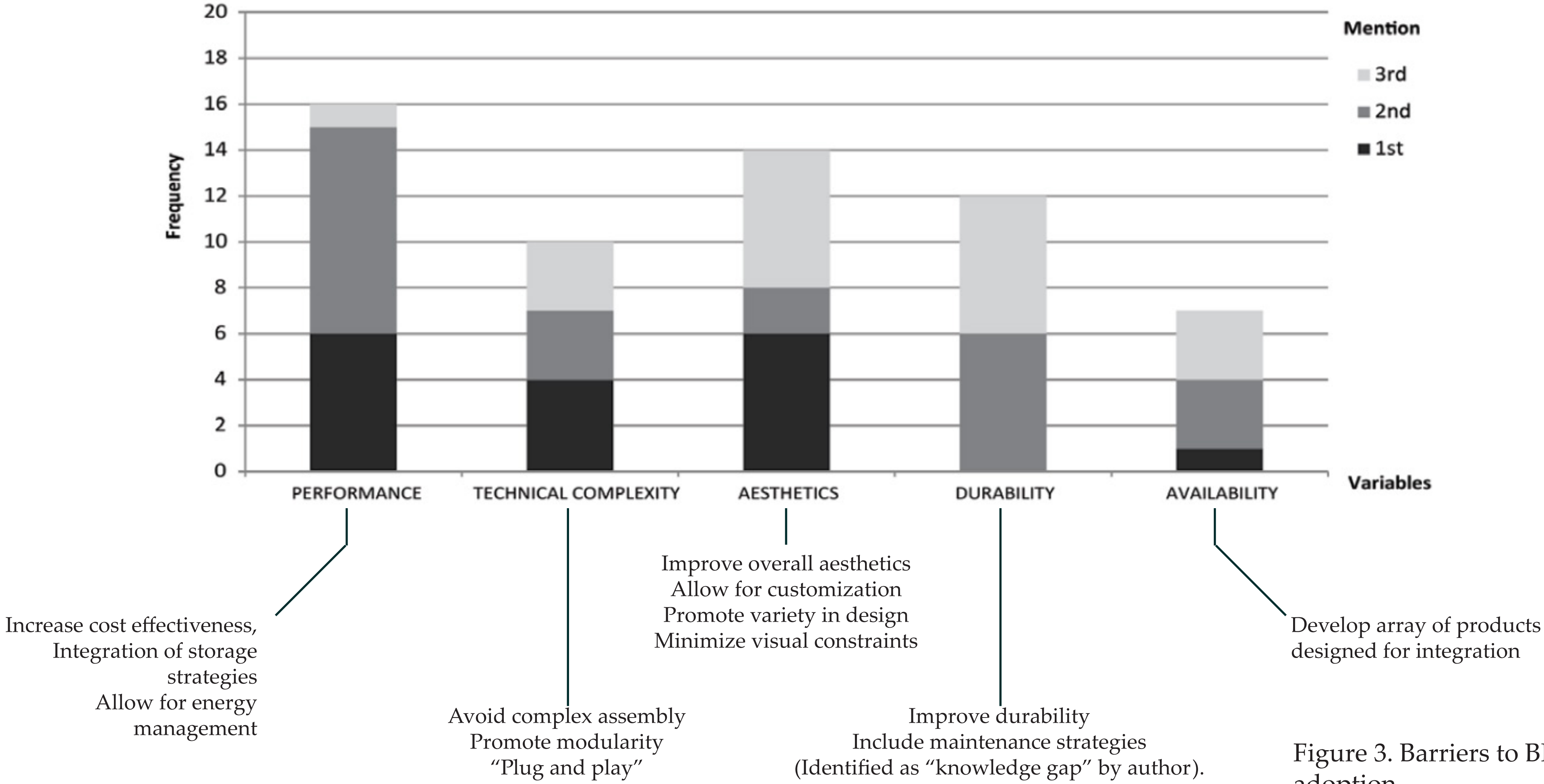


Figure 3. Barriers to BIPV adoption.

BIPV currently makes up only 2-3% of the total installed PV capacity. Why is adoption in facades so low? And what can we do about it? This chapter covers the question of why the worlds of solar design and architectural design do not have the desired synergy that is necessary to make the zero-energy architecture ambition a reality. Firstly, the issue is covered by the current state of architects' attitudes towards BIPV. Secondly, facades and aesthetics in architecture are discussed in a more general manner. The chapter ends with a discussion of how these two topics come together and how solar design can bridge the gap between PV technology and architectural design.

To gain insight into why BIPV adoption is lacking, two main sources were consulted: Haghighi et al. (2021) and Prieto et al. (2017). Both of these papers turned to build environment experts to research their attitudes towards BIPV and found barriers that need to be overcome to make BIPV a commercial success.

To analyze the current state of architectural design with a focus on aesthetics in facades, two architectural views were studied. The minimalist movement and a contemporary counter-reaction to said movement.

When Prieto et al. (2017) surveyed architects and engineers about their perceived barriers to BIPV adoption they responded with the answers displayed in Figure 3. The key aspects to overcome are noted below. It shows that "performance" seems to be the most important issue based on the total amount of mentions. However, "aesthetics" comes second and was mentioned first by most participants. Remarks about the aesthetics of current products regarded the lack of customization in design and promoting a variety of terms shape, colors, size, texture, and transparency. "Technical complexity" and "durability" followed and were about the need for "plug and play" systems and the issue of taking care of the panels respectively. The latter is described as a "knowledge gap" by the author. Finally, the issue of availability was addressed. Here the participants complained about a lack of products to choose from in the market.

Haghighi et al. largely agreed with the results described by Prieto et. al. However, in this paper, the context of architects applying BIPV to their design process was taken into consideration. Their findings suggest that there was a direct link between the moment when PV was introduced to the design process, the type of PV product, and the surface used for the application of PV. Introducing PV late into the design process often makes it difficult to blend it as a part of the architecture. Another interesting finding from this paper was a division in vision on PV in architecture. There seemed to be two main attitudes regarding integration. The first is that PV materials should be displayed in full vision. The other is that PV materials should be hidden and seamlessly blend in with the building.

Whatever the building style, integration is about being a part of the concept of a building. Modern architecture is often characterized by its minimalistic appearance. Going even as far as associating the use of ornament with crime (Loos, 1997). As a result, modernist buildings were often composed of pure forms and were justified by their economic practicality and utilitarian qualities. There is a counter-movement on the rise though. Among them is architecture professor Nikos Salingaros. He suggests that details and ornamentation in architectural design play an important role in establishing a human connection to geometric structures such as buildings. Our brains are naturally wired to quickly identify patterns and areas of high contrast, and an appropriate level of ornamentation can help to stimulate the brain. Instead of making everything smooth and blank, we should strive for "ordered complexity" (Complexity & Order | rootedinnature, z.d.). Therefore, incorporating ornamentation in architectural design can not only enhance the aesthetic appeal of buildings but also contribute to the overall wellbeing of individuals interacting with the built environment.

The current challenge to increase BIPV adoption mainly comprises of improving aesthetics while minimizing performance loss and aiding architects in the design process. I am of the belief that this can go hand in hand with the return of ornament in architecture since PV material has the ability to make ornaments functional additions to a building rather than a "mere" decorative element which ornaments are currently criticized for.

PV customization options

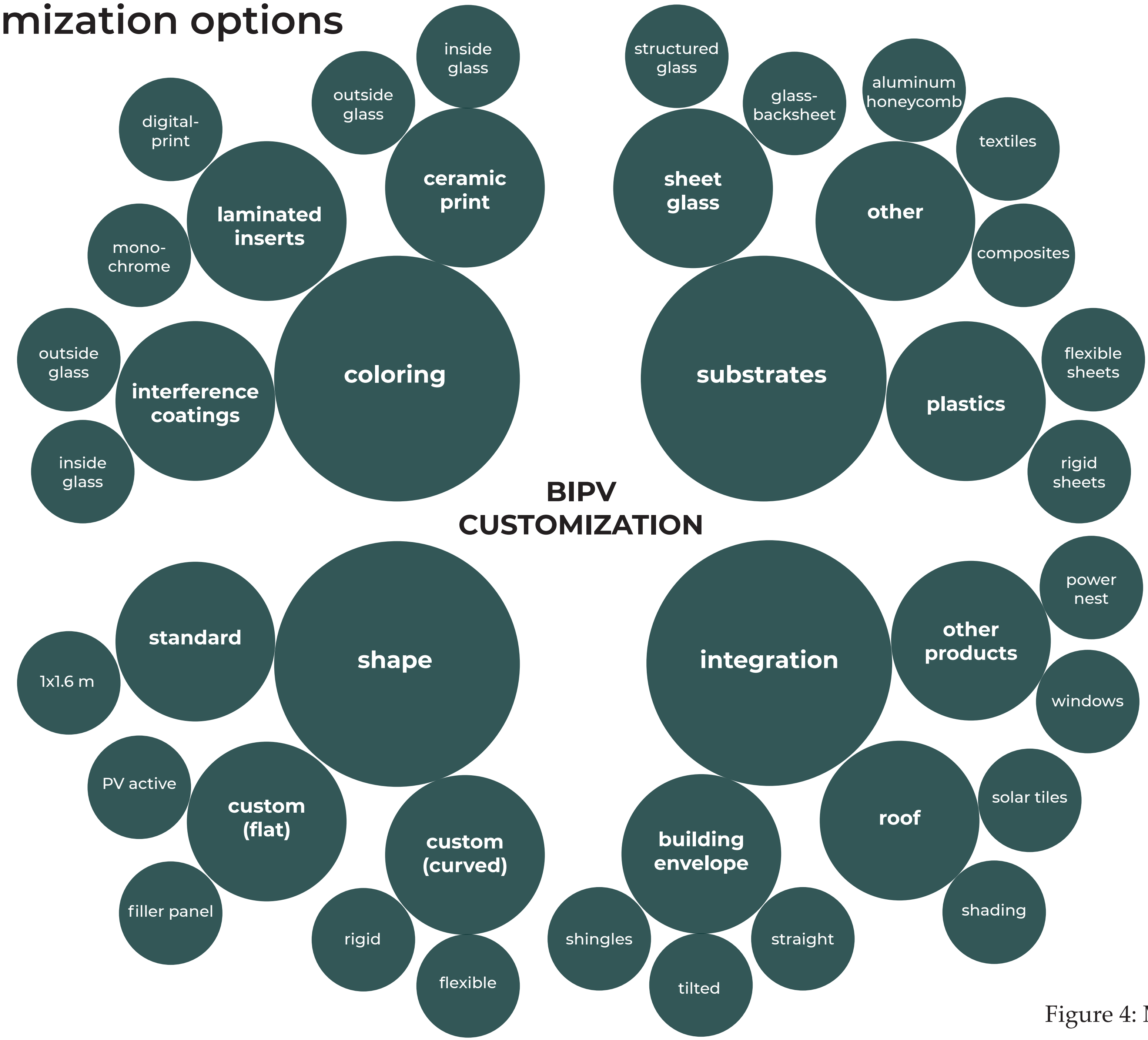


Figure 4: Material taxonomy

The customization of BIPV materials is a crucial aspect of solar design. As mentioned in the methods section of this report, solar cells were interpreted as a material. They are the base ingredient and this material taxonomy provides an overview of the processes and steps that can be undertaken to tailor PV products to the vision of an architect or a designer.

The material taxonomy was developed through a combination of literature reviews, interviews and experiencing the process of making solar modules. Sources included commercial BIPV manufacturer's websites (Kameleon Solar | Home, 2023.), and webinars on PV customization (Mass Customization Archives - Solliance, z.d.). Interviews with manufacturers of BIPV products (Reddy, 2022). The taxonomy was developed by classifying PV materials according to their shape, substrate types, coloring methods, and ways to integrate PV materials into buildings.
No specific PV technology was chosen as the base for the taxonomy. Most options are applicable to all PV technologies. There are some exceptions though so one will always need to check whether it makes sense to use a certain operation with the base technology of choice.

Coloring:
The main three coloring methods are interference coatings, laminated inserts, and ceramic prints. Interference coatings provide a uniform color by selectively reflecting one wavelength of color (Lizcano et al., 2021). Laminated inserts are colored films, laminated in the PV panel stack. These can be used for opaque or transparent applications (Onyx Solar, z.d.). Lastly, there are dot prints. Here a dotted pattern is applied to a sheet of glass to color a PV module (Kameleon Solar | Home, 2023). Depending on the desired effect and the nature of the process, color can be applied behind the front sheet or on top of the front sheet to reduce glare.

Substrates:
There are several possibilities when it comes to substrate types, including glass, plastic, and composites. Glass is a common choice due to its high transparency, durability, and weather resistance. Plastic substrates are tough and lightweight, making them ideal for use in BIPV and BAPV applications. If the base technology allows it plastic substrates can also be used to make flexible solar panels. Composite substrates are lightweight, flexible, and can be molded into different shapes, making them suitable for curved or irregular surfaces.

Integration:
The appearance of a building can be enhanced by various ways of integrating BIPV products into it. One of the most common ways is to use PV panels as a building envelope. A frequently used method is the use of solar shingles. Another approach is to use solar roofing, which either replaces traditional roof tiles or provides shading while allowing for natural light to pass through. Lastly, there are the other more experimental forms of integration such as solar windows (Home - Ubiquitous Energy, 2023) and solar-wind combinations (Hernieuwbare Energieoplossing PowerNEST – IBIS Power, z.d.).

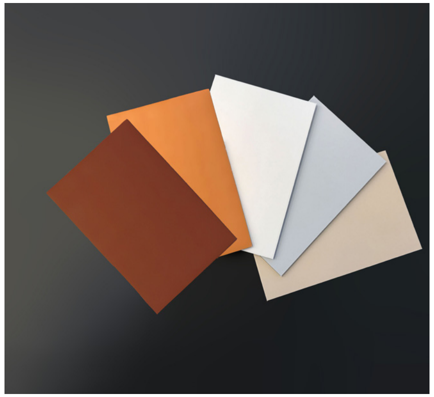
Shape:
A standard, mass-produced shape of a solar panel is a rectangle of about 1x1.6m. For BIPV applications custom sizes are often desired. Basically, any shape can be made as the base unit of your technology of choice can fit into the panel. This is not always the most practical approach and often filler panels are used that are not PV active.

The material taxonomy provides a framework for designing customized BIPV products by showing the selection of shapes, substrate types, coloring methods, and integration approaches.
For each process, it is important to check whether it is compatible with other desired options. Considering these complex underlying conditions it is wise to start with either the architect's/designers' vision or with another important criterion such as the PV technology that will be used and work from there.

Benchmark

Interference coatings (Si)
Image: Kromatix

Laminated color films
Image: Solaxess

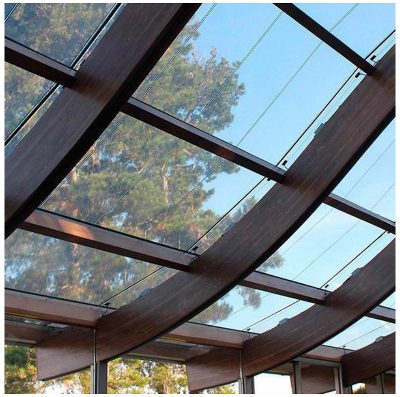


Ceramic prints
Image: Kameleon Solar

Laminated print films
Image: Team Harmony

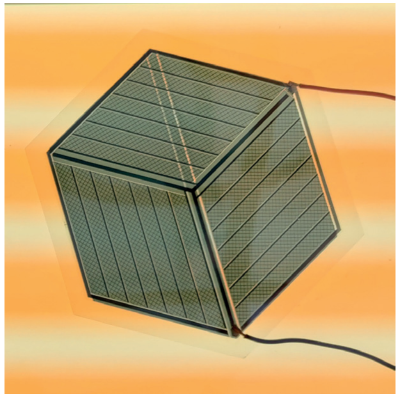
design freedom

CdTe with colored PVB
Image: PV Magazine



Amorphous silicion skylight
Image: Onyx Solar

efficiency



OPV film

Figure 5: Benchmark map

A product benchmark was performed to find products with commercial and technical success. The aim of this section was to find patterns in what makes a successful BIPV product and to draw inspiration from what is already on the market. It also served as an overview to compare the outcomes of this project.
The benchmarking was conducted by selecting seven BIPV design products that are representative of the current market. The selected products were:

1. Interference coatings: Kromatix colors are produced by manipulating light waves that interfere with each other, resulting in vibrant colors. Kromatix provides a relatively low design freedom for the only customizable factor is the color. The decrease in PV efficiency is minimal though, as the coating only reduces the efficiency by about 2-4%.

2. Colored films: Solaxess provides a range of colored films that can be applied to solar modules. The films are laminated on top of the cells, providing a degree of design freedom, as the material of substrate can be chosen by the designer. However, the decrease in PV efficiency is higher than interference coatings, as the films reduce the efficiency by up to 10%.

3. Amorphous silicon skylight (Onyx Solar): Onyx Solar offers an amorphous silicon skylight that can be customized in terms of size and shape, color, and grade of transparency. This provides a high degree of design. The decrease in PV efficiency is moderate because of the nature of A-Si technology.

4. Semi-transparent CdTe modules offer a medium because the transparency degree can be customized. However, it is more difficult to customize the shape. The low amount of suppliers also makes the threshold rather high for experimentation. Monochrome interlayers can be added though to customize the color of the modules.

5. Ceramic printed modules (Kameleon Solar): Kameleon Solar offers a range of ceramic printed modules that can display any graphic. The modules provide a high degree of design freedom, as they can be printed in a range of colors and patterns. However, the decrease in PV efficiency is significant, as the printing process reduces the efficiency from 20% up to 40% depending on the coverage rate of the print.

6. Laminated graphic films: Powergraphic offers a range of laminated graphic films that can be customized according to the building's architecture. The films provide a high degree of design freedom, as they can be printed with high-resolution images and highly vibrant colors. However, the decrease in PV efficiency is high, as this process reduces the efficiency by about 40 to 50%.

7. Organic PV film: ASCA offers an organic PV film that can be applied to a range of surfaces. The film provides a high degree of design freedom, as it can be customized according to the building's architecture. However, the efficiency is rather low compared to other products.

The criteria to rate the design freedom included the nature of coloring techniques, whether a product could be combined with different types of substrates, freedom in shape and size flexibility in curvature, and other characteristics specific to a certain product. The efficiency of the products was found in spec sheets or online.

The first thing that the benchmark showed was that the amount of design freedom negatively relates to the efficiency of a product for commercially available products. Even products having a reduction in efficiency of up to 50% have a right to exist as long as they offer aesthetic value, design freedom, or another key advantage. The success of a BIPV product seems to depend on striking a balance between design freedom and PV efficiency.

Analysis - discussion

This analysis provided a wide range of insights about the important topics in solar design on a technical, design, architectural, and historical/societal level. By simultaneously analyzing the theoretical aspects of solar design and working hands-on and iteratively on prototypes both a practical feeling and a theoretical expertise on PV materials was gained.

The low adoption of BIPV products in architecture has several reasons. Firstly, BIPV is still a relatively new technology, and the market is still developing. Secondly, BIPV systems are often more expensive than traditional rooftop solar systems, which can be a barrier for many building owners and developers. However, as seen in the historic analysis, improving technology in combination with stimulating policies and regulations could change rather quickly.

Moreover, there may also be a lack of awareness among architects and designers about the benefits of BIPV (Prieto et al., 2017), such as energy savings and aesthetic potential, which is there as seen by the various ways PV materials can be customized on a cell, module, and integration level.

With the increasing focus on sustainable building practices, the need to reduce carbon emissions, increasing energy prices, and political incentives to become more energy-independent, BIPV is expected to grow in popularity in the coming years. The challenge in designing a successful product lies in striking a balance between design freedom, aesthetic effect, and maximizing yield efficiency. More design freedom often means less module efficiency. However, less design freedom does not necessarily mean less aesthetic value. Making clever use of the available customization technologies can combine efficiency with a highly aesthetic look and feel.

Material vision

There are currently two options when BIPV is used in architecture. The first option is that PV panels are added later in on in the design process. It is then difficult to integrate as part of the architectural concept and budget wise there will be problems. It will most likely look like an add-on than a seamless part of the building. The second option is that the architect knows BIPV will be part of the concept and they can take it into account from the start. The options are fairly limited though and the threshold to use the products seems rather high.

I envision a future where architects choosing PV materials in their designs is the rule rather than the exception. A wide range of products will be available with unique and distinct looks and feels. BIPV products should be aesthetic and desired materials for their appearance in the first place and their ability to generate electricity should almost be taken for granted. I draw inspiration from the way exclusive car brands present the electrification of their vehicles. First and foremost they offer a car that provides the same luxurious feel as their customers love them for. Secondly, it is electric so it is cleaner, pulls up fast, and is more sustainable. The fact that it is a little less economical is of nobody's concern.

For this vision to become reality there is still a lot that needs to happen. The range of available products will greatly need to increase, the threshold for working with PV materials should lower and regulations and policies will need to continue to be implemented. I believe the first step in this transition is to show the beauty and diversity that can be achieved with PV materials as the basis.

MAIN DRIVERS

Main Drivers for material design:

> ***Aesthetics and design***: the outcome of the project should provide a high amount of design freedom for architects and designers to let them create aesthetic buildings and objects.
>
> ***Performance*** needs to be maximized and rival or outperform current comparable commercially available solutions.
>
> A ***Technology readiness*** level of 4 should be achieved: lab-scale working prototypes are the goal.
>
> The material developments should be ***Future proof*** by taking emerging PV technologies and design opportunities into account.
>
> The material concepts should be ***Integratable***. Meaning the outcomes can be a seamless part of architectural and/or design concepts.

Main Drivers for material design:

> The demonstrator should ***communicate the broad range of possibilities*** of solar design.
>
> ***Display the aesthetic value*** of the prototypes and catch the attention of people that pass by.
>
> It needs to ***show the PV functionalities*** of the panels without the need for signs saying “I am a solar panel”.
>
> It should also be ***easily rearranged*** and adjustable to different settings.

IDEATION

Ideation

This chapter covers the ideation phase of the project. It was conducted partly before and partly simultaneously with the analysis phase. If there was no deadline on this project it would have continued to this day.

The process of ideation consisted of an alternation between exploring the aesthetic and technical characteristics of light transmissive materials, implementing information from the analysis phase in prototypes and pre-concept ideas, and getting inspiration from architecture and design examples.
Aesthetic qualities were explored firstly on a material look and feel basis. Coloring possibilities, surface structures, and various treatments of different materials such as glass, plastics, and wood were explored. Often various iterations were needed to get to the desired effect. Most PV materials are black because that absorbs the highest amount of light. Therefore, solutions needed to be applied to a black background. This was easily replicated using black paper, black spray paint, or other black materials that were easily accessible.

Each layer that was put in front of PV cells reduced the yield to a certain amount. To get an idea of the power yield, technical specifications from suppliers were used. If this was not available, the materials were placed above a functioning PV cell illuminated by a solar simulator. The IV curves were measured. From this, an estimation of power reduction was estimated. The measurement results and calculations can be found in the Appendix B.

Other technical properties besides light transmission of additional layers were used as input for ideation as well. The characteristics on a cell technology level were taken into account. Some PV technologies offer characteristics such as flexibility or lightweight. This offered interesting opportunities on multiple levels such as the ability adapt to the shape of different substrates. Another example was the transparency of PV cell technology. This characteristic was used as a starting point and from experience with coloring and structuring glass, interesting customizations could be made.

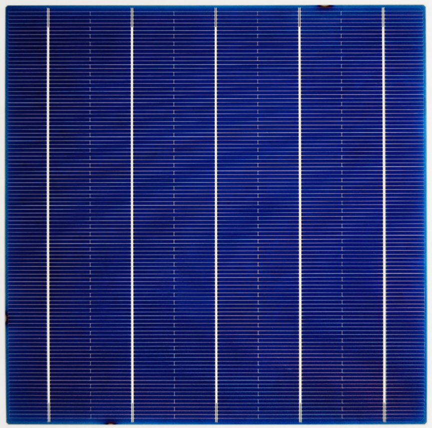
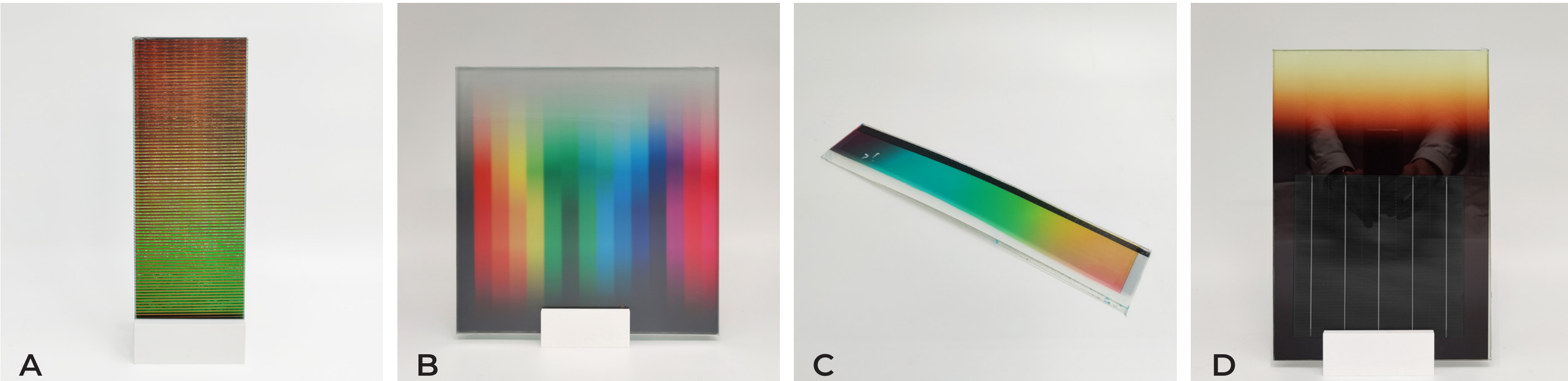


Figure 6:
This image shows a PERC silicon (Si) cell. This is one of the various types of Si cells. For most PV design applications this will be the main ingredient. It is up to the designer to either show or hide this key component. In the case of the former, the challenge lies in creatively making use of its basic appearance. In the case of the latter, there is a trade-off between energy efficiency and aesthetics. A good understanding of the reflection and transmission of the layers in front of the cell is essential in the design of the composition.

Technical characterization

Dichroic structures
155 Wp/m^2
technology: C-Si
Glass - glass
Opaque
Colors: 8 base colors
Other options: structured glass

Color flex
60 Wp/m^2
Technology: CIGS
Plastic laminate
Opaque
Digital print



Stained solar glass
56 Wp/m^2
technology: CdTe
Glass - glass
Translucent
Digital print
Structured glass

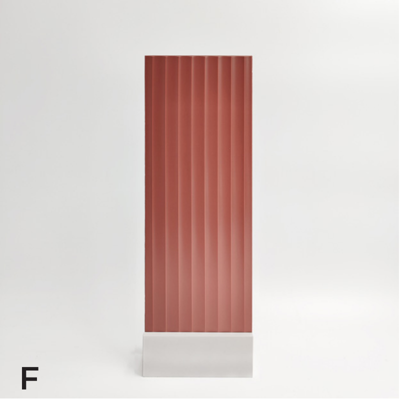
Solar fades
172 Wp/m^2 (no power loss in active area)
technology: C-Si
Glass - glass
Opaque to transparent
Black

Figure 7A:
Technical characterization part 1

Technical characterization

Solar mirror
125 Wp/m^2
technology: C-Si
Glass - glass
Opaque
Digtial print
Other options: structured glass

Solar wood
107 Wp/m^2
technology: C-Si
Wood - glass
Opaque
Light wood



Ceramic solar
146 Wp/m^2
technology: C-Si
Glass - glass
Opaque
Base colors
Other options: structures

Solar channels
25 Wp/m2
technology: thin film
Glass
translucent

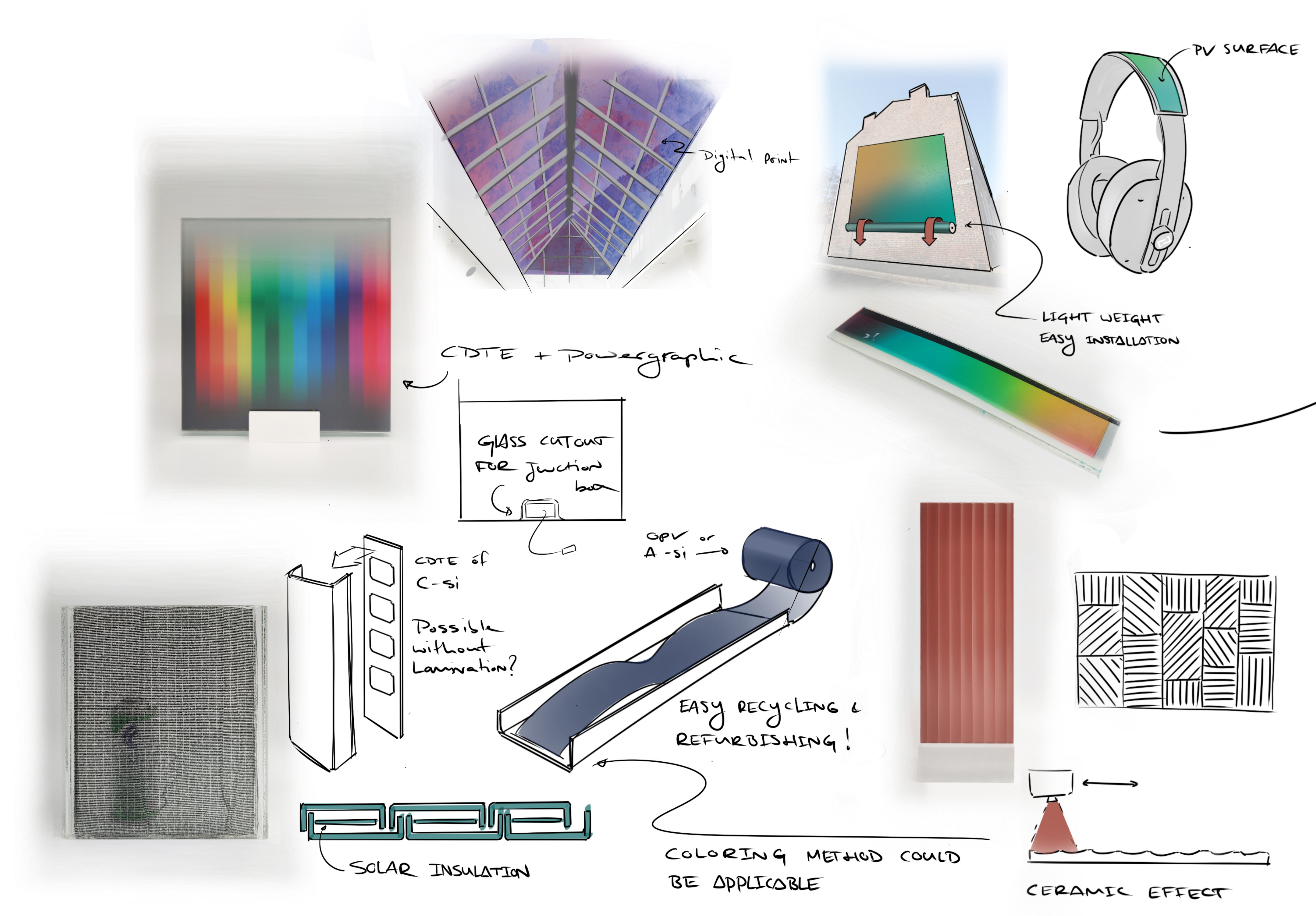
Figure 7B:
Technical characterization part 2

Ideas were also taken from manufacturing methods that were both researched in the analysis phase and experienced by making samples. For instance, the method for applying a coating greatly affected the types of substrates it could be applied on. This offered surface finishes that impacted the look and feel of a prototype and whether glare would be an issue or not, to name an example. Producing many samples also resulted in a cross-pollination of ideas. An example was the idea to use the coloring technology of sample E with a flexible substrate so it could be applied to sample C which was colored using another method. An illustration of the ideation approach can be found in on the following pages.

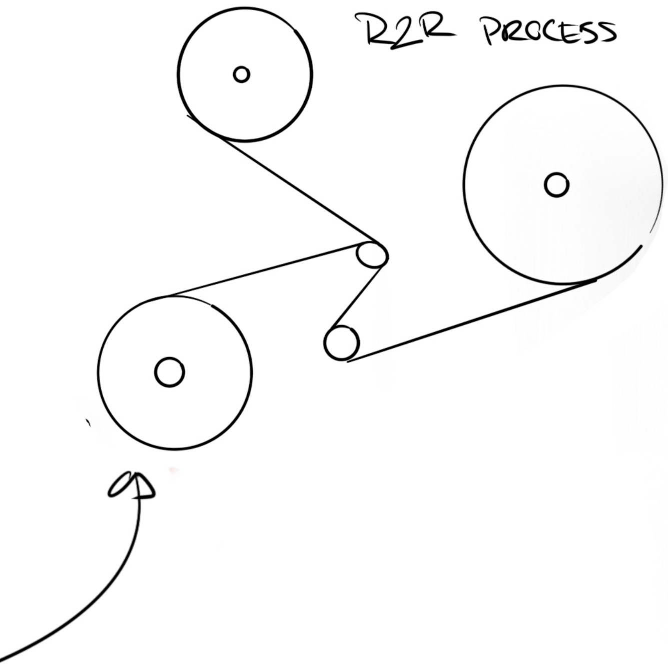
Inspiration was found in architectural solutions and design items that are currently being applied. An example was the façade of the Depot Booijmans van Beuningen. It contains mirrors that fade from reflective to transparent. This raised the question of how solar panels could be made such that they fade from opaque PV materials to transparent windows.

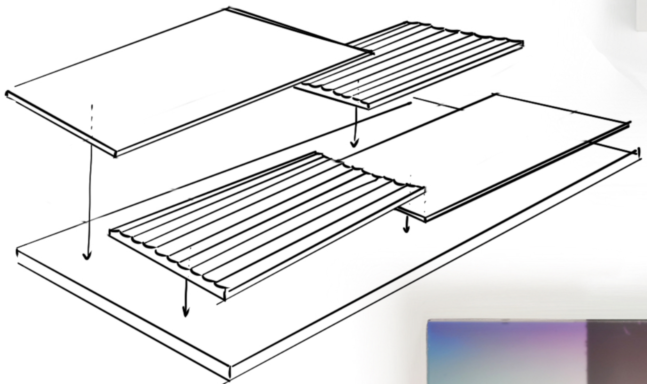
The ideation phase resulted in 8 final samples with a total of 17 variations of the main principles. Estimations of power yield of the most promissing samples were made from the technical characterization. The samples served as input for the concept phase following this chapter.

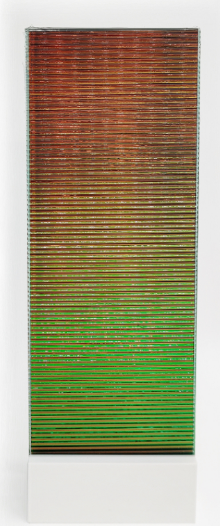
Overall the ideation phase provided the basis from which the concept phase took off. Furthermore, the experience of handling the material provided a feeling for PV materials in general.

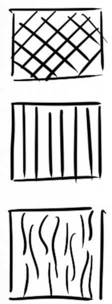

Digital print
PV SURFACE
LIGHT WEIGHT
EASY INSTALLATION
CDTE + Powergraphic
GLASS CUTOUT
FOR junction box
CDTE of
C-si
Possible
without
Lamination?
OPV or
A-si
EASY RECYCLING &
REFURBISHING!
SOLAR INSULATION
COLORING METHOD COULD
BE APPLICABLE
CERAMIC EFFECT

R2R PROCESS

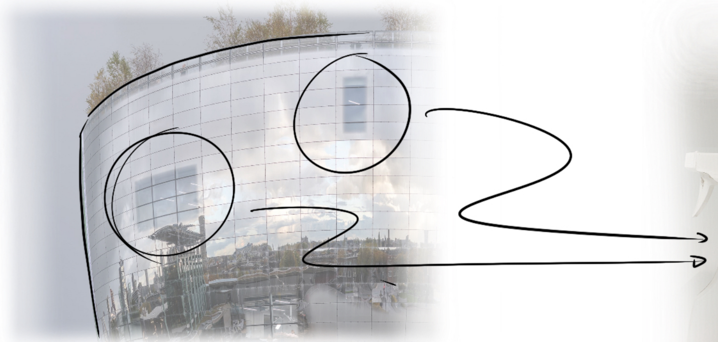




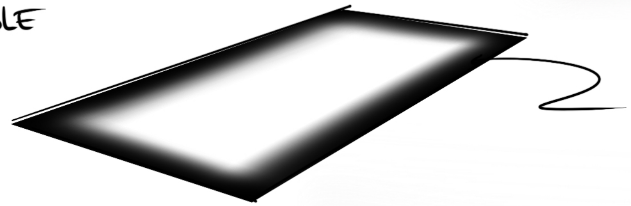




DIFFERENT FINISHES POSSIBLE

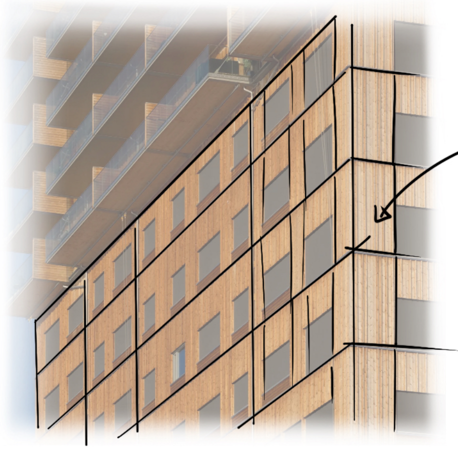


FADING FROM OPAQUE TO TRANSPARENT



CERAMIC FRIT? OR INTERLAYER

ALL WOOD SOLAR PANELS (CARBON CAPTURE)



CONCEPTS

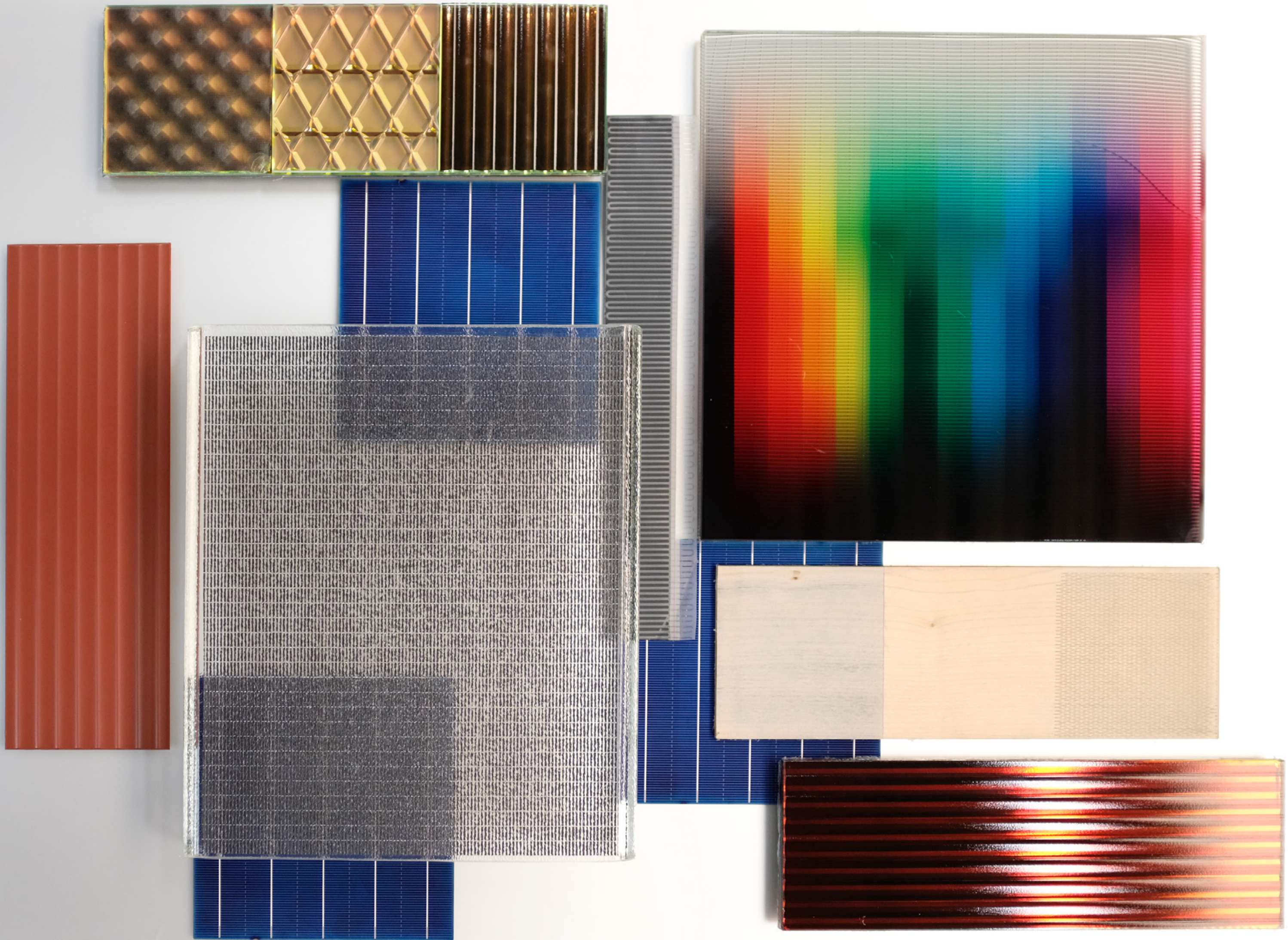
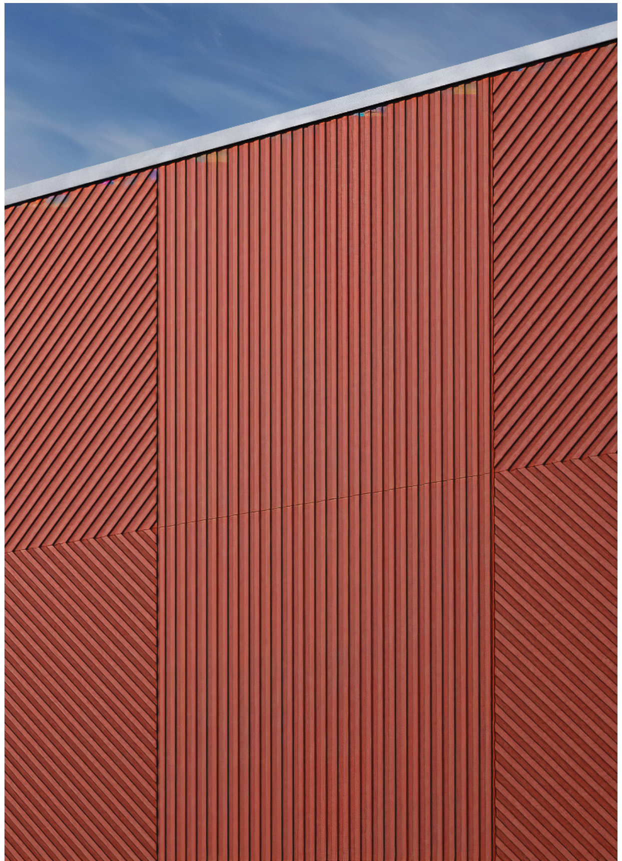


Figure 9: The result of the ideation phase was the tangible input for the concept phase.

This chapter covers the conceptualization phase of the project. The results of the ideation phase were used as input for the concepts described on the next pages. A total of four concepts were explored and a selection was chosen to further develop into a prototype. The four concepts all have different underlying technologies on either a cell level, a coloring level, a substrate level, or a combination thereof. The visualizations display one of the possibilities with the specific underlying technology that was applied. The concepts functioned as examples of the unique opportunities that were made possible by the different technologies. The goal was mainly to communicate the possibilities to potential clients to gain insights into their attitudes towards the matter.

What follows is a presentation of each concept including an architectural visualization, a summary of the key characteristics in terms of design possibilities, and an estimation of the power yield in Watt peak per m^2. The yearly energy yield estimation was calculated using a method by (Broersma, 2023). Calculations can be found in Appendix C.

Based on the feedback of architects and designers in combination with an evaluation of the main drivers, one concept was chosen to further develop into a functioning prototype.



Ceramic solar

Module type: Glass-glass with custom coating
Colour options: Base colours

Other options: Custom front structure

Power: 146 Wp/m2
Yield: 120 kWh/year*m2

“Ceramic Solar” technology provides a unique aesthetic with a texture and appearance similar to ceramic sheet materials. The technology offers a range of base colors to choose from, with darker colors resulting in higher module efficiencies. Standard shapes are available, but custom dimensions can also be accommodated. Additionally, various surface structures are available to further enhance the visual appeal of the modules.

Yearly energy yield estimation per m^2 of a facade per orientation:

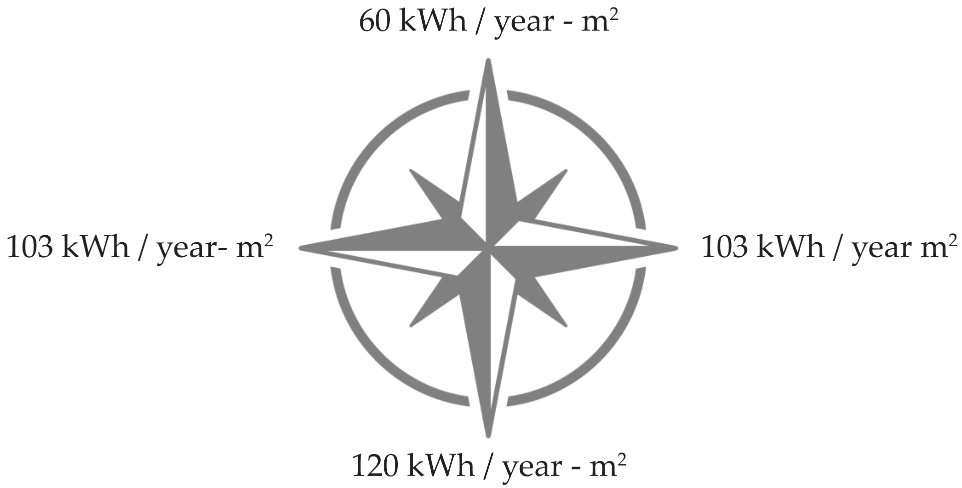
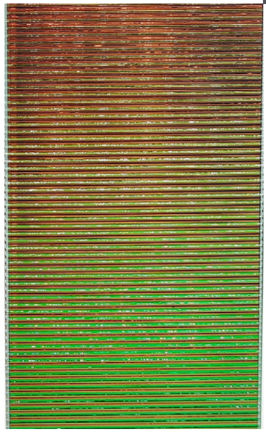


Image credit:
La Defense Offices
UNStudio



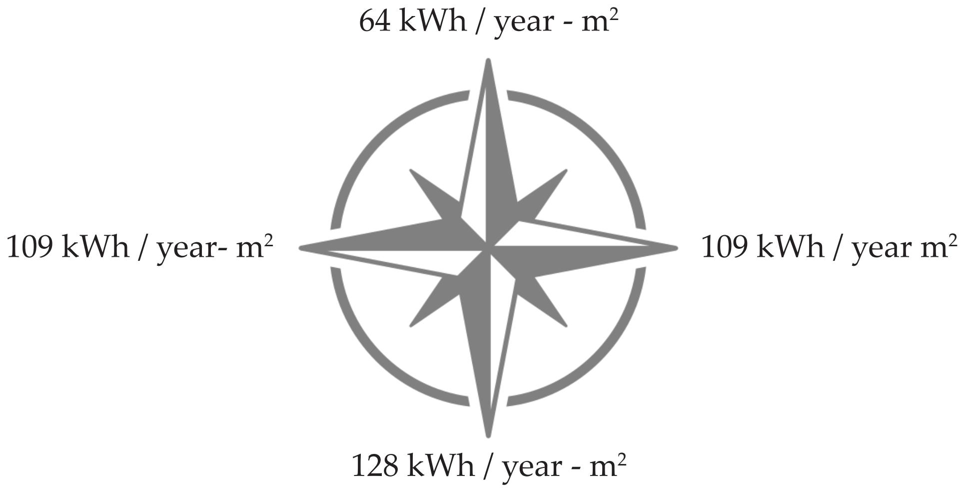
Dichroic structures

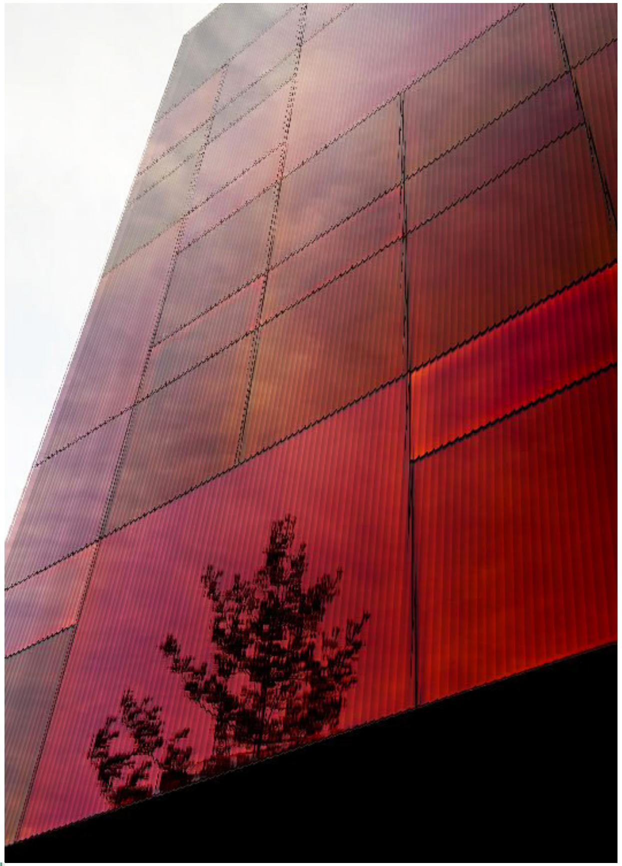
Module type: glass-glass
Colour options: base colours
Other options: custom front structures

Power: 155 Wp/m2
Yield: 128 kWh/year*m2

"Dichroic structures" are PV modules that offer a captivating visual effect. By combining structured glass with this module, you can achieve an iridescent look that changes color depending on the angle it is viewed from. One can choose from eight different base colors to suit the vision of the designer. Dichroic structures can add a bold look to the facade of a building.

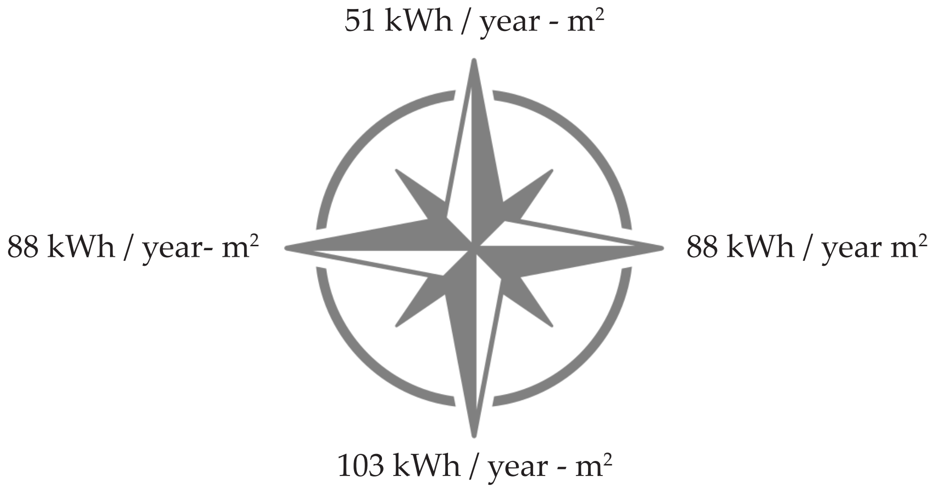
Yearly energy yield estimation per m^2 of a facade per orientation:





“Solar Mirror” consists of PV modules that have the appearance of a colored mirror. On this mirror colors can be applied using digital printing-like technology, offering a high degree of graphic freedom. Depending on the color density, the modules work more or less efficiently. The structure of the front of the module can be customized with different structures to create unique effects.

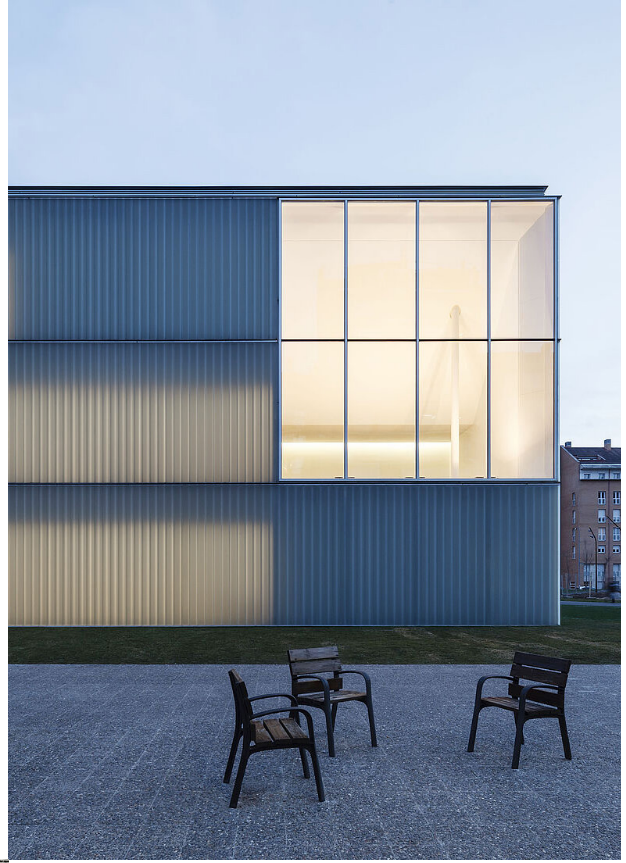
Yearly energy yield estimation per m^2 of a facade per orientation:

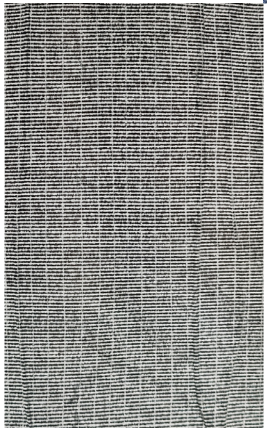


Solar mirror

Module type: Glass-Glass
Colour options: Digital print upon base color
Other options: Custom front structure

Power: 125 Wp/m2
Yield: 103 kWh/year*m2 (south facing)





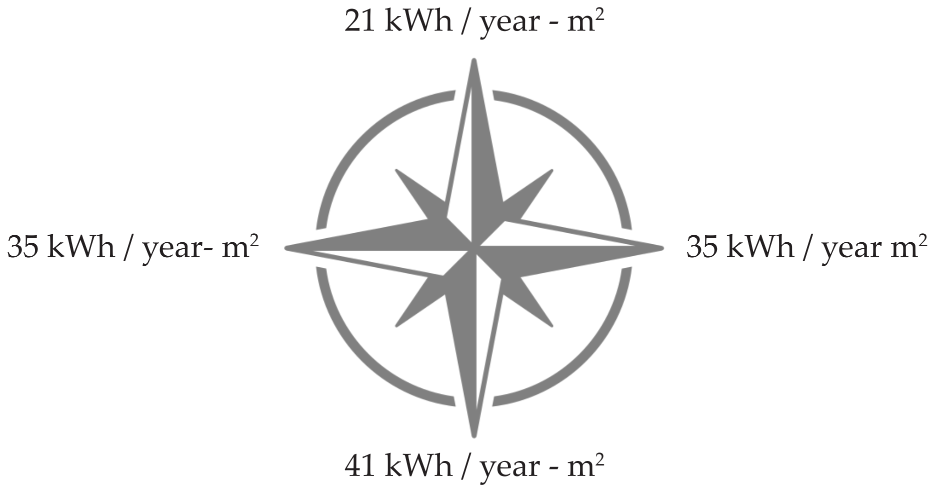
Solar channels

Module type: Channel glass integrated
Colour options: Base colours or digital print
Other options: Adjustable transparency

Power: 50 Wp/m2 (40% transparent)
Yield: 41 kWh/year*m2

“Solar Channels” is the solarfication of an iconic architectural material. Channel glass is often applied when natural light is desired without a completely transparent look. The density of the PV layer can be selected from a range of 10% to 80% transparency. Advantages include a relatively low investment and an easy replacement of the PV layer at the end of its life.

Yearly energy yield estimation per m^2 of a facade per orientation:



Material concept choice

The concept choice was divided into two parts. Firstly, the choice of which material composition to develop further into a working prototype. Secondly, a concept to present the developments of this project was chosen.

The main drivers served as the criteria in a Harris Profile. The score assigned for each main driver is explained on the following page.

	Ceramic solar	Solar channels	Dichroic structures	Solar mirror
Aesthetics & design	+	-	+	++
Performance	++	-	++	+
Technology readiness	++	-	+	+
Future proof	+	++	+	++
Integratable	++	++	+	++
score	8	4	6	8

Figure 10: Harris profile of the material concepts.

Aesthetics & design
The score for aesthetics and design was assessed by a combination of my own aesthetic preference, the amount of design freedom I see in the customization options, and the input from architects and designers from interviews. To read more about the interviews, see the chapter I, architect & designer validation.

Ceramic Solar looks like a clean ceramic sheet material. It provides a moderate level of design freedom because a selection of colors and surface structures can be chosen. Although most architects indicated they were most likely to work with this concept, they did not mention it as the most aesthetic one.

Solar channels are a "solarfied" take on a conventional architectural material. It is not a remarkable material but a popular one nonetheless. This option is more about functionality and blending in rather than standing out.

Dichroic structures provide a unique and bold effect. Design freedom is moderate because base colors can be chosen and the structure can be picked. However, there is always an iridescent effect that makes it a less versatile option. This was also mentioned by the architects: something that you would use one time otherwise it becomes too much.

Solar Mirror was rated the highest in aesthetics and design because it was mentioned as the most aesthetic sample in all interviews. It provides a high amount of design freedom since graphic design can be applied and glass structures can be chosen.

Performance*
Ceramic solar and Dichroic structures score the highest on performance with an estimated 155 Wp/m2 and 146 Wp/m2 respectively. Solar mirror comes in second with an estimated yield of 127 Wp/m2. Solar channels score the lowest with 25 Wp/m2. However, it should be taken into account that natural light still passes through and the channels provide building insulation as well.

Technology readiness
Ceramic solar scores highest on technology readiness because it is a drop-in replacement for a currently used technology. Dichroic structures and Solar mirrors score lower because the coloring technologies are both available in a small size and need to be upscaled. Solar channels score the lowest because they rely on thin film technology that is still in the testing phase and is difficult to obtain commercially.

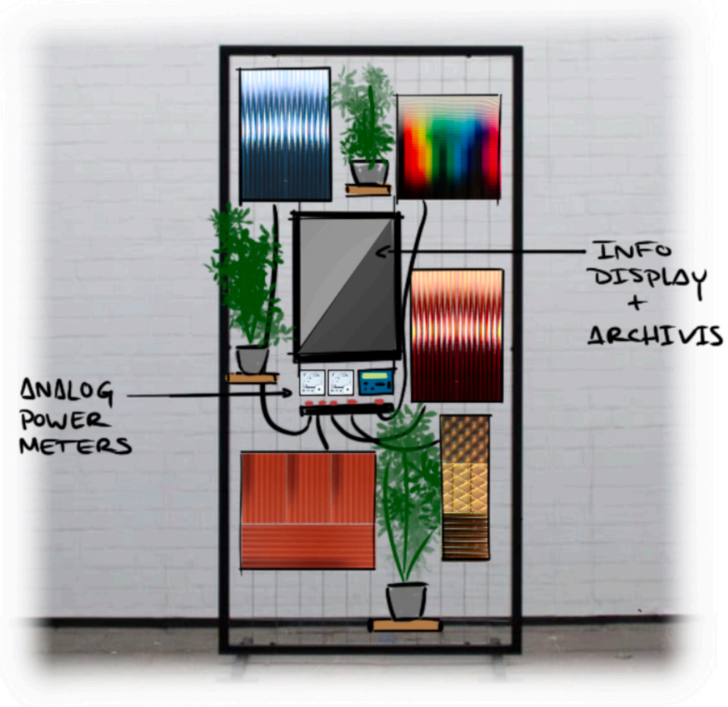
Future proof
Second and third-generation technologies are expected to be the future of PV. Therefore the concepts should be compatible with these technologies. A key characteristic of these technologies is flexibility. Because solar mirror technology is compatible with flexibility, it was given the highest score. Solar channels score high as well because they provide the needed protection against the elements for third-generation technology without the need for lamination between glass sheets.

Integratable
Integratable was defined as how well the material can be used as a part of an architectural concept (see main drivers). Ceramic solar and Solar channels score high because they already have the appearance of conventional architectural materials. Solar mirrors score high because of their versatility. Dichroic structures score lower because of their distinctive nature which is more difficult to widely apply.

The decision was made to further develop the Solar Mirror concept into a working prototype. Although it scores tied with Ceramic Solar, the aesthetic qualities are unique and provide more opportunities to create distinctive designs. Prototypes of the other concepts will be included in the demonstrator as well to communicate the possibilities.

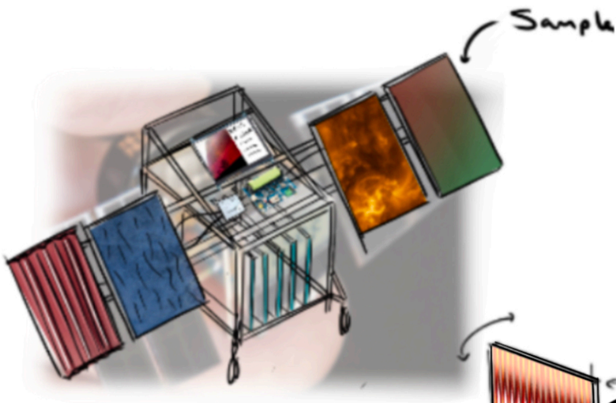
* Performance was estimated by comparison to a reference mono-si PV module under standard testing conditions (STC).

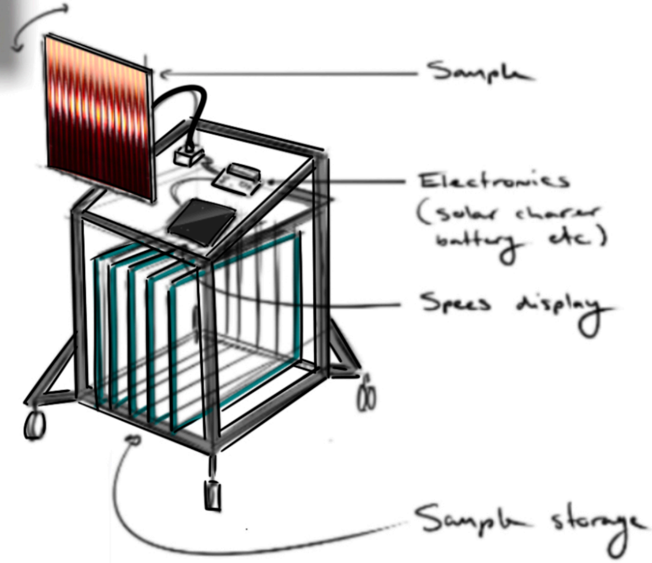
Demonstrator concepts & choice

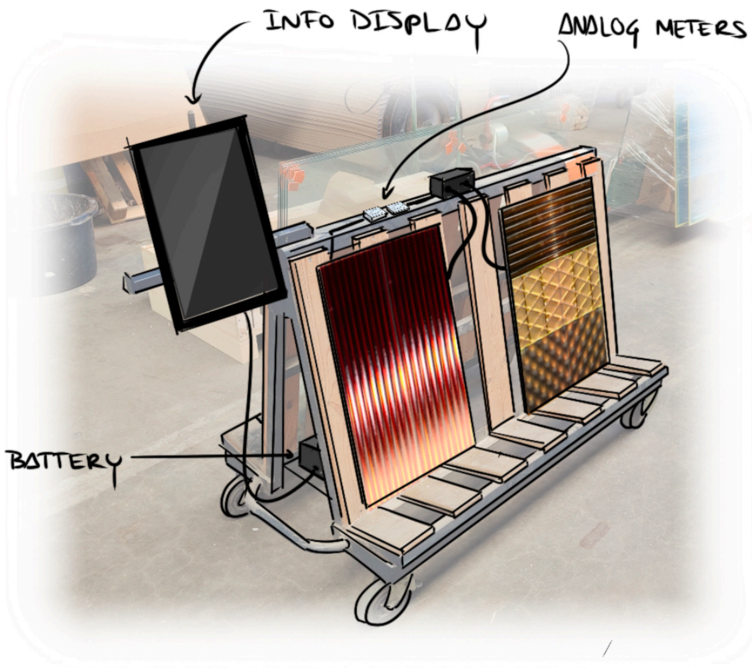


Display board
A portable board that can be configured with various samples. It communicates its power-generating function with analog meters connected to the PV prototypes.

Solar satallites
A playful take on satellites that make use of solar power. Instead of the black PV modules that are normally used, the prototypes would be used. The construction would resemble a space satellite and also function as storage for other samples.







Glass cart
A conventional glass cart used in factories is converted to a prototype display.
A monitor is attached to a handle to provide information.

Communicate the broad range of possibilities of solar design.
The display board scores the highest because it was the most versatile option. It makes it easy to show prototypes of different dimensions. It is also possible to backlight transparent prototypes.

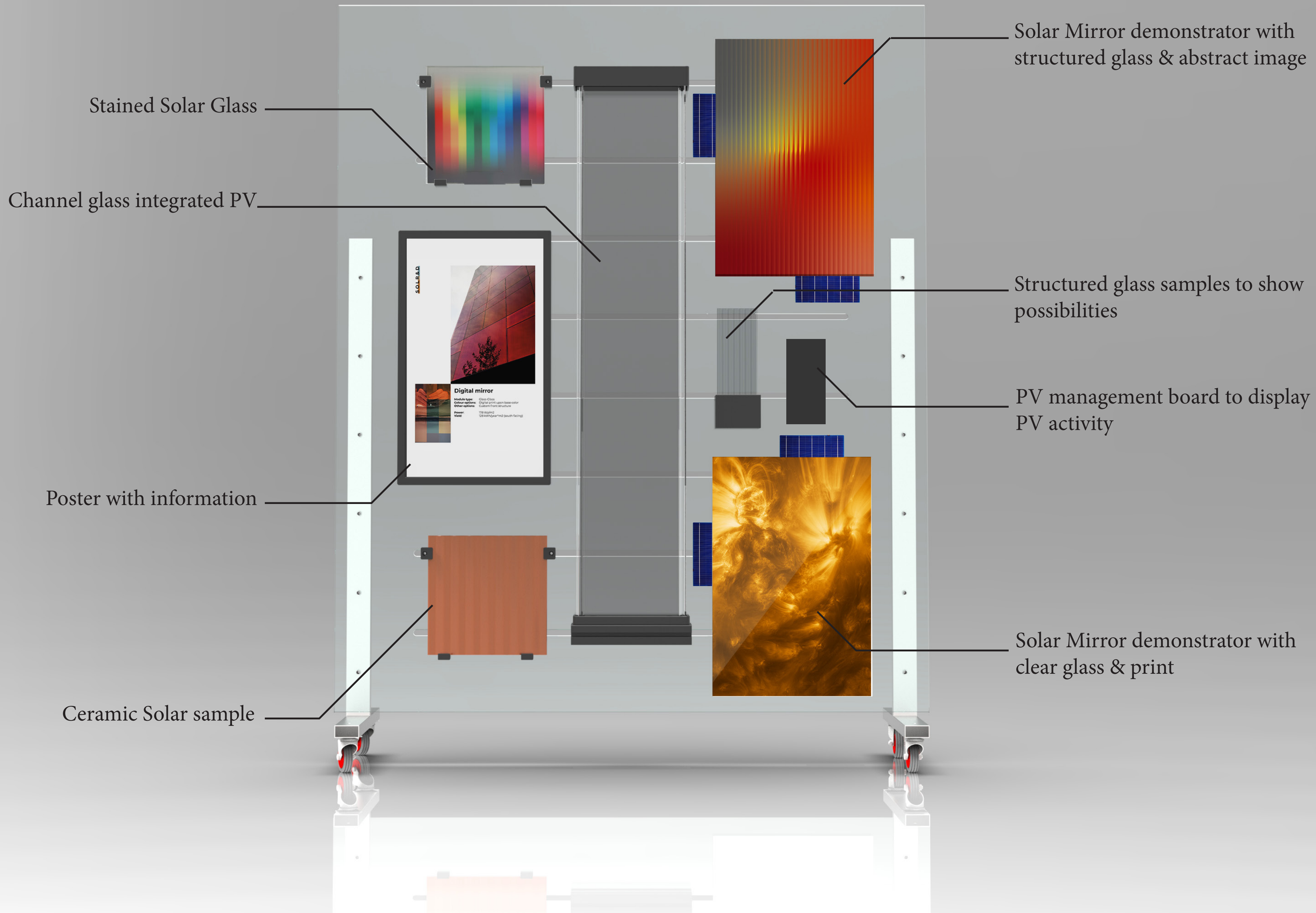
Show aesthetic value and catch attention.
Again, the display board wins because it displays the prototypes vertically and at eye level. Although the satellite prototype itself is more playful and unique, the display would be more suitable for displaying prototypes because it does not move the attention to the display medium.

Show the functional properties.
All demonstrators would showcase the functional aspect of solar panels by means of power or volt meters in combination with practical use for the harnessed energy.

Easily rearranged/adjustable
Because of the reconfigurable nature of the display board, this concept was most suitable. Material combinations can also be easily evaluated. Other benefits include the fact that objects besides panels can be attached to them as well rather easily.

The display board was chosen to demonstrate the PV material prototypes. It did need some changes though to take it to the next level. These are elaborated on in the next chapter.

EMBODIMENT


Stained Solar Glass
Channel glass integrated PV
Poster with information
Ceramic Solar sample
Digital mirror
Solar Mirror demonstrator with structured glass & abstract image
Structured glass samples to show possibilities
PV management board to display PV activity
Solar Mirror demonstrator with clear glass & print

Demonstrator design

The display board consists of a tempered glass sheet with slots that can be used to attach PV panels and other objects. The glass sheet is supported by two stainless steel legs on wheels to make it mobile. The slots afford reconfigurability: objects of different sizes can be positioned both vertically and horizontally. This offers flexibility to showcase various prototypes.

Four types of PV products were displayed on the demonstrator, the most prominent being the two Solar Mirror prototypes. These were produced as working prototypes. One is made using a custom graphic in combination with structured glass. The other one is made with “regular” low iron glass in combination with a crop from a high-resolution image of the sun made by the European Space Agency (The Sun in high resolution, z.d.). The PV functionality of the working prototypes was communicated by hooking them up to a PV power management board and attaching that to a mini fridge containing a beer can. A voltmeter was added as well as an extra means to show electric properties.

The other prototypes are non-working but for display impressions only. They include a small Ceramic Solar, a Solar Channel, and a semi-transparent Stained Solar Glass sample.
To quickly and easily show the visual effect of using different types of front glass, a container with various sorts of structured glass was added as well.

Finally, a poster board was included to show additional visuals, process photos or other relevant information.

PV module design

The working Solar Mirrors were made using Interdigitated Back Contact (IBC) cells. These cells are highly efficient, with an average efficiency of 27% of the sunlight being converted to electricity. Another advantage is the black appearance of the cells. This enabled the panels to have a homogeneously black background to build color upon. Each panel contained 12 cells in total (three times a string of four cells).

The PV modules served to demonstrate the appearance of the coloring technology and to validate the effect on the power loss. Therefore the decision was made to use a plastic back sheet rather than a glass back sheet. This required fewer materials and it simplified the lamination process.

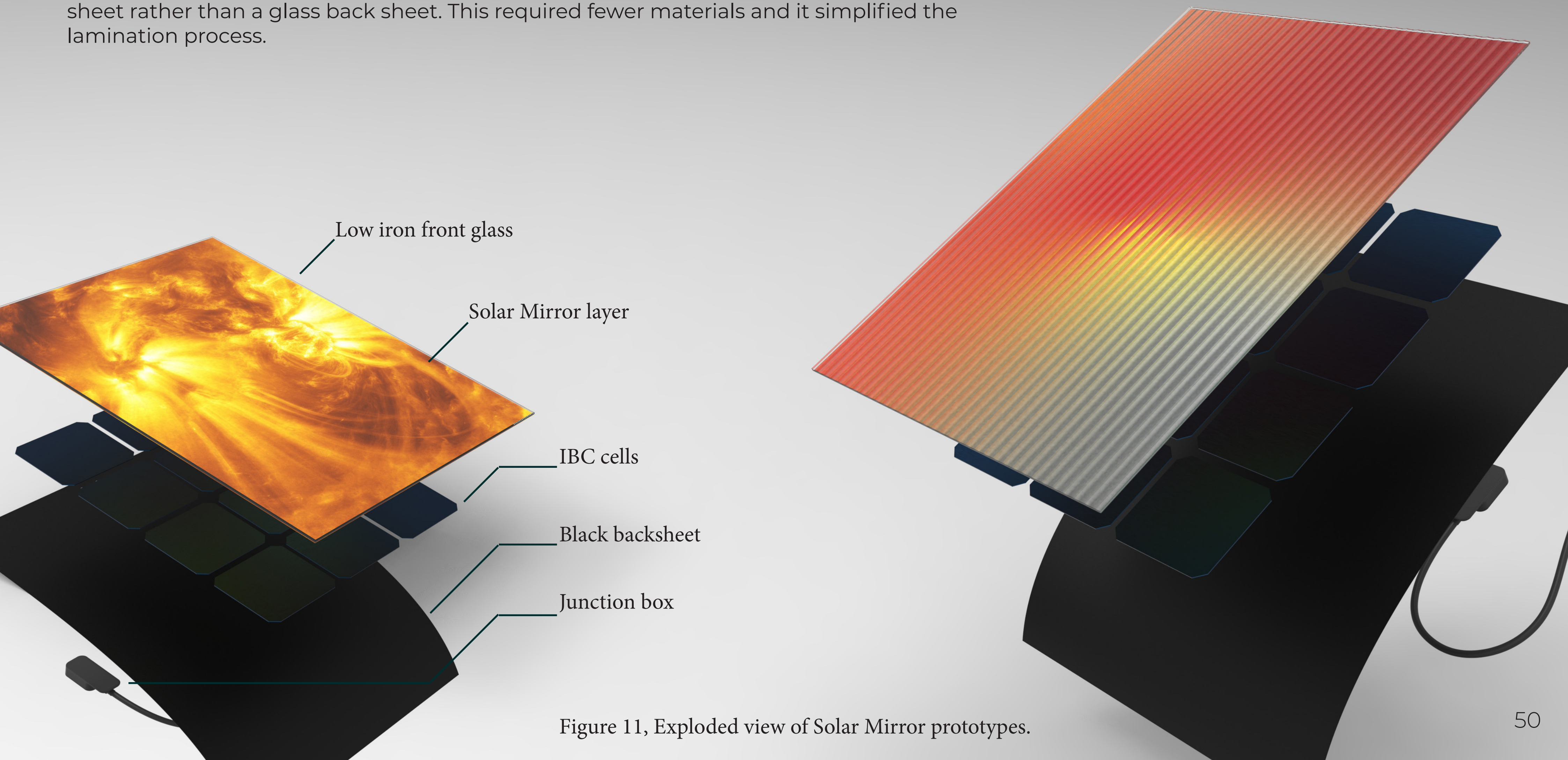


Figure 11, Exploded view of Solar Mirror prototypes.

Before making the panels, the coloring technology needed to be validated. This was done by performing transmission measurements with a spectrophotometer. With the measurements as input, a model was used to predict the loss in power output. The power loss varied with different colors and averaged around 25%. More about this can be found in the chapter “Technical validation”.

The other prototypes that were displayed on the demonstrator setup were the Solar Channels, a Stained Solar Glass, and a Ceramic Solar prototype. All these were dummy prototypes and had no functioning PV elements. They did imitate the look and feel of the potential product though, and yield estimations could be made with information from suppliers. The PV layer in the Solar Channels was imitated by adding a printed film on the backside of the front glass. The Stained Solar Glass sample was made using an actual CdTe glass sample and laminating it with a custom-colored insert. Finally, the Ceramic Solar dummy was made by applying a metallic coating on the structured glass that was laminated against a black-coated back glass.

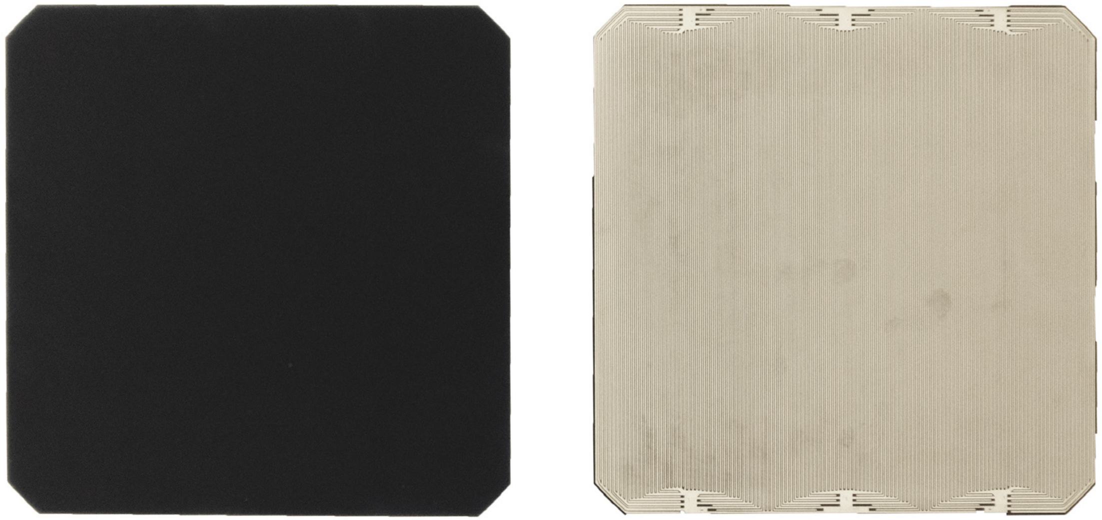


Figure 12, the IBC cells used in the Solar Mirrors.

Prototype presentation

Figure 13, The demonstrator installation

Figure 14, A mini fridge powered by the prototypes via a solar controller. A Volt meter shows the functionallity of the modules. Behind the fridge is a container with structured glass samples.

Figure 15, Close up photo of the Solar Mirror with the ESA sun image.

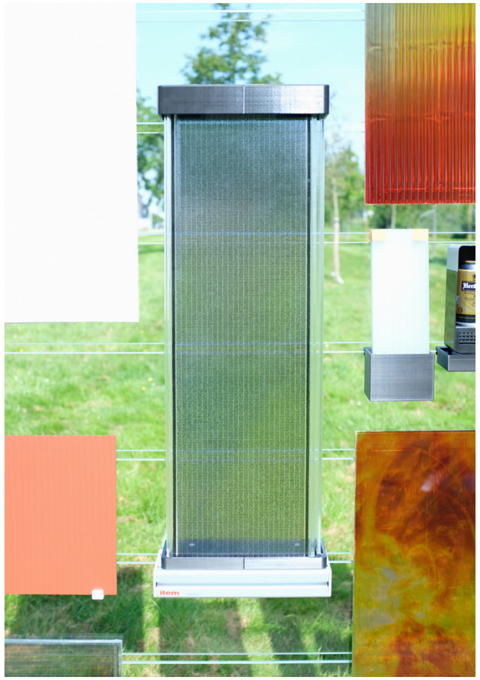


Figure 16, Close up photo of the Solar Channel prototype.

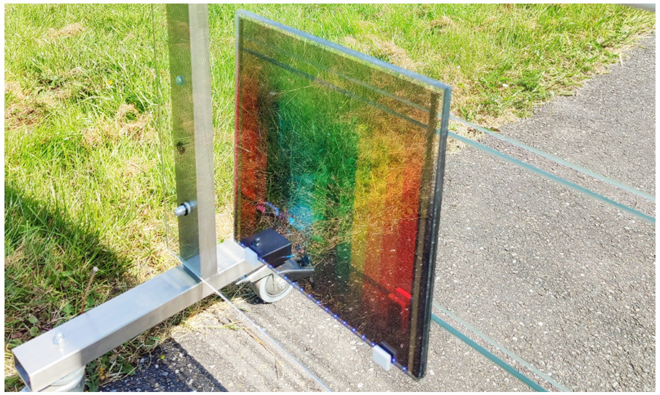


Figure 17, Close up photo Stained Solar prototype.

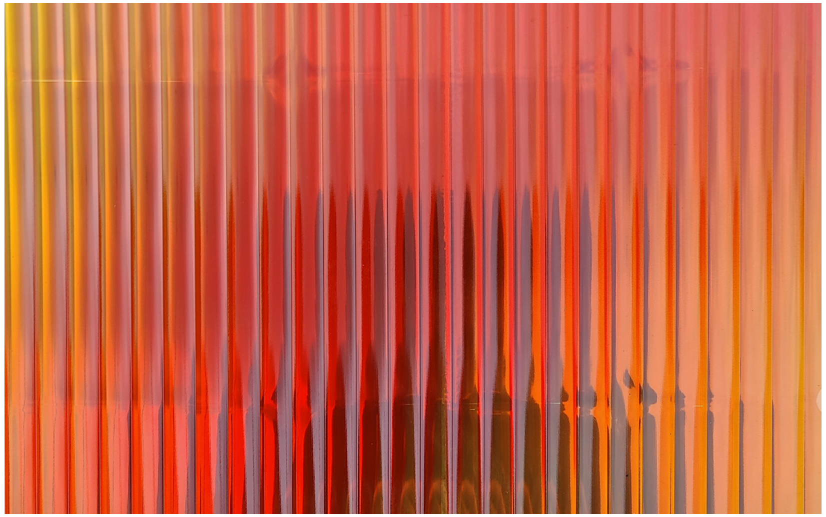


Figure 18, Close up photo of the fluted Solar Mirror prototype.

VALIDATION

Design concept validation

Figure 19, Interview with a designer

To validate the desirability of the material design concepts, four architects and one designer were interviewed.

The aims of the interviews were to get an overall picture of the way the architects and designers work and how their decisions processes go. I also wanted to understand their attitudes towards BIPV and solar panels in general. And of course, get to know their opinions about the prototypes and design concepts.

Three of the architects had specific specializations: designing schools, libraries, or private homes. One architect was more all allround. The designer worked in high-end sculptures and interior objects and was moving towards designing public installations.

The interviews were semi-structured. Firstly, their general approaches to sustainable design were asked about, followed by questions about how material decisions were made. Then the interview moved toward the use of solar panels and the participants' attitudes toward the options that are currently available. Finally, the samples were revealed along with conceptual visuals of the materials integrated into buildings. The participants were asked to evaluate the materials and concepts and to think out loud while doing so.

More information about the setup of the interviews can be found in Appendix I.

Two architects mentioned they were already actively trying to comply with “Zero Energy Building” (ZEB) requirements rather than the currently obliged “Near Zero Energy Building (NZEB)”. The reason for this was to make buildings more future-proof since at some point in time they had to comply with these regulations anyway. All architects mentioned that complying with NZEB was no particularly big challenge. The requirements could be met by designing well-insulated buildings, being clever with light irradiation, and adding solar panels on rooftops. However, ZEB building was only possible when there was space on the roof available to place enough solar panels to provide for the energy consumption of the building. When asked about working with PV, three architects indicated that they were of the opinion that they were ugly but necessary. One architect mentioned that the appearance of PV panels did not matter: “we need them and people will get used to how they look.” He did acknowledge that PV panels could cause discrepancies in the appearance of (old) buildings. All architects had not considered BIPV solutions yet because there was no urgency in doing so to comply with regulations. Therefore they were unfamiliar with the solution that is currently available.

When introduced to the samples and concept visualizations the main reaction was surprise that PV panels could look like that. It was interesting to see the skepticism of applying PV panels to facades shift towards enthusiasm for the materials. This was characterized by one of the architects saying: “It is an added value because now you are working with a material and not with a solar panel”. The most popular samples were that Solar Mirror with fluted glass and Ceramic Solar which were associated with ornaments.

Ceramic solar: All participants immediately mentioned a resemblance to ceramics, despite not having seen the name yet. One architect mentioned that you could play with the orientation of the structure for a nice effect. Another architect mentioned that it could be a suitable application for any façade that would otherwise use tiles.

Solar mirror (fluted): All architects mentioned the high-end appearance of the sample. The high-end feeling came from its play on light and the depth caused by the structures and the colored reflections. Possible applications were suggested for large-scale utility buildings such as offices or banks on one side, another association was expensive apartments in Milan.

Dichroic structures were perceived as more niche, something you would only use once or twice. Some architects did not find it suited for European buildings but associated it with “Emirate style”.

The solar channels received less attention, probably because none of the architects had used them in exterior applications before.

Financial issues were mentioned by all architects but not by the designer. Three architects mentioned that they expected the solutions would cause budget issues. Even though the investments would eventually pay back. The other architect did not see the problem for the budget end and expected early adopters would pay the price.

Other remarks were made about how the panels would be integrated. The desire for “blind fixation” was mentioned as well as the need to make facades feel solid rather than “panels slapped onto a wall”.

All in all the architects and designers were positive about the appearance and expected energy yield of the solutions. Two even showed interest in applying the products in projects. Furthermore were interesting points of concern raised to take into account in further development.

Technical validation

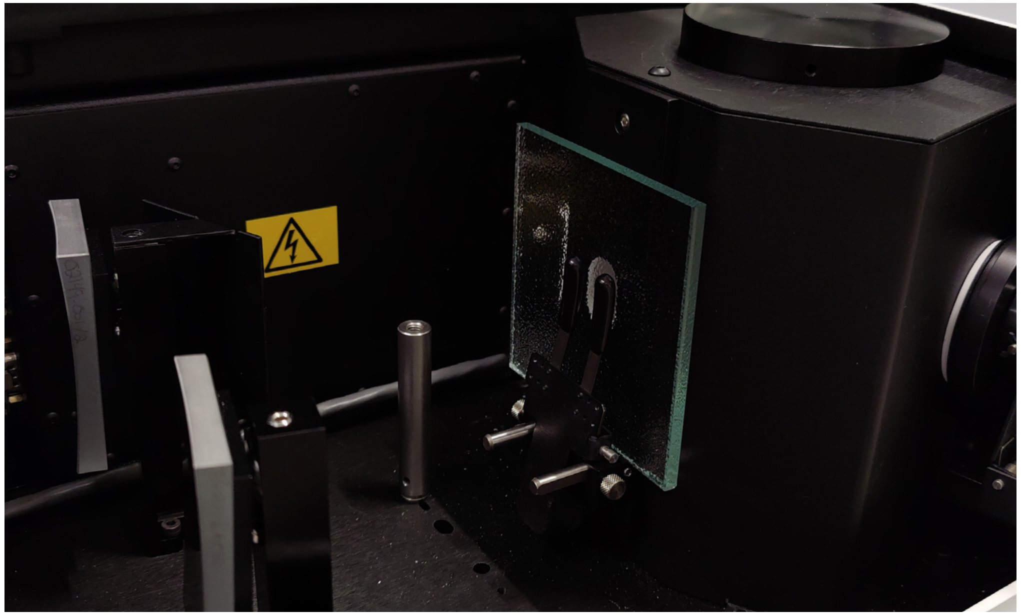


Figure 20, transmission measurements in the spectrophotometer

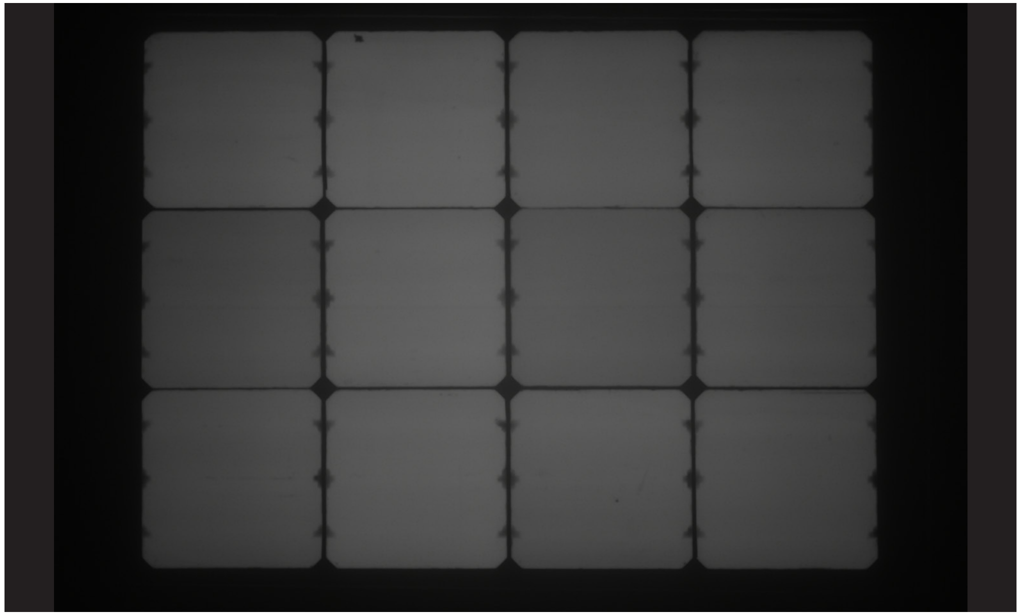


Figure 21, electroluminicence (EL) phototgraphy of module 1.

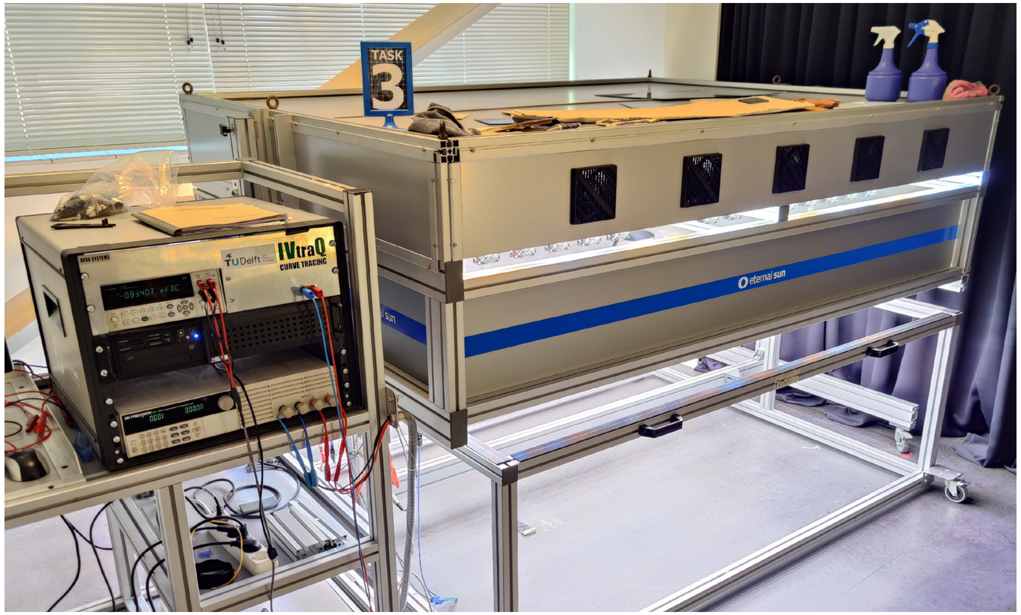


Figure 22, IV curve measurement with a sun simulator

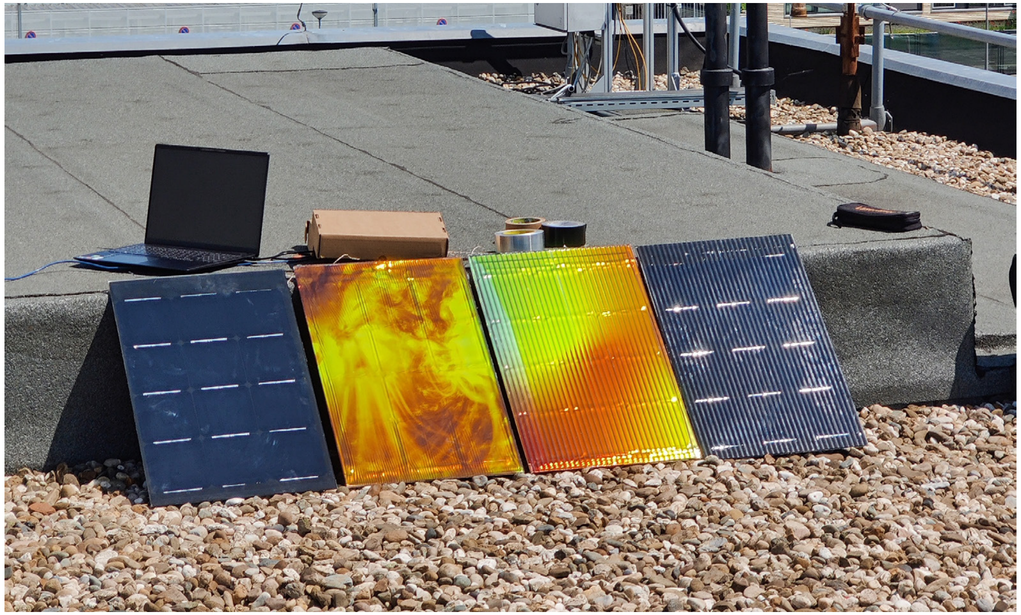


Figure 23, module temperature measurements outside

A technical validation was performed to test the feasibility of the proposed coloring technology and module design. The first test was done before making the modules and consisted of using transmission measurements to estimate the loss of power. After promising results, two modules were made using said color filters. Two reference panels without color filters were also fabricated to compare the results. To measure the power output, IV curves were measured under a sun simulator. Additionally, temperature measurements were done to see the effect of the coloring technology on the temperature of the modules (cell efficiency decreases with higher temperatures).

A total of four modules were made:
module 1: with color filters and with low iron glass front.
module 2: without color filters and with low iron glass front.
module 3: with color filters and with fluted glass front.
module 4: without color filters and with a fluted glass front.

The modules without color filters served as references to compare the effect of the color filters.

Transmission measurements and power loss model
Transmission measurements were conducted using a Lambda 1050 spectrophotometer to determine the transmission percentage of wavelengths from 300 to 1200 nm for cyan, magenta, yellow, and black filters. The relative power loss was estimated using the solar cell's external quantum efficiency (EQE), the AM1.5g Photon spectrum, and the transmittance measurements. To provide a reference for comparison, the transmission percentage of extra clear (low iron) glass was also measured using the same method. The outcomes of the color filters were compared to the transmission of the extra clear glass since nearly all PV modules are built with glass front sheets.

The relative power loss varied depending on the color filter used, ranging from 24% to 31%. The black filter resulted in the highest power loss of 49%. More information about this experiment can be found in Appendix D.

Electrolumenecense (EL) photography
Solar cells work in reverse as well, when applying a current to them, they emit light in the infrared (IR) spectrum. By capturing this light with an IR-sensitive camera, defects in the cells can be found. No defects were found in the modules 1 and 2. Some defects were found in module 3 and many in module 4 as a result of errors in the lamination process. Therefore there was no use in measuring its IV curve under STC to estimate the power loss. The images can be found in Appendix E.

IV curve measurement
The IV (current-voltage) curve of modules 1-3 was measured. It showed how the current output changed with varying sunlight intensity, revealing that as sunlight increases, the module produces more current but at a lower voltage. This curve helped determine the module's maximum power point (MPP). The IV measurements showed that the colored module generated about 80% of the power of the reference module without color. The fluted module without color delivered around 95% of the power of the reference module. Read more about this experiment in Appendix F

Temperature measurement
The modules were equipped with thermocouples and the temperatures were logged until they reached a stable level. No significant differences between colored and non-colored modules were found. Extra information about the setup can be found in Appendix G. The results mean that the coloring technology has no negative effect on module efficiency that could be caused by light absorption and that optical loss is the sole cause of power loss.

From the technical validation can be concluded that the coloring technology and the combination with structured glass front sheets are valid methods to customize PV modules. Furthermore, the technical validation provided a learning experience about the key metrics to assess a PV module's performance and quality. It should be noted though that more extensive testing with larger modules and more colors is necessary to be more certain about the results.

Validation evaluation

In this section the results of the project are evaluated. The main drivers, as setup after the analysis phase were used to test the outcomes of the designs. Also, desirability, viability and feasibility were evaluated.

Aesthetics and design:
The different modules integrated in the demonstrator provide architects and designers with various product options and customization options within the different products. Different colors, textures, transparencies, and shapes were offered. Surface structures and matt/shiny finishing options were made possible as well.

The architects and designer all mentioned that they had a positive impression on the overall look and feel of the prototypes and concept visualizations. Associations were made ranging from luxury apartments to high end utility buildings.

Performance
The measured power loss of the Solar Mirror prototypes and the expected power loss of Ceramic Solar and Dichroic Structures all ranged from 10 to 30 percent. Depending on the colors this is either comparable to, or outperforms current products that are commercially available.

Technology readiness level 4
Two lab scale modules of the Solar mirror concept have been made and were tested in a lab setting, which constitutes to TRL 4. However, the manufacturing process needs more attention to improve the appearance. The other concepts were not that far. These reached TRL 1, 2 or 3.

Future proof
The customization methods used for the designs should be compatible with second and third generation solar technologies. Both the method for applying the Ceramic Solar coating and the flexible nature of Solar mirror color filters are compatible with flexible and curved surfaces offered by future PV technologies. They would also be compatible with Perovskite-Silicon tandems, which show a lot of potential to become widely used.

Integratable
Since the prototypes resemble conventional architectural materials while offering something new and versatile the outcomes can be considered integratable. However, there remains a challenge in incorporating the modules in the facade seamlessly because of the need for fitting panels and blind fixation.

Desirability
One architect and the designer showed concrete interest to work with the Ceramic Solar and Solar Mirror respectively. Next to that, the PVMD group indicated that they would like to continue with the development of the technology in the future.

Viability
The shift towards renewable energy and the expected growth of the BIPV sector in combination with the current complaints about ugly solar panels and need for local energy production show a promising case for viability. High investment costs remain an issue though.

Feasibility
The main challenge in moving up in TRL level for the Solar Mirror concept is getting the lamination process under control. The first prototypes showed potential but more iterations are needed to get it right. Ceramic solar modules are expected to not cause major manufacturing issues.

Demonstrator validation
The demonstrator communicates a broad range of PV design possibilities by showing three different PV products with various colors, structures and transparencies. It showed the PV functionalities of the panels by means of a Volt meter and mini fridge connected to the panels. Finally, it can be rearranged with different products the same way as mirrors can be installed to wall, making it easy to swap panels or reposition them.

All in all the main drivers were met successfully in spite of some challenges that still remain present.

CONCLUSIONS

To make conclusions about the project, the outcome was compared with the assignment. This is done by a short description of how each topic of this report and the design results have contributed to the execution of the assignment.

The assignment was “To design new photovoltaic (PV) products for architectural and design applications that are visually appealing, provide design freedom, and are functional.” Focus on materialization and finding new and creative ways to make solar panels an aesthetic material to design with.

An unexpected addition to this assignment was the design and fabrication of a demonstrator setup to showcase the outcomes of the PV product/material design concepts.

During the analysis phase, the topic of solar design was researched from a technological, historical, architectural, and product design engineering perspective. The analyses led to the conclusion that a series of products were preferred to provide design freedom rather than a single product that tries to offer as much design freedom as possible. Furthermore, it provided an overview of the context of PV integration and the opportunities for designing with PV materials. This led to the vision that BIPV products should be aesthetic and desired materials for their appearance in the first place and their ability to generate electricity should almost be taken for granted.

The ideation phase in combination with technical characterizations provided a practical understanding of working with PV materials, building color upon a black background while keeping high light transmission, and a realization that the game of solar design is about finding a balance between aesthetic appearance and maintaining a high module efficiency. Material properties, manufacturing processes, design objects, and buildings served as input. The results were 8 different PV material combinations, four of which were further developed into concepts.

With these concepts, four architects and a designer were asked about their attitudes toward them. A combination of architectural visualizations, material samples, and yield calculations were used to convey the concepts. Reactions about appearance and performance were positive. Two participants indicated a desire to use the products in future projects, validating the desirability of the concepts. Furthermore, some important issues were found for future development.

A demonstrator was designed that showed 4 different PV products that were developed in this project. One of them was worked out into two functional prototype variations: the Solar Mirrors. Feasibility was validated using technical tests including transmission measurements, IV curve measurements, and temperature measurements. The results were positive and showed a power reduction from the customization methods of 20% to 25% compared to regular solar panels.

To conclude: the results were visually appealing, as validated by architects and a designer. Design freedom was provided by offering different colors, structures, transparencies, and finishes in different products. The means to realize this was based on novel material combinations and manufacturing methods. Therefore the assignment can be considered successfully fulfilled.

RECOMMENDATIONS

The following recommendations are made to turn the developments of this project into a success.

Continue with the development of the Ceramic Solar and Solar Mirror concepts. These received the most positive feedback on appearance and had a relatively low power loss. Besides that, the base technologies are probably compatible with future PV developments. For Solar Mirror: iterate on the lamination process. The working principle has been validated. Now more research about power loss prediction from different colors is needed on a larger scale. Besides that, more design studies need to be conducted to explore color and glass combinations. Another challenge is to design a stable process that neatly laminates all layers into a stack. Also, focus on making glass-glass modules rather than glass-back sheet modules. This eliminates the need for aluminum frames and increases the durability of the modules.

To further develop the concepts, the correct partners will need to be found. Firstly, agreements with the correct manufacturers and suppliers will need to be made. Secondly, pilot projects need to be arranged with architects and designers. Then the other stakeholders such as contractors and project developers can be approached. Other stakeholders should be taken into account as well. For a full overview of relevant stakeholders and their connection to the project see Appendix H.

Before reaching out to partners and other parties, an intellectual property (IP) strategy needs to be worked out. An IP attorney was consulted to find IP related matters that need attention. There is potential for patents in some of the concepts. An important consideration is where to file the patent, choosing more countries covers the IP more extensively but comes at a hefty price tag. Other IP considerations include the setup of entities that own intellectual property (IP) another one that does the actual work. Finally, non-disclosure agreements (NDAs) and non-use agreements (NUAs) will need to be set up when discussing projects with clients and (potential) partners.

REFLECTION

I started this project with the feeling that there were many opportunities in the field of solar design. And after completing the project, I know this for a fact.

My expectation was to find one or two ways to customize solar panels and work that out to show different possibilities with these methods. In reality, I just scratched the surface of what PV integration really means. I have already seen even more options in other potential PV products while the results of the project have not even been fully worked out. Luckily I now know what it takes to go from idea to design from a technical perspective thanks to the help from the PVMD group. Special thanks go out to Olindo Isabella and Juan Lizcano for their technical expertise and assistance. Now I have the know-how to continue development, have insight into what tests to do myself, and when to get a certain expert involved.

Furthermore, I learned what it takes to go from a PV material to a product in a broader sense but I struggled to do this in a structured manner. The lesson was to envision an outcome, work towards it and only start something new when it can be crossed off the list. It will probably take a couple more projects to really master this though. Thanks to Erik Tempelman and Ianus Keller for the lessons about this process and also for the other lessons that have yet to sink in.

Finally, I'd like to thank Van Dijken Glas Beleving B.V. for providing know-how in conventional and innovative glass processing and having me witness top-level designers and architects at work. This had me develop an eye for a different type of design than what is taught in the IPD program. This background in combination with an education that provided technical skills as well as different disciplines of a social, business, and scientific nature allowed me to have a unique position in solar design and design in general. I believe this is how I differentiate myself from other designers and that the result of this project is an embodiment of that.

Figure 24, reflections in a cleanroom while making a solar panel

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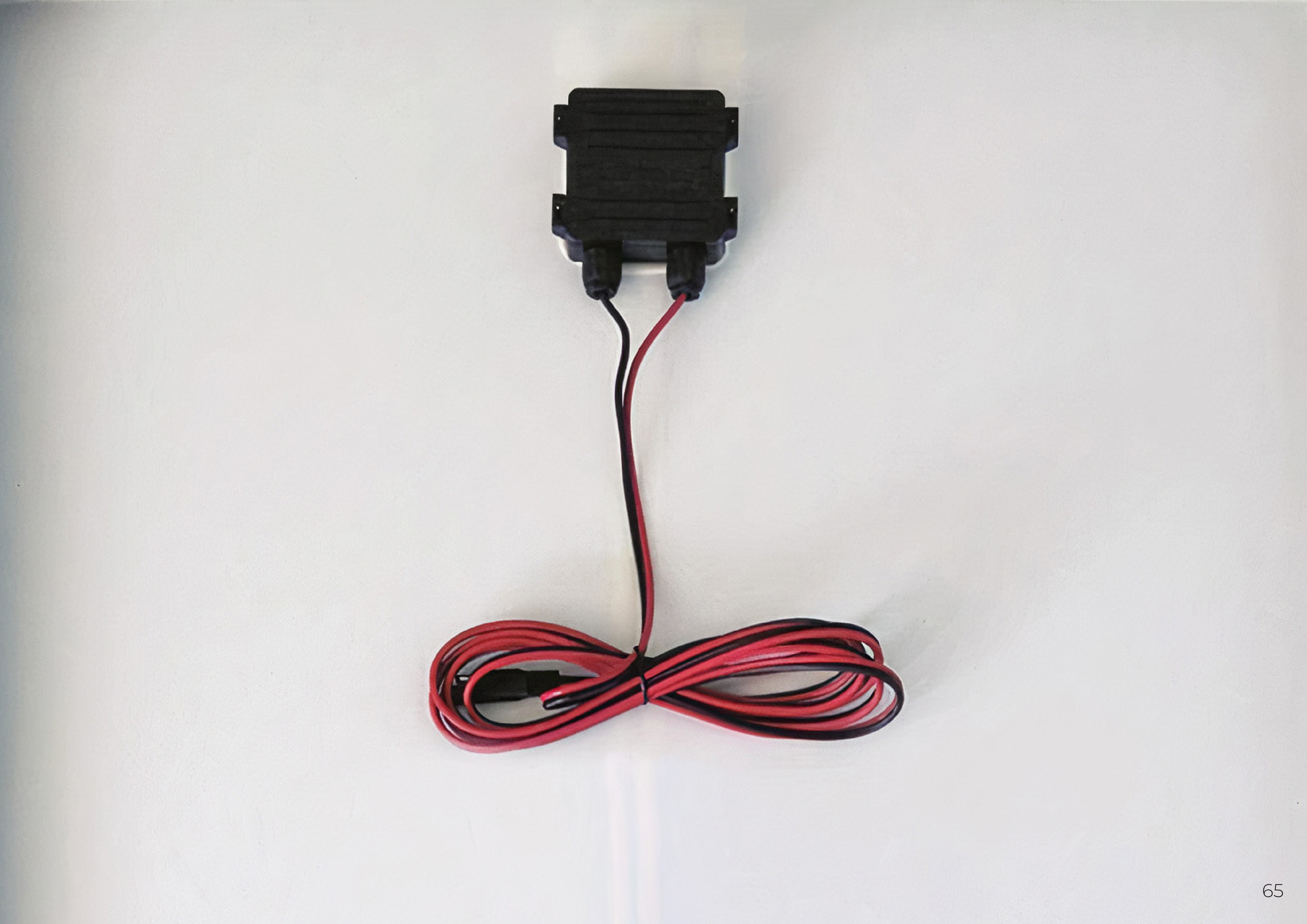
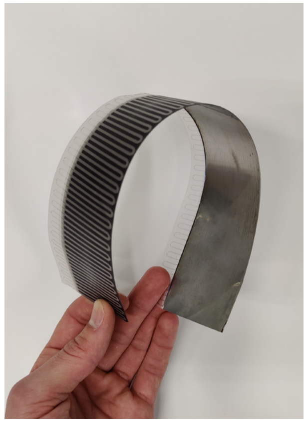
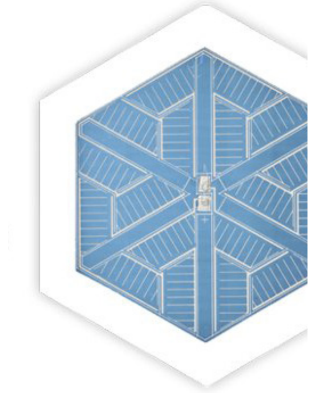
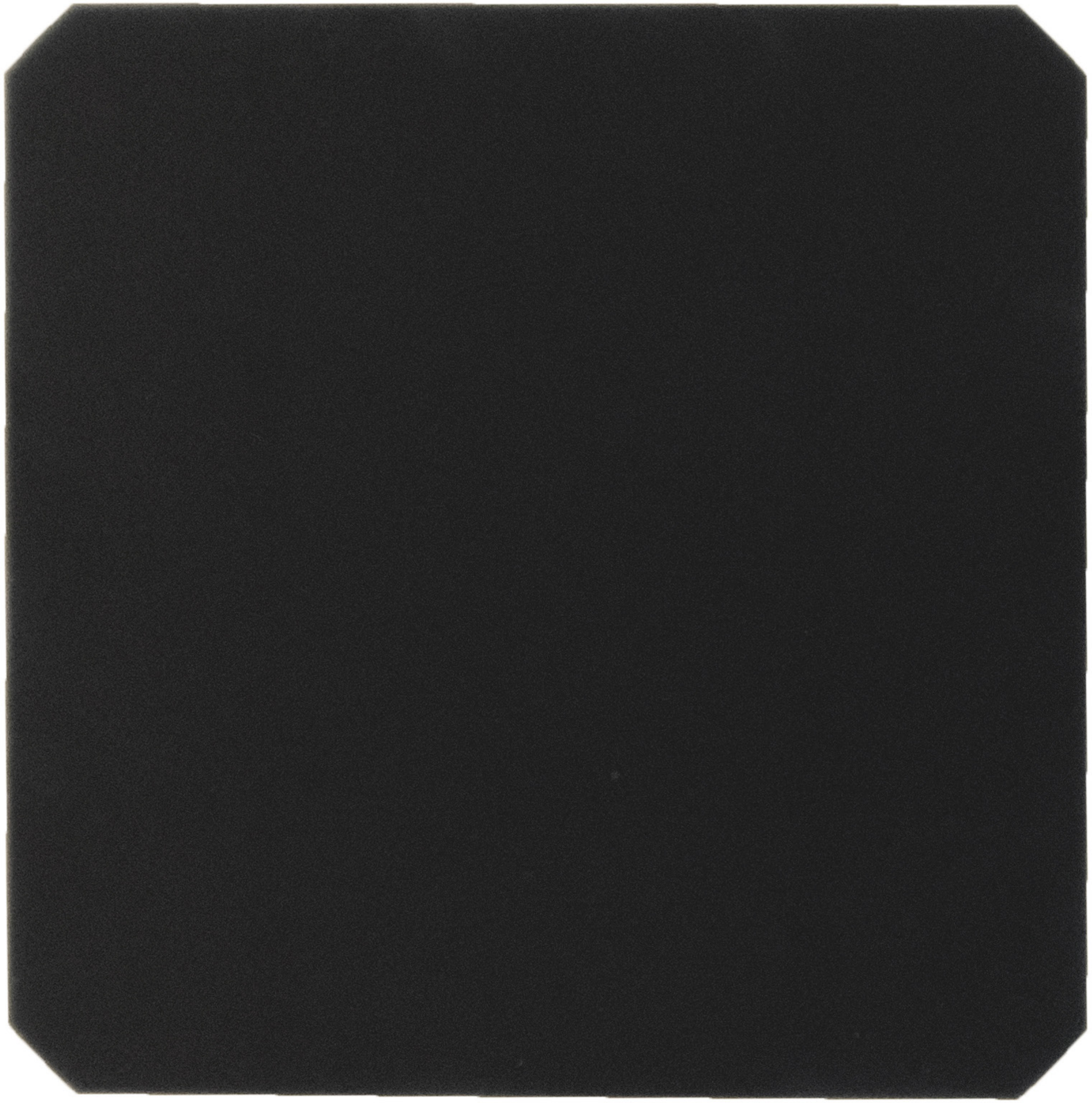
Thanks for reading



Appendix A - solar tech

	1st gen.	2nd gen.			3rd gen.
					
	Crystalline	**CdTe**	**CIGS**	**A-si**	**Organic**
Efficiency	19-24%	19%	19-24%	19-24%	19-24%
Temp. sensitivity	0.32 %/C	0.15 %/C	0.32 %/C	0.32 %/C	0.32 %/C
Color	Black/blue	Black	Black/blue	Black/blue	Black/blue
Base size	15.6x15.6mm	N.A.	15.6x15.6mm	15.6x15.6mm	15.6x15.6mm
Shape	Square (cutable)	Rectangular	Square (cutable)	Square (cutable)	Square (cutable)
Translucency	No	Yes	No	No	No
Color options	Yes	Yes	Yes	Yes	Yes
Panel size	Customizable	Customizable	Customizable	Customizable	Customizable



Appendix B - Ideation, yield estimation

To estimate the power reduction of the applied color and customization methods, different methods were used. For some materials transmission specifications were provided by suppliers. For other prototypes measurements had to be taken. For each prototype, this section shortly describes how the yield estimation was made.

Dichroic structured:
The supplier of the material provided the information on the percentage of reflected light. This was used to estimate the transmittance. It was assumed that the transmission percentage was directly related to power reduction. For a more accurate estimation the spectral response of the cell and the transmitted wavelengths should be taken in to account as well.

Stained solar glass:
The conversion percentage of irradiation to power was provided by the supplier. This was multiplied by 1000 kWh/m2, also the norm for standard testing conditions. https://sinovoltaics.com/learning-center/quality/standard-test-conditions-stc-definition-and-problems/.

Color flex:
Consists of a combination of flexible solar cells and Powergraphic coloring technology. The conversion percentage of irradiation to power was provided by the supplier of the cells and the power loss from the coloring technology was provided by the supplier of the color filter.

Solar fades:
The black areas function the same as conventional solar modules, so yield stays the same. The transparent parts do not generate power.

Stained mirror:
Measured using a Quicksun sun simulator. The color layers in combination with glass were placed above a PV cell. The whole stack was illuminated with 1000 W/m2. The IV curve of the PV cell was measured and compared to a measurement without the layers of the prototype. Three variations were measured. Because the PV cell was not laminated with the layers of the prototype, there was an extra air gap in between. The loss this caused was compensator for by multiplying the IV measured power by 1.12 (12%).

Ceramic solar
Supplier provided the yield reduction percentage. This was subtracted from a standard solar panel yield.

Solar wood
Was calculated using the same method as the stained mirror prototype. For Solar Wood 3, the assumption was made that removing 50% of the material in respect to Solar Wood 2, also reduced the power loss caused by the material by 50%. No measurements were taken for this sample.

Solar channels
The specifications of the PV materials were provided by the supplier. No extra layers were added that could reduce the power yield.

The results can be found in Table 1. Figure 1 and figure 2 show the IV measurement setup.
This technical characterization provided the necessary insight about the power converting properties of the prototypes to decide which prototypes to continue with in the next stage of the design process.

			source				
Reference mono Si panel	172	Wp/m2	https://photovoltaicsolarenergy.org/solar-panel-yield-per-square-meter/				
sample	**method**	**information**	**source**	**Calculation**	**result**	**unit**	**remark**
Dichroic structured	Transmission value provide by supplier	10% reflection	Film supplier	172Wp x 90%	155	Wp/m2	could be less due to absorption
Stained solar glass	Power yield provided by supplier	5.6% conversion rate	Solar first	1000watt (STC) x 5.6%	56	Wp/m2	at 50% transparency
Color flex	Yield reduction provided by supplier	50% reduction of 12% conversion	SOL-R&D, Solliance	1000watt (STC) x 12% x 50%	60	Wp/m2	
Solar fades	n.a.	same as mono Si panel	n.a.		172	Wp/m2	
Stained mirror clear	Measured IV curve	26% reduction	IV measurment KS	172Wp x 74%	127	Wp/m2	air gap taken into account
Stained mirror etched	Measured IV curve	29% reduction	IV measurment KS	172Wp x 71%	122	Wp/m2	air gap taken into account
Stained mirror fluted	Measured IV curve	26% reduction	IV measurment KS	172Wp x 74%	127	Wp/m2	air gap taken into account
Ceramic solar	Yield reduction provided by supplier	5-20% reduction	Coating supplier	172Wp x 85%	146	Wp/m2	need to check with stuctured glass
Solar wood 1	Measured IV curve	85% reduction	IV measurment KS	172Wp x 15%	26	Wp/m2	
Solar wood 2	Measured IV curve	65% reduction**	IV measurment KS	172Wp x 35%	52	Wp/m2	
Solar wood 3	Estimation based on IV curve	50% less material than SW 2, so 37.5%	n.a.	172Wp x 62.5%	107	Wp/m2	estimation after laser cutting
Solar channel	Power yield provided by supplier	40 W/m2 for 80% transparent	ASCA	(40/80) x 50	25	Wp/m2	

table A, estimation of yield for first samples

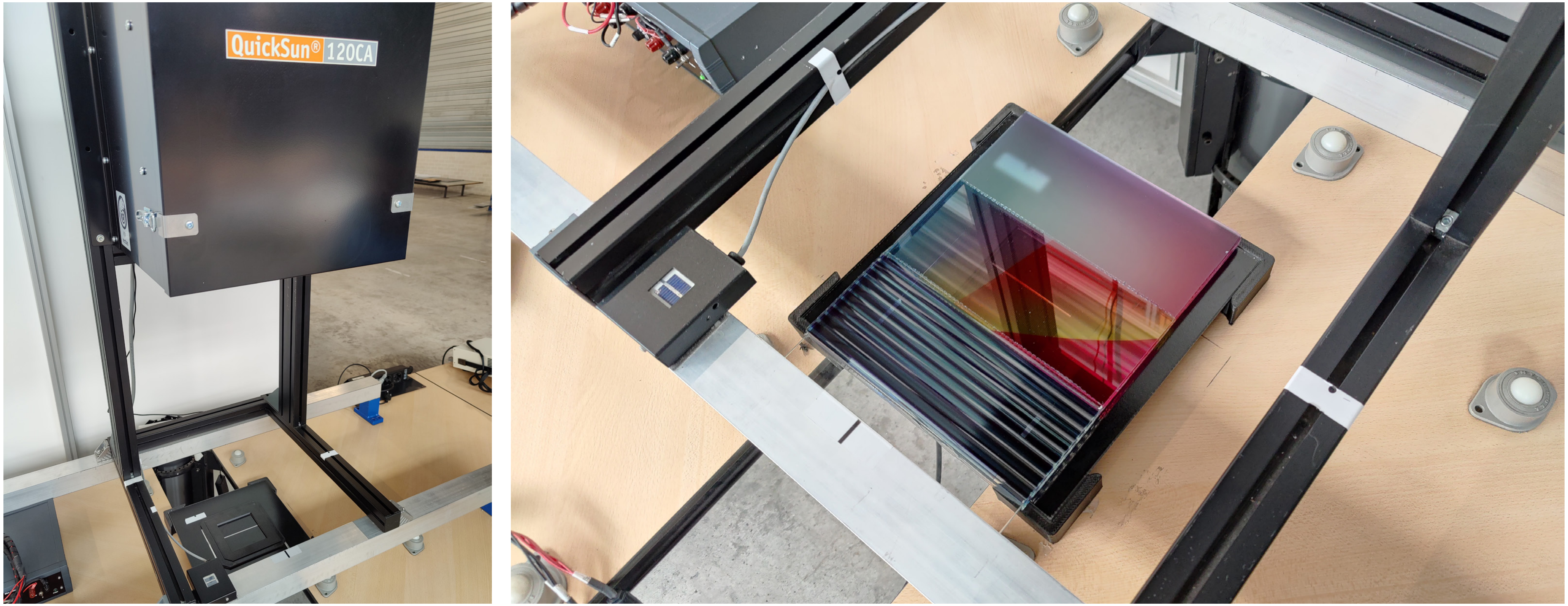


figure A, setup of IV measurements

Appendix C - Concept yield estimation

For all concepts energy yield calculations were made. The estimations were made by taking the total yearly light irradiance on Amsterdam and multiplying it by the efficiency of the panels and a factor to account for the loss caused by the vertical orientation of the panels. The method for this calculation was taken from a presentation by (Broersma, 2023).

An average of 1000 kWh per m2 hits the surface of Amsterdam per year. Depending on the angle and orientation of a solar panel, a certain amount of energy is converted to electricity. Figure A, shows the loss factor per angle and orientation compared to the optimum level. The following formula can be used to calculate the yearly energy yield:

Energy yield (kWh/year-module) = Area (m2) x Irradiance (W/m2) x PV panel efficiency (%) x orientation contour level (%) / reference contour level (%).

The orientation contour level can be read from figure A. In case of the concept vertical façade integration was assumed (90 degrees). The reference contour level is 85%, when a panel is placed vertically.

An estimation of the financial gain was made as well. This was done by multiplying the estimated yearly yield with the business price for electricity excluding VAT.
The yield estimations provide a rough estimation for architects and building owners to use in their decision making process.

Broersma, S. 2023, March, 20. 230320 Solar Electricity [powerpoint slides]. Department of architecture, TU Delft. https://collegeramavideoportal.tudelft.nl/catalogue/ar0132-zero-energy-design/

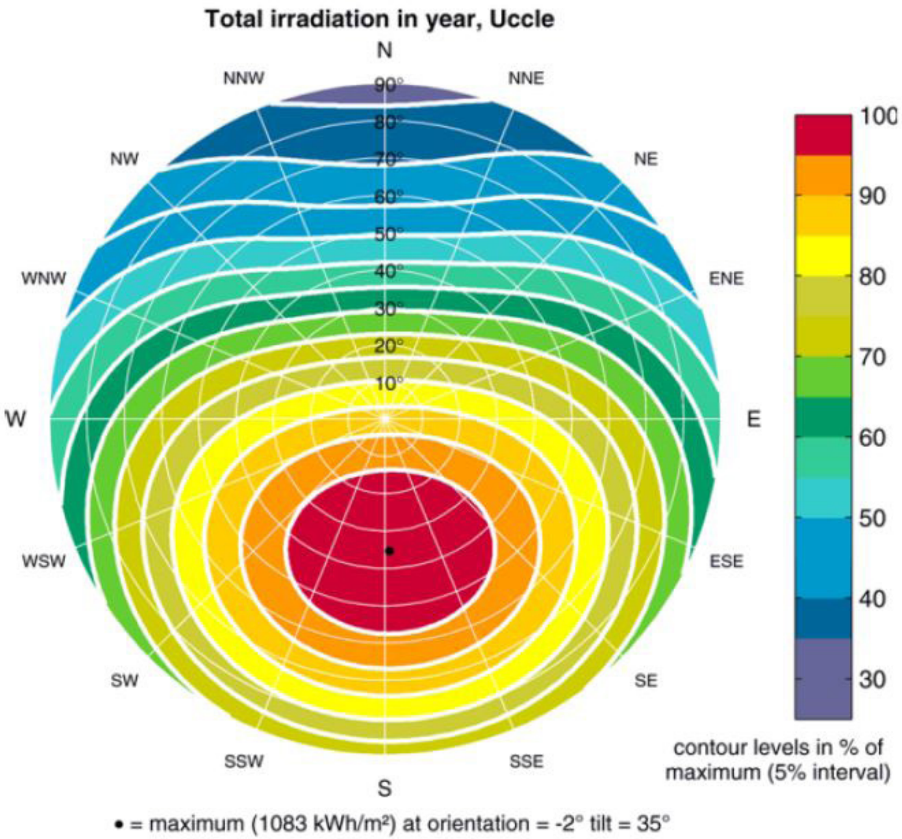


Figure A, contour levels per angel and orientation

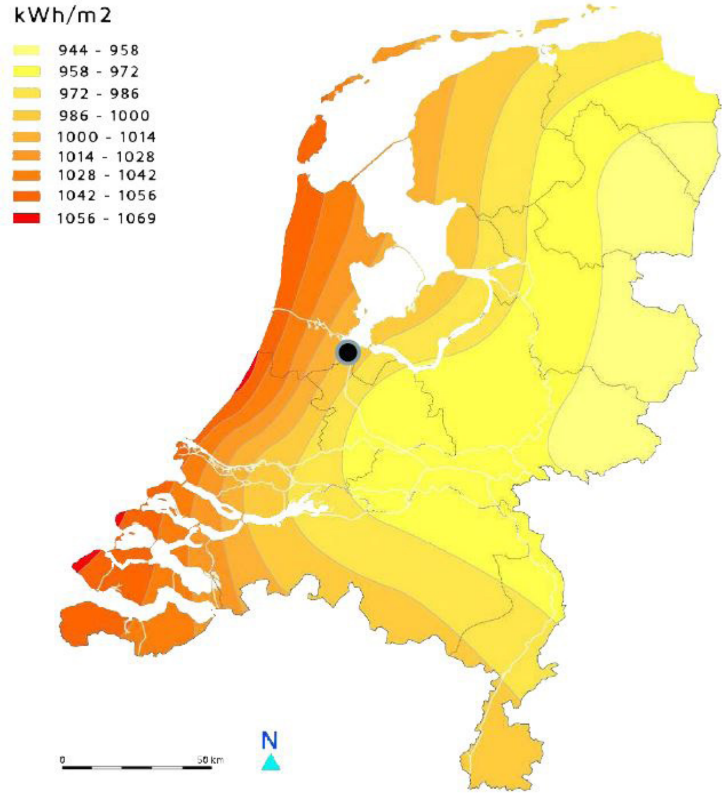


Figure B, yearly solar irradience

Concept	**Wp/m2**	**efficiency**	**source**
Ceramic solar	146	14.6%	estimated from suppliers specs
Dichroic structures	155	15.5%	estimated from suppliers specs
Solar mirror	125	12.5%	IV curve measurements KS
Solar channels	50	5.0%	supplier specs
Yearly irradience	1000	watt/m2	Amsterdam

Concept	**north**	**east**	**south**	**west**	
Ceramic solar	60	103	120	103	kWh/year-m2
Dichroic structures	64	109	128	109	kWh/year-m2
Solar mirror	51	88	103	88	kWh/year-m2
Solar channels	21	35	41	35	kWh/year-m2

kWh price business	€ 0.1005	https://www.energievergelijk.nl/nieuw	excluding VAT, for consumption 10.000 to 50.000 kWh/year

Concept	**north**	**east**	**south**	**west**	
Ceramic solar	€ 6.04	€ 10.35	€ 12.08	€ 10.35	€/year-m2
Dichroic structures	€ 6.41	€ 10.99	€ 12.82	€ 10.99	€/year-m2
Solar mirror	€ 5.17	€ 8.86	€ 10.34	€ 8.86	€/year-m2
Solar channels	€ 2.07	€ 3.55	€ 4.14	€ 3.55	€/year-m2

Table A, energy yield calculation per concept

Appendix D - Relative power loss estimation coloring method

After the fabrication of the first samples, the coloring method proved to deliver a desired effect on aesthetic quality. However, the application of color filters would also reduce the power yield of the solar cell by absorbing or reflecting certain wavelengths of light. Therefore, it was essential to investigate the impact of color filters on power yield and identify the potential of different color methods in solar design.

Transmission measurements were conducted using a Lambda 1050 spectrophotometer to determine the transmission percentage of wavelengths from 300 to 1200 nm for cyan, magenta, yellow, and black filters. The measurements were taken at perpendicular incidence of light. To account for the spectral sensitivity of solar cells, the loss per wavelength was measured. The relative power loss was estimated using the solar cell external quantum efficiency (EQE), the AM1.5g Photon spectrum, and the transmittance measurements.
To provide a reference for comparison, the transmission percentage of extra clear (low iron) glass was also measured using the same method. The outcomes of the color filters were compared to the transmission of the extra clear glass since nearly all PV modules are built with glass front sheets.
The transmission measurement results and relative power loss calculations are presented in the figure 1 and 2 respectively.
The relative power loss varied depending on the color filter used, ranging from 24% to 31%. The black filter resulted in the highest power loss of 49%.

The results of this study demonstrate that the proposed coloring method is a versatile option for coloring PV modules, providing a good balance between aesthetics and performance. However, further research is necessary to investigate the impact of other color filters on power yield.

Additionally, to validate the measurements and model, a PV module using these color filters would need to be constructed and tested. It should also be noted that the use of the color black should be done carefully. Firstly because the relative loss is the highest. Secondly because a too start contrast between power losses within the same PV module might cause hot spots and damage the PV cells.

It should be noted that the current color filters used in this study are not yet optimized for PV applications, so the relative power loss may be reduced by future developments in color filter technology. Additionally, further investigations are necessary to explore the potential of other color combinations beside cyan, magenta, yellow and black. While this study provides insight into the impact of color filters on power yield, the results should be validated using a PV module incorporating these color filters.

In conclusion, this study provided a useful foundation for future research to optimize the selection of color filters in PV modules to balance the need for aesthetics with the requirement for high power yield. The optimization of color filters could lead to significant improvements in the performance and aesthetics of PV modules.

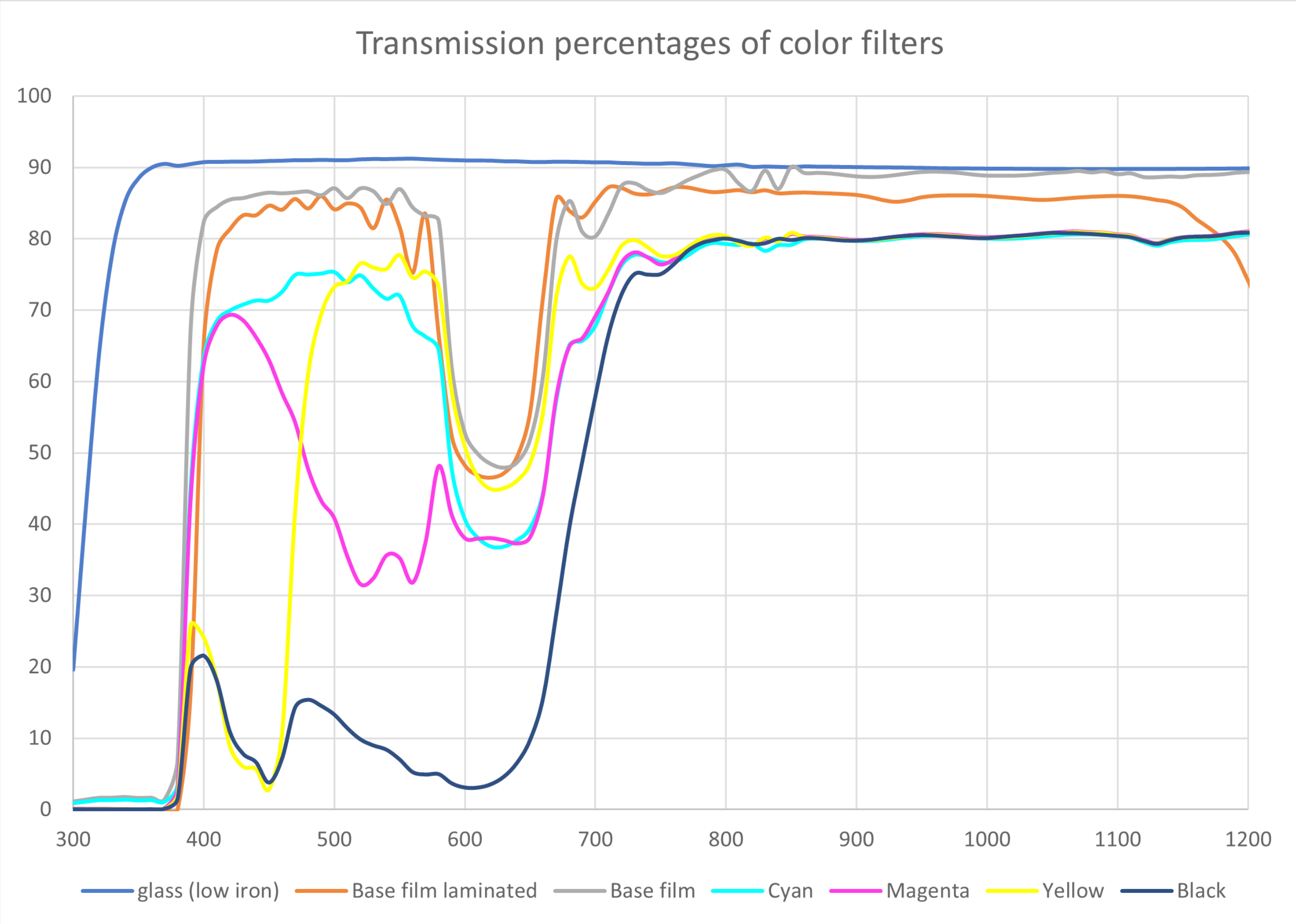


figure A: transmission percentages per wavelenght of light for color filters.

Sample	Jsc(mA/cm2)	Isc (A)	Imp(A)	Vmp (V)	Pmax (W)	Relative loss (%)
Glass (low iron)	37.51	5.74	5.42	0.58	3.14	
Base film laminated	32.47	4.97	4.69	0.58	2.72	13%
Base film	33.41	5.11	4.83	0.58	2.80	11%
Base film Cyan	28.63	4.38	4.14	0.58	2.40	24%
Base film Magenta	26.03	3.98	3.76	0.58	2.18	31%
Base film Yellow	27.75	4.25	4.01	0.58	2.33	26%
Base film black	19.48	2.98	2.82	0.58	1.63	48%

Table A: Relative power loss estimations

Appendix E - Electroluminescence (EL) photography

Solar cells work in reverse as well, when applying a current to them, they emit light in the infrared (IR) spectrum. By capturing this light with an IR-sensitive camera, defects in the cells can be found. The pictures were taken in a completely dark environment. The camera used a long-exposure shot to capture the IR light coming from the cells.

A total of four modules were made:
module 1: with color filters and with low iron glass front.
module 2: without color filters and with low iron glass front.
module 3: with color filters and with fluted glass front.
module 4: without color filters and with a fluted glass front.

No defects were found in the modules 1 and 2. Some defects were found in module 3. Cracks forming at the soldered connections can be seen. This would have a negative effect on the endurance of the module. Luckily it could still be used for IV curve measurments. Many defects could be seen in module 4 as a result of errors in the lamination process. Because the last three cells were completely off, the whole module had become unusable.

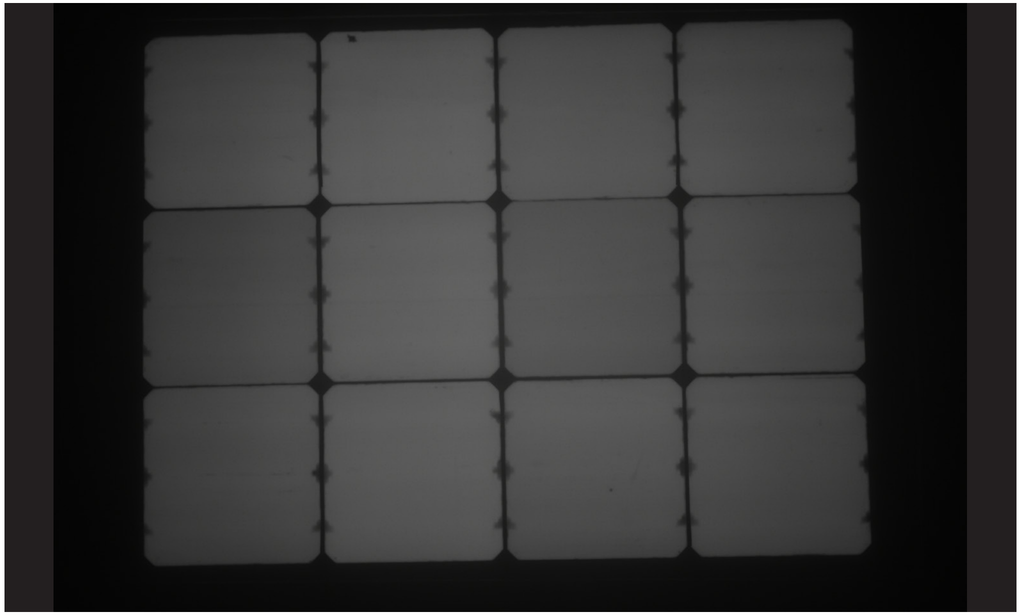


Figure A, EL phototgraphy of module 1.

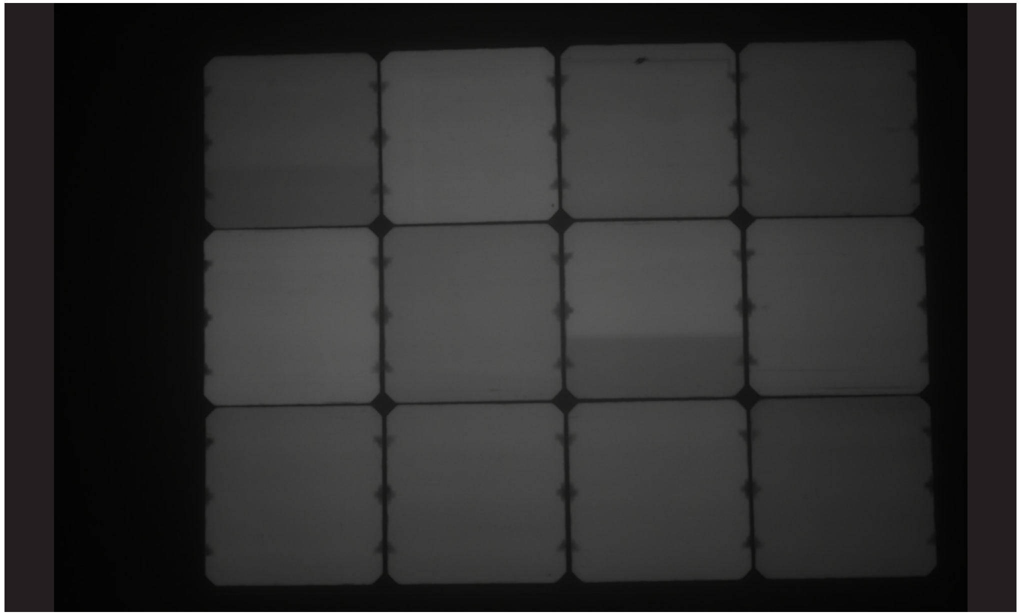


Figure B, EL phototgraphy of module 2.

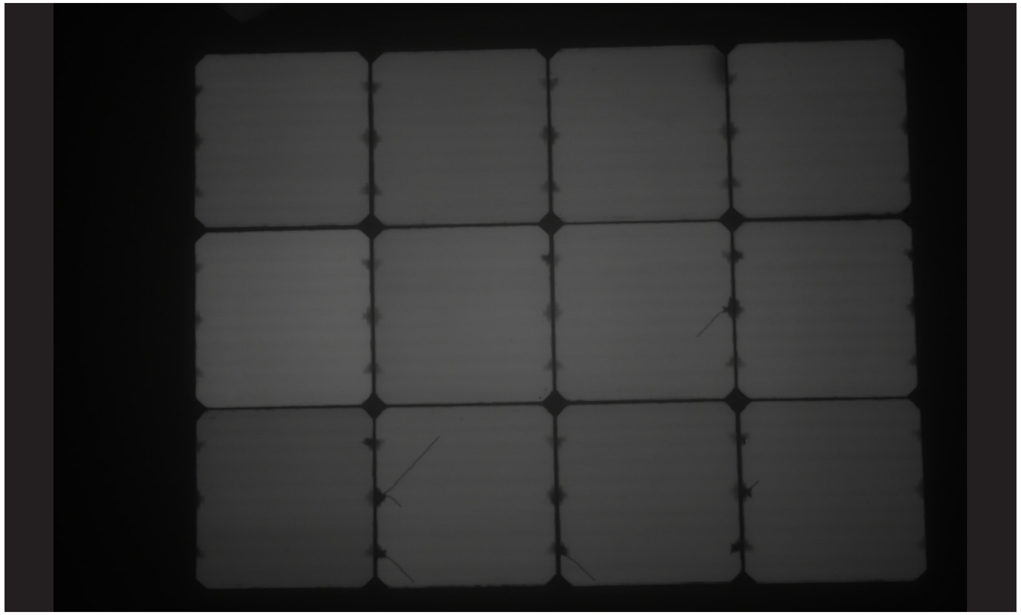


Figure C, EL phototgraphy of module 3.

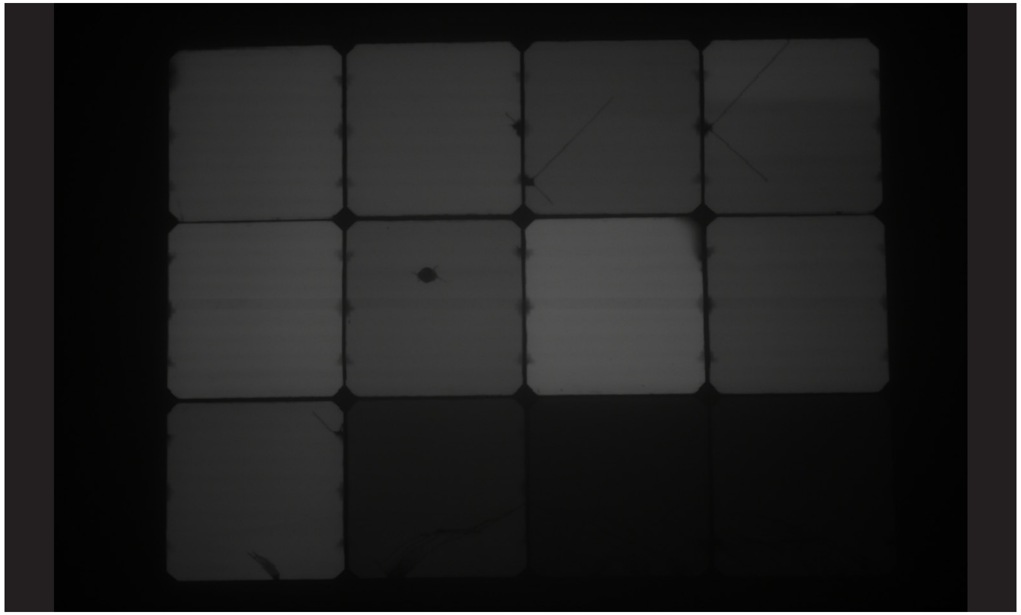


Figure D, EL phototgraphy of module 4.

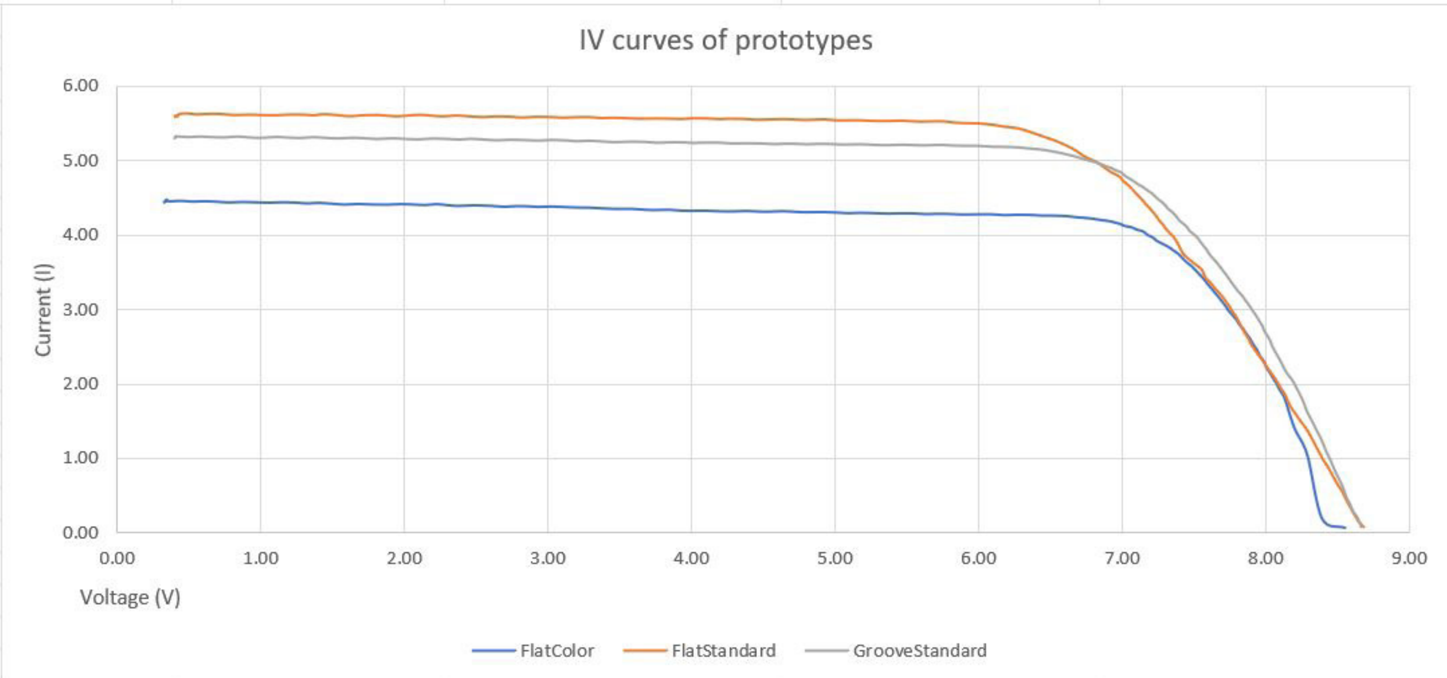
Appendix F - Current-voltage (IV) curve measurement

IV curves were made to compare the power output of the different modules. IV curves can also tell a lot about the health of a PV module so it serves as a quality check too.

A total of four modules were made:
module 1: with color filters and with low iron glass front.
module 2: without color filters and with low iron glass front.
module 3: with color filters and with fluted glass front.
module 4: without color filters and with a fluted glass front.

Because the cells of module 4 broke during lamination, the IV curves of modules 1-3 were measured. It showed how the current output changed with varying sunlight intensity, revealing that as sunlight increases, the module produces more current but at a lower voltage. This curve helped determine the module's maximum power point (MPP). The IV measurements showed that the colored module generated about 80% of the power of the reference module without color. The fluted module without color delivered around 95% of the power of the reference module. From this we can derive that the module with color and fluted front glass would put out roughly 75% of the power of a conventional all black module (20% loss from color and 5% from the glass type).

It is important to note that small modules of 600x400mm are not ideal for measuring IV curves and that larges modules in greater number are needed to accurately compare the IV curves of modules with and without the coloring technology and different glass types. However, it does give a promissiong first impression.



Module type	Short circuit current (Isc)	Isc % compared to FlatStandard	Maximum Power Point (Wp)	Wp % compared to FlatStandard
FlatStandard	5.60	n.a.	34.42	n.a.
FlatColor	4.43	79%	28.96	84%
GrooveStandard	5.32	95%	33.89	98%

Figure A, IV curves of the prototypes

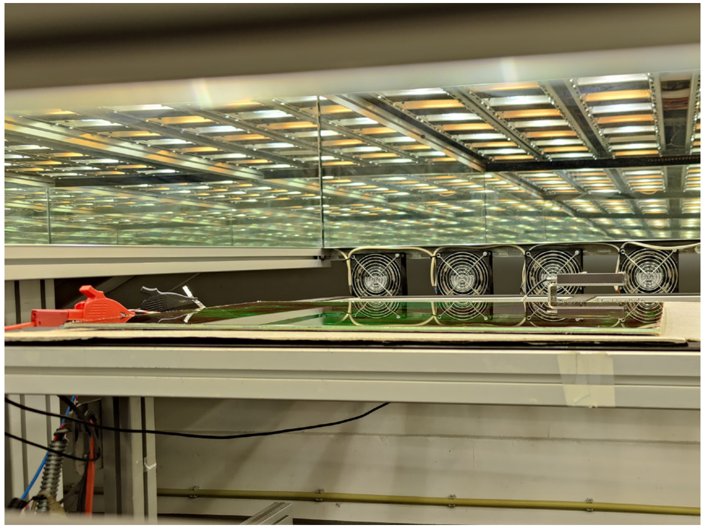


Figure B, module 1 in the sun simulator

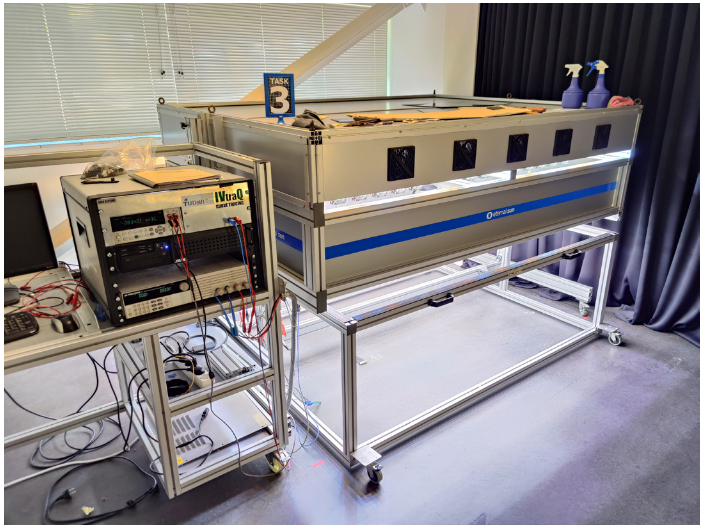


Figure C, IV measurement setup

Appendix G - Module temperature measurement

High temperatures cause crystalline silicon cells to decrease in efficiency. Furthermore, PV modules with a lower average temperature tend to more efficient over their entire life time. Therefore it was important to know what the effect of the coloring technique and the glass structure was on the temperature of the module.

The modules were equipped with thermocouples and placed at a 40-degree angle, facing a southwest direction. The ambient temperature was around 16 degrees, and horizontal solar irradiance was around 870 W/m2. The temperatures of all modules were logged until they reached a stable level. No significant differences between colored and non-colored modules were found.

The results mean that the coloring technology has no negative effect on module efficiency that could be caused by light absorption and that optical loss is the sole cause of power loss.

It should be noted that for different colors the results could be different. Therefore additional research would be nescesarry to completely understand the influence of the coloring technology on module temperature.

Figure A, fist layer of heat conducting tape to transfer heat to temperature probe.

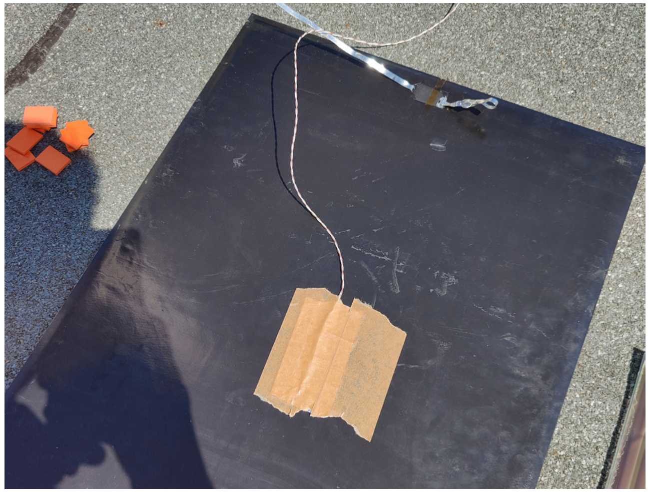


Figure B, second layer of isolation tape to trap the heat.

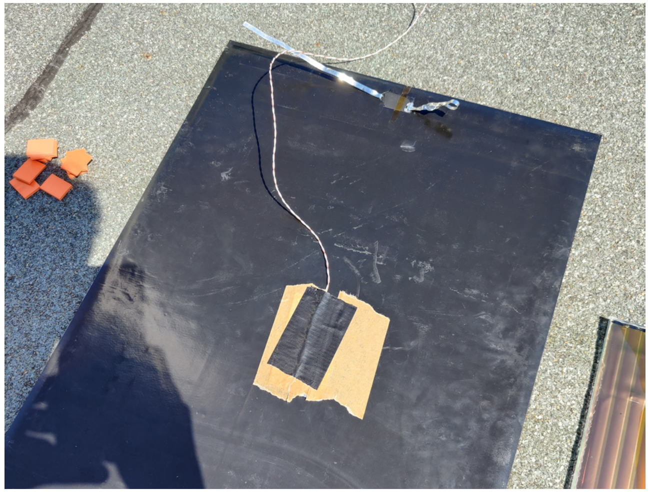


Figure C, third layer of blackout tape to prevent block warmth from irradiation.

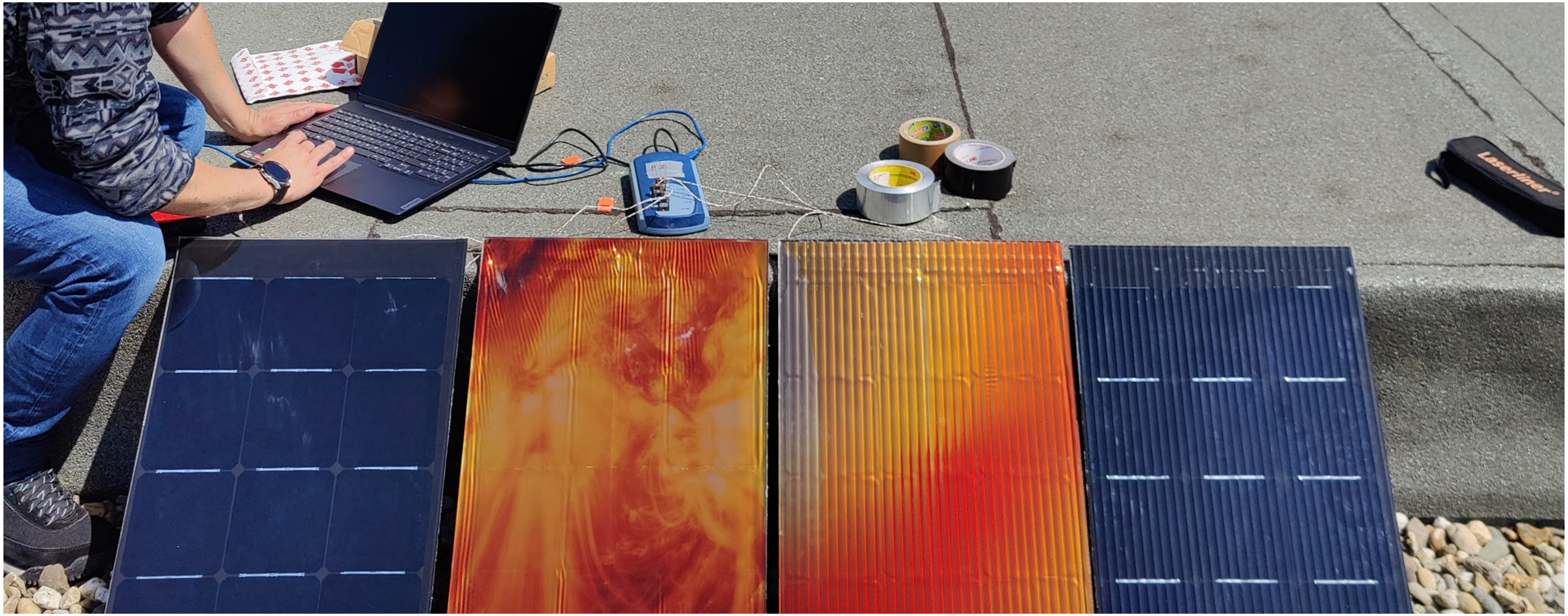


Figure D, logging the temperature.

Appendix H - Stakeholder overview

A stakeholder overview was made to keep track of the important organizations to watch. This was made to get an overview of the ecosystem of the BIPV sector. This could be used as input for strategic positioning, finding partners and spotting important topics to take into account. A paper by Osseweijer et al. (2017) was used as a general framework for the stakeholder overview. The stakeholders from this paper were listed with a short description of their relation with this project.

Municipalities, national government and European Union
Should be watched for developments in regulations, policies and subsidies. Examples include (N)ZEB building on European level and (B)ENG on a national level.

Building energy consultants & industry associations
Building energy consultants provide advice on criteria such as energy regulation and performance and certification procedures. They can recommend the use of BIPV in the building. An example of such an organization is Dutch green building council. Industry associations could be useful because of the knowledge they possess and distribute to move the industry forth as a whole. Next to that they provide an overview of relevant players that are members of the association. In the Netherlands this organization in BIPV Nederland.

Universities and research institutions
Universities and research institutions develop extensive knowledge on technological developments for PV and BIPV. Their publications should be watched to stay up to date on developments, look for methods they use and spot important topics to take into account. Especially the output of the PVMD group and BIPV related group in Build Environment faculty should be on the watch list.
Another interesting institution to keep an eye on is Solliance. They are developing promising flexible solar technology. They could be a potential development partner.

Manufacturers & suppliers
Manufacturers are both potential partners as well as potential competitors. Cooperation is need to build modules. At the same time they offer their own products that compete. A good partnership needs to be found for successful launch of the developments of this project. Examples of manufacturers as Kameleon Solar, Studio Solarix, and Biosphere solar.
Suppliers provide PV cells, semi-finished products and can offer expertise in for integration and manufacturing.

Architects & designers
Architects are important in the decision-making process of implementing BIPV products. They should be familiar with the concept op BIPV and the products we offer. They are also an important source of information about the qualities of a good BIPV product. There should be a back and forth of inspiration and feedback between architects and the new company. Designers are generally more independent and have more freedom in the materials they choose. Therefore there is a lower threshold in working with them. A positive consequence is the project showcase aesthetic qualities of the products.

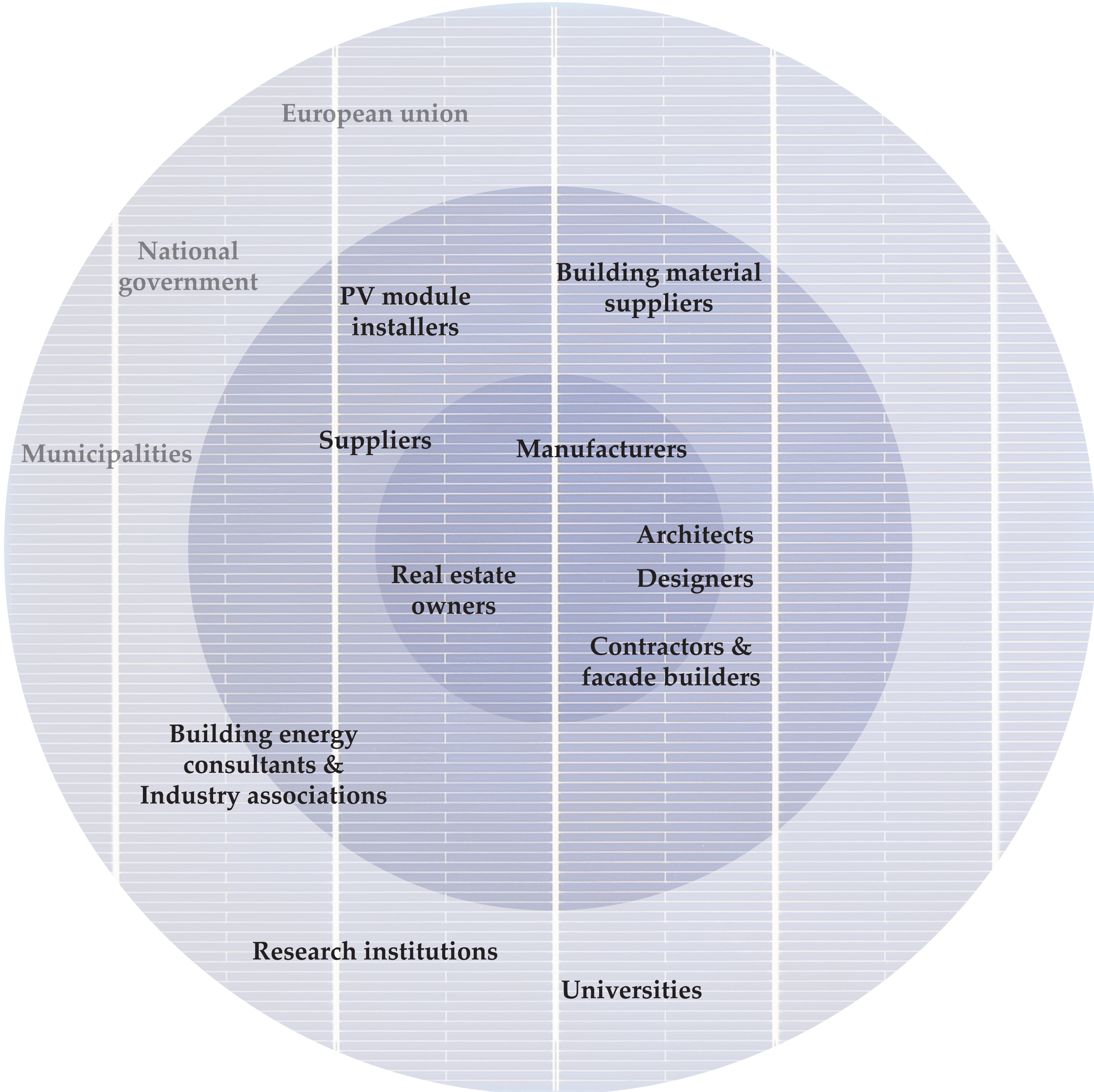
Contractors & façade builders
Often contractors and/or façade builders are the ones in charge of which materials are applied and they hold responsibility for the installation. They should therefore be familiar with the products. Another opportunity is that they can add BIPV products to their current offerings and be a reseller/agent.

Real estate
The final decision makers are in real estate. It therefore this group that needs to be convinced directly or indirectly to apply BIPV products. Distinctions can be made between project developers (CBRE), social housing corporations (Ymere), business owners, private home owners or other sorts of building owners.

The stakeholder overview provides a valuable tool by identifying and understanding the various stakeholders in the industry. It can be used to in decision making regarding strategic positioning and making partnerships.
Municipalities, national governments, and the European Union should be monitored for regulatory developments and subsidies. Building energy consultants and industry associations provide knowledge and recommendations for BIPV adoption. Universities and research institutions offer insights into technological developments and potential development partners. Manufacturers and suppliers may be competitors or partners in module development, and architects and designers are important for product adoption and aesthetic qualities. Contractors and façade builders are responsible for installation and could be potential resellers or agents. Finally, real estate developers and building owners make the final decision on BIPV product adoption.

By building relationships with relevant stakeholders, the chances of success can be increased and a competitive advantage in the BIPV sector can be gained.

Osseweijer, F. J., Van Den Hurk, L. B., Teunissen, E., & Van Sark, W. (2017). A Review of the Dutch Ecosystem for Building Integrated Photovoltaics. Energy Procedia, 111, 974–981. https://doi.org/10.1016/j.egypro.2017.03.260


European union
National government
Municipalities
PV module installers
Building material suppliers
Suppliers
Manufacturers
Architects
Designers
Real estate owners
Contractors & facade builders
Building energy consultants & Industry associations
Research institutions
Universities

Appendix I - Design concept validation

Interview questions Dutch:

Kunt u beschrijven hoe u nu omgaat met bijna energie neutraal bouwen?

Tegen welke uitdagingen loopt u hierbij aan?

Wat is uw ambitie m.b.t. bijna energie neutraal bouwen?

Wat is het effect van het realiseren van die ambitie?

Wat zou dat betekenen voor jullie?

Welke rol hebben zonnepanelen hierin?

Welke rol speelt een gebouw façade hierin?

Heeft u ervaring met het toepassen van zonnepanelen in de gevel?

[Over naar samples, korte beschrijven van ieder concept]

Graag eerste indruk van look and feel van alle samples. □ hardop nadenken.

Zijn er projecten geweest waarin u dit had toe kunnen passen? Waarom wel/niet?

Interview questions English:

Can you describe how you now deal with near energy neutral building?

What challenges do you face?

What is your ambition with regard to near-zero energy building?

What is the effect of realizing that ambition?

What would that mean for you?

What role do solar panels play in this?

What role does a building facade play in this?

Do you have experience with the application of solar panels in the facade?

[Over to samples, brief description of each concept]

Eager to get first impression of look and feel of all samples. □ thinking out loud.

Have there been any projects where you could have applied this? Why yes/no?

Concent form

Was asked to be filled in and signed by all participants.

U wordt uitgenodigd om deel te nemen aan een onderzoek genaamd Sol-R&D. Dit onderzoek wordt uitgevoerd door Max van Dijken van de TU Delft voor zijn afstudeerproject (MSc Integrated Product Design).

Het doel van dit onderzoek is om inzicht te krijgen in de indruk van architecten van nieuwe fotovoltaïsche (PV) materialen en zal ongeveer 30 minuten in beslag nemen. De data zal gebruikt worden voor het afstudeerverslag. U wordt gevraagd om uw inzichten te delen in een interview.

Uw deelname aan dit onderzoek is volledig vrijwillig, en u kunt zich elk moment terugtrekken zonder reden op te geven. U bent vrij om vragen niet te beantwoorden.

Contactgegeven van de onderzoeker:

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. Ik heb de informatie over het onderzoek gedateerd 06-03-2023 gelezen en begrepen, of deze is aan mij voorgelezen. Ik heb de mogelijkheid gehad om vragen te stellen over het onderzoek en mijn vragen zijn naar tevredenheid beantwoord.	☐	☐
2. Ik doe vrijwillig mee aan dit onderzoek, en ik begrijp dat ik kan weigeren vragen te beantwoorden en mij op elk moment kan terugtrekken uit de studie, zonder een reden op te hoeven geven.	☐	☐
3. Ik begrijp dat mijn deelname aan het onderzoek de volgende punten betekent: Het geluid van het interview zal opgenomen worden. De audio opname zal na het verloop van het project in april vernietigt worden. Er bestaat een mogelijkheid dat delen uit een transcript anoniem gepubliceerd zullen worden in het afstudeerverslag.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)	☐	☐
4. Ik begrijp dat de persoonlijke informatie die over mij verzameld wordt en mij kan identificeren, zoals naam en woonplaats niet gedeeld worden buiten het studieteam.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
5. Ik begrijp dat na het onderzoek de geanonimiseerde informatie gebruikt zal worden voor publicatie in het afstudeerverslag.	☐	☐
6. Ik geef toestemming om mijn antwoorden, ideeën of andere bijdrages anoniem te quoten in resulterende producten.		
7. Ik geef toestemming om mijn naam te gebruiken voor quotes in resulterende producten		

Appendix I - Design concept validation

The interviews were recorded and afterwards processed afterwards. Here are the resutls in Dutch.

BENG moet, proberen ENG waar mogelijk. Gebouw voor 40 jaar. Als het kan meteen meenemen. Als het niet kan meteen voorbereiden.

Soms een belemmering. Waarom? Soms niet genoeg dak voor genoeg zonnepanelen. Soms probleem met andere systemen op het dak. HVAC.

BENG goed te doen: juiste isolatie, juiste materialen. (warmtepompen etc.)

Balans zoeken: voorzien in eigen behoefte.

Dualistisch: meer isolatie en duurzaamheid kan botsen met andere belangrijke dingen zoals ventilatie en licht toegang.

Op natuurlijke manier licht binnen willen hebben. Wel opletten met warmte binnen kunnen halen. Energie van zon naar binnen willen halen wanneer je wil. Wel in de winter, niet in de zomer.

Al een naar BIPV oplossingen gekeken? We weten dat er oplossingen zijn. Je wil wel transparantie hebben dus dat is lastig. Misschien als er systemen zijn dat je zon kan weren energie kan opwekken tegelijkertijd wanneer je het wil.

Nog meer onderzocht in de delen die niet transparant zijn? Daar kan je toepassen wat je wil. Daar hebben we nog niet naar gekeken. De noodzaak om verder dan het dak te zoeken is nog niet voorgekomen. Het rendement wordt ook minder en we zoeken toch naar de goedkoopste en meest effectieve oplossing.

[samples introduceren]

Bij deze heb ik meteen de associatie met spiegelende kantoorgebouwen. [solar mirror].

Wat je je afvraagt is of je wel of niet wil zien of er zonnepanelen op het gebouw zitten.

Over profilit: dat is gaaf ja.

Terugverdientijd van 12 jaar is best oke op een levensduur van 40 jaar. Afhankelijk van de investeringskosten natuurlijk.

Isolatiewaarden zijn wel een ding.

Het is wel mooi want je lost twee dingen op: je gevelbekleding en je energie.

Over dichroic: oh wauw heel gaaf. Dan doet het echt iets anders met het licht.

Het leuke vind ik wel als je er echt een gevel mee kan maken (Ceramic). Het is een mooie gevel en “toevallig” wekt het ook energie op. De andere opties lijken meer op zonnepanelen. Door reflecties en het oppervlak. Dat is echt een paneel. Dit lijkt wat anders. Door de structuur gebeurt er wat mee.

Soms wil je wel of juist niet laten zien dat je zonnepanelen hebt of niet. Bij ons kan het bijvoorbeeld educatief leuk zijn.

Deze spreekt me het meest aan door de spiegeling en dynamiek die erin zit. [solar mirror met canale]. Je begrijpt niet meteen waar je naar kijkt dat maakt het spannend.

Maar als je dit een andere kleur had gegeven vond ik dit misschien beter. (ceramic solar). Want het is wel leuk want je kan er alle kanten mee op. Variëren in kleur en dan liggend of staand.

Ik vind het een meerwaarde want dan ben je met een materiaal bezig en niet met een zonnepaneel. Het mooie is dat je het met één materiaal kan oplossen in plaats van een samenraapsel waar dan zonnepanelen op moeten. Dat hadden we vroeger ook met antennes en die hebben we nu ook netjes weg kunnen werken. Dit is een leuke ontwikkeling die daar binnen past.

Als u terugdenkt aan een van de projecten die jullie gerealiseerd hebben, zou een van de producten daar dan tussen kunnen passen?

Ja de bouwacademie in Waddinxveen. Daar zitten verschillende materialen in zoals hout, verschillende metselwerken steen en mataal. Het zou harstikke leuk zijn om deze (ceramic) daarin mee te nemen en te laten zien hoe je dat in een gevel kan verwerken.

Welke factoren zijn het belangrijkst of iets wel of niet toegepast wordt: geld natuurlijk. De duurzaamheidsambities zijn vaak heel hoog maar er moet altijd gekeken worden wat er mogelijk is qua kosten. Je moet alles van te voren financieren en het rendement komt later. Daar is niet altijd budget voor. Wat natuurlijk suf is want je kan het maar beter in een keer goed regelen. Dan verdien je het vanzelf terug. Met een materiaal als dit moet je de kennis ervan hebben en het meenemen om ze [klanten] te verleiden om ervoor te gaan.

Hoe wordt budget verdeeld? Je komt met een voorstel met een soort kern die heilig is. Dan zit daar een soort schil omheen die steeds zachter wordt waar je op in kan leveren. Dan is het belangrijk dat dit in die kern zit.

Vooral particulieren, zowel renovaties als nieuwbouw.

Energiehuishouding speelt belangrijke rol. Je moet van het gas zijn bij nieuwbouw. Isolatie speelt ook een grote rol en zonnepanelen zijn bijna altijd nodig.

Waar lopen jullie tegenaan als het om zonnepanelen gaat: Dat ze niet mooi zijn. Bij een plat dak zijn ze uit het zicht, dan is het geen probleem. Maar als je een kap wil ontwerpen kan het toch een probleem zijn. Wat veel gedaan wordt is dat ze op de pannen liggen. Dan is een in-dak systeem mooier. Daar zijn nog weinig oplossingen voor. Brandgevaar aanwezig. Daar zouden wij graag meer producten in zien. We hebben een producent die het netjes kan verwerken maar het product zelf is nog niet heel mooi. (Exasun)

Wat is er mis met het zwarte paneel? Met donkere pannen is het niet erg maar op het moment dat je een andere kleur pan hebt dan kan het storend zijn. Als je het hele dak kan benutten is het geen probleem (uniforme uitstraling). Stel je wil een zadeldak bekleden met zonnepanelen dan kom je bij schoorsteen bijvoorbeeld al in de problemen omdat je dan niet uitkomt met je afmetingen. Dan moet je met paspanelen gaan werken in de kleur van het pv paneel. Als je een product kan vinden dat dezelfde uitstraling heeft als de rode pannen zou dat perfect zijn.

Andere pains behalve kleur en verwerking: Het wordt steeds beter hoe ze geschakeld zijn maar daar hebben wij niet veel me te maken. Maatvoering is wel een ding. Dat is best passen en meten soms. Dan moet je met passtukken gaan werken. Dat kan maar het zou mooi zijn als je flexibeler bent. De vraag is of je naar maatwerk kan. Als je 30 woningen neerzet is dat aantrekkelijker maar wij werken veel met particulieren. Wat me ook opvalt is dat zonnecollectoren en PV panelen nooit dezelfde maat hebben. Dus dan kan je nooit een mooie rij maken. Dan steken de collectoren weer een stuk uit. Vrijheid in maatvoering zou mooi zijn.

Situatie te weinig dak? Komen wij niet heel vaak tegen. De meesten gaan er al vanuit dat ze toch niet alles zelf kunnen opwekken dus die feedback krijgen we niet echt. Met 80/90% zijn de meesten al tevreden. Het is ook een wisselwerking tussen installateur en architect wat het beste is.

[samples introductie].

Ceramic: Ik denk dat dit vooral voor grote kantoren of bedrijfspanden een oplossing is.

Solar mirror met canale introductie: Mooi. (probeert opbouw te begrijpen). “Dat is optisch wel heel gaaf.”

De kleur is heel bedrieglijk (solar mirror zonder canale). Dat is best lastig om mee te ontwerpen. Als je iets voor ogen hebt en het ziet er anders uit als je de hoek om loopt, is dat best lastig om mee om te gaan.

Dichroic structured: Dat is ook wel interessant.

Hoeveel is het rendement van deze? Als dit nou 30% is dan is de keuze snel gemaakt. Want dat is best belangrijk.

Aan de andere kant: als je een hele gevel zou bekleden, wek je dan niet veel te veel op?

Appendix I - Design concept validation

Dit doe je een of twee keer [dichroic structured] want je wil niet te veel van dit soort gebouwen neerzetten. Want het is best wel extreem in zijn verschijningsvorm. Je wil er geen stad mee volbouwen, dan wordt je gek.

Heeft u weleens met kanaalglas/profilit gewerkt? Ja voor binnenwanden alleen.

Kan je nog in kleuren variëren? Ja [uitleg over kleurmogelijkheden].

Wat ik mij afvraag: als dit een gevelpaneel is, op het moment dat ik raamopeningen maak, doe je dat dan op traditionele wijze of kan je daar nog een lijn in trekken? Als ik een vlakke plaat heb, dat je kan variëren in of je naar binnen of buiten kan kijken?

[laat gradient to clear zien].

[Haalt collega's erbij].

"Ziet er tof uit." Van glas tot bijna Keramisch.

"Wat ik mij afvraag is of het niet te project specifiek zou zijn?"

Ik zou het misschien project specifiek toepassen, niet als een algemeen product dat je vele malen probeert.

Wat voor type project?

Vanwege de paneelverschijning zou ik zelf aan grootschalige utiliteitsbouw denken. Of misschien juist wel kleinere omdat het zo specifiek en in your face is. Vraag ik mij af of je er wel 100en meters van wil zien. Of bijvoorbeeld die lullige transformatorhuisjes van de Eneco. Daar zou dit perfect voor zijn.

[collega]: Is het niet dat het glas vrij specifiek is omdat je met kleurkeuzes zit. Maar als je in die hoek zit (ceramic) dan is het niet heel anders dan een bouwsteen. Dit is ook wel gaaf dat het van kleur veranderd.

Eigenlijk op alle gevels waarop je ook tegels zou gebruiken kan je dit toepassen. Het is ook gaaf als je bij een woongebouw als je alleen de balkons doet.

[a2g]: Dat je het als ornamenten gaat zien.

[collega 2]: Je hebt nu al die galerij flatgebouwen die ze moeten gaan verduurzamen. Die zijn vaak in structuur helemaal goed maar hebben een slechte naam. Als je daar iets tofs mee kan doen, kan dat wat zijn.

[collega 1]: Daar zit in NL een grote opgave in. De belijning is heel mooi en die gaan echt niet weg. En dan is dit wel heel gaaf. Dan kan je heel veel vlak pakken om die zonnepanelen op een leuke manier toe te passen.

[a2g]: Wat ik lastig vind aan dit soort producten, dan schrijf je ze voor. En dan hoor je, "ontzettend leuk" maar wat kost het? En dan wordt het toch een suf golfplaatje. Hoe verantwoord de besparing van het opwekken tot de prijs van de gevel?

[C1] Het zou best een aantal jaar mogen duren. Ik zou zeggen 10 jaar?.

C2: Ik vind eigenlijk dat we af moeten van het idee van terugverdientijd want er is geen alternatief.

A2G: Ik zie het als oke ik heb er 20k ingestoken, wanneer heb ik die 20k terug? Vanaf dat punt ga ik verdienen op mijn investering. Terwijl wij niet meerekenen wat hebben verdient op het milieu. Dat wordt eigenlijk nooit meegerekend.

C2: Stel nou ik heb een bedrijfspand en deze oplossing blijkt te duur en we zetten er voor 50k aan golfplaat tegenaan, dan is er ook niemand die vraagt wat de terugverdientijd is.

Gezamenlijk: terugverdientijd gaat om het bedrag dat er extra in is gestopt om er solar van te maken. Tegelijkertijd zou je kunnen zeggen dat het daar niet meer om gaat. Maar de investeerders zullen dat blijven zeggen.

[hier een deel over opslag, wissel- en gelijkstroom en systeem dingen].

C1: Ik vind het wel een heel mooi product. Het is ook zo lelijk om een zonnepaneel op een dak te leggen. En laatst reden we langs die velden. Oh wat lelijk. Je moet eigenlijk helemaal terug en mooi gaan bouwen met waar het in zit.

C2: Voor kleinschalige woningbouw is het wel een lastig product. We gaan meer richting de houtbouw.

Bibliotheken.

H: Bibliotheekbouw en inrichting. Het komt voornamelijk neer op hergebruik. Maar soms ook nieuwbouw. Soms alleen inrichting. De gemene deler is dat het altijd om een bibliotheek gaat. Meestal gaat het om bibliotheek concept en inrichting. Als het om nieuwbouw gaat, zit ik in een team waarbij de bouwkunde door een ander gedaan wordt. Bij renovatie wel bouwkundig werk erbij. Bijvoorbeeld bij de chocoladefabriek in Gouda.

Wat houdt “het concept in”.

H: We denken ook na over de toekomst van bibliotheekwerk. Dat houdt ook rekening met het grote plaatje. Dat gaat verder dan gewoon een nieuw gebouw neerzetten. Je moet ook op de deur van de directeur willen zitten en conceptueel nadenken om te vernieuwen.

Welke rol speelt verduurzaming bij jullie:

H: We proberen veel natuurlijke materialen te gebruiken en zo te bouwen dat het lang mee kan. We maken tijdloze ontwerpen. Als je het met minder kan doen is dat per definitie het meest duurzaam. Dat is voor de overheid ook belangrijk. Zij willen alles label A geven en een BENG label eraan kunnen hangen. Dat nemen we ook allemaal mee. Dat is niet heel spannend. Het gaat vooral om de juiste isolatie, 3 dubbel glas etc. Dat nemen wij ook mee.

Een ander voorbeeld in IJsland, in samenwerking met een Rotterdams bureau. Dan zitten dat soort keuzes bij hen.

Obstakels/uitdagingen voor BENG?

H: Greenwashing. Dat dingen groener worden voorgedaan dan ze zijn. Voorbeeld plaatmaterialen met houtprintjes en folies. Dat zou duurzaam FSC hout zijn maar het woord lijm werd niet genoemd terwijl dat er wel in zit. En toen ik ernaar vroeg stonden ze met een mond vol tanden. Het is makkelijk om te doen alsof maar is het echt zo? Zit het echt in je bedrijf of bij de marketing afdeling?

Hoe komt dat terug in jullie manier van werken?

H: we zijn voorzichtig met materiaalkeuzes. We maken zoveel mogelijk gebruik van natuurlijke materialen en vermijden aan elkaar geplakte composieten. Hennep isolatie bijvoorbeeld.

Het gaat dus vooral om circulariteit over CO2 uitstoot?

Ja voor ons wel. Ik vind dat die labels weinig voorstellen. Dat is geen integraal verhaal. Als de spreadsheet klopt is iedereen blij maar dat heeft niet per se met echte duurzaamheid te maken.

Hoe zit het bij jullie met energie opwekken?

Warmtepomp etc. Warmtedistributie is ook een topic. Bijvoorbeeld vloerverwarming of IR panelen.

En zonnepanelen?

H: Ja in gouda bijvoobeeld komen er 140 op het dak te liggen. Voor platte daken is dat geen probleem en voor residentieel snap ik het ook wel. Maar ik vind wel dat op de schuine daken in het stadslandschap (niet appartementen maar gezinswoningen) met die lelijke panelen die nooit mooi uitkomen, dat het er niet fraaier op wordt. En dan ben ik nieuwsgierig of zo’n initiatief van Tesla met de dakpannen nog van de grond gaat komen.

Speelt deze issue voor jullie al een rol? Dat de oplossingen niet mooi genoeg zijn?

H: in Leidschendam zitten er huurwoningen boven de bibliotheek. En de VVE wil geen PV panelen op het dak van hun appartementen hebben.

Hebben jullie weleens overwogen om zonnepanelen toe te passen in de façade?

H: nog niet.

Waarom niet?

H: Nog niet aan de orde geweest. Kan het ook op transparant plakken zodat je er nog doorheen kan kijken?

Ja, [uitleg transparante toepassingen]. [samples introduceren]

H: wat is het doel van je afstuderen?

Zonnepanelen mooi verwerken in gebouwen.

[samples neerleggen en vragen om reactie].

H: Dit lijkt bijna keramisch. Maar het is glas toch? Wat doet dat met de opwekking?

Ongeveer 80% houd je over.

H: oke een beetje verlies.

H: En bij deze (mirror met canale) is het effect van de zon niet heel heftig. Dat er een auto smelt door de weerkaatsing? Ik denk het niet want het breekt het licht. Ik kan me dit wel voorstellen. Ik denk wel als je een stedelijke uitstraling wil hebben zonder dat het eentonig wordt, dat je heel veel verschillende soorten nodig hebt. En ik ben ook benieuwd wat het doet als je het van grote afstand ziet. Of het effect dan niet weg is.

H: En dat het verticaal geplaatst is, ipv onder 45 graden?

Er is een factor van 0.8 voor het verticaal plaatsen. En een factor van 0.8 voor de kleurtechniek.

H: Oke. Dit blijft altijd een soort vliesgevel systeem. Met een kitrand ertussen?

Er kan een kleine ruimte tussen. Er kan ook een profiel tussen zitten.

H: Bestaat dit al als product?

Nee nog niet, dit zijn alleen visuals.

[introductie channels]

Appendix I - Design concept validation

H: oh dat is wel gaaf.

H: Wat is de levensduur?

Garantie tot 20/25 jaar maar het gaat langer mee.

H: Het is wel beter als je kan nadenken over oplossingen die net zo lang mee gaan als het gebouw. Dan hoef je niet je hele gevel te vervangen als de zonnecellen het niet meer doen.

Of zo'n oplossing (channels) waarbij je alleen een folie hoeft vervangen?

H: ja dat kan ook.

H: Voorkeur voor film in channels dan wafers. Omdat je het minder ervaart.

H: Ik kan me wel voorstellen dat ik dit toepas. Ik denk niet in het hele gebouw maar een gedeelte. Ik denk dat het wel een elegante oplossing is.

Heb je weleens gebruik gemaakt van kanaalglas?

H: nee, wel glazen bouwstenen. Wel heb ik gewerkt aan gebouwen waar ze al in zaten. Maar toen werden ze toegepaste als scheidingswanden.

Als je terugdenkt aan eerder projecten. Zou een van deze oplossingen er dan inpassen?

H: Het is een ander soort architectuur maar misschien wel. Ik heb in Barendrecht een theater zaal gedaan. Die heeft een gevel gekregen waar we een soort gordijn van aluminium omheen zat. Zo'n zaal komt geen natuurlijk licht binnen en dat leent zich om het op een manier te behandelen. Daar zie ik zoiets wel toegepast worden. Zolang het binnen het concept past. Wat ik hier nu zie is dat het allemaal vlakke gevels zijn met een anders soort structuur. Ik zou moeten kijken hoe je het combineert met andere materialen. Dit lijkt al gauw op van die distributiedozen die langs de snelweg staan. En als je een gebouw maakt in de stad dan moet het aanzicht van afstand ook interessant zijn. Dan moet je denken aan combinaties met hout, beton of glas. Bijvoorbeeld de zeevaartschool. Een golfplaten gebouw. Bij dit soort architectuur zie ik het wel echt toegepast worden. Dat zie ik wel voor me.

H: Wat je zal zien is dat het een kostenverhaal wordt. Hoe de investering en terugverdientijd uitvalt zal ook bepalend zijn. De goedkope import van Chinese panelen zal dan wel een concurrent zijn. Het is nu nog vaak een best effort. Als je het dak vol legt is het wel goed.

H: Ik ben wel benieuw of het er van grote afstand niet te vlak uit ziet. Want qua structuur is het niet heel veel.

[voorbeeld school copenhagen]

H: ja op die manier kan je het wel spannend maken. Is dit helemaal solar? Ook de noordkant?

Ja.

H: Ik kan me voorstellen dat het goed kan werken.

Welke spreekt je het meest aan?

H: Deze twee: (solar mirror + canale en ceramic solar). Dit vind ik te veel arabisch overkomen (dichroic structured) Misschien is dat iets voor Dubai of de Emiraten. En dat kan dus ook in blauw of een andere kleur?

H: Hoe zou je het vastmaken aan een gevel?

Wat het meest wordt gedaan is het bevestigen met beugels op de achterkant. Of een frame met klemmen.

H: Gevoelsmatig vind ik klemmen een veiligere oplossing omdat dat andere een lijmverbinding is. Ik kan me zo voorstellen dat na 30 jaar er toch iets los gaat laten.

H: ik ben hier fan van voor gevels (ceramic) en dit als verbijzondering van gevels (solar mirror + canale). Daar zou ik geen gebouw mee vol zetten.

H: Wij zijn onder andere architecten. Ik heb ook een bureau dat visualisaties maakt voor architecten en projectontwikkelaars. Wij doen woningbouw. Wij moeten werken met BENG. Die classificatie haal je alleen als je een deel van je energieconsumptie zelf opwekt. Dat kan bijna alleen met PV panelen. Er is ook nog ENG en NOM (nul om de meter). Je kan nu nog compenseren maar dat gaat misschien wel veranderen. De laatste twee kan je eigenlijk alleen bereiken met PV panelen. Bij de visualisatie spelen PV panelen wel een grote rol. Vaak moeten ze geplaats worden op een plek waar je ook een dakkapel zou willen of waar een dakterras moet komen. Dat is best tricky. Wat we tegenkomen is dat we visualisatie maken maar dat we nog gebruik hebben gemaakt van oude (blauwe) panelen en dan willen ze zwarte zonder randje.

M: Zijn er dan nog zaken waar jullie tegenaan lopen?

H: Ik vind ze niet lelijk. Ik denk dat dat arbitrair is. Ik denk dat we een dakpan mooi vinden omdat we eraan gewend zijn. Maar we lopen tegen weinig dingen aan. Behalve, we willen panelen en we willen er veel. Het is eigenlijk een no brainer. Ze leveren snel hun geld op. Het bijt wel een beetje met traditionele architectuur. Dan heb je er een vrij moderne plakkaat op. Dat is een discrepantie. Het past niet echt bij de nostalgie maar ik ben sowieso niet echt een voorstander van nostalgie. Ik denk we moeten gewoon verder. Daar horen andere manieren van energie opwekken bij.

M: Komen jullie de situatie tegen wanneer er te weinig panelen op het dak passen?

H: Wat is genoeg? Als je NOM wil dan is het wel lastig. Zeker met hoogbouw waarbij je een klein dakoppervlak hebt. Dat is een “probleem”. Wat we tegenkomen is dat ze de panelen bij een geluidswal zetten. Ze hoeven dus niet op het gebouw te zitten. Ze kunnen ook op de gevel zitten of in het glas. Ik weet dat dat bestaat maar ik ken het nog niet uit de praktijk. Het is ook een beetje een balans. Het is niet zo dat je per se alles zelf moet opwekken. Het is niet zo dat we niet kunnen bouwen omdat we de ruimte voor de panelen niet hebben. We willen het zo goed mogelijk doen. Dan haal je de BENG toch wel. Met goed isoleren, elektrisch verwarmen en zoveel mogelijk PV panelen. Er is nu nog geen urgentie om de norm te halen zoals dat bij stikstof wel is.

Bezig met opslag oplossingen omdat H zelf veel PV panelen heeft. Vooral veel energie nodig voor verwarming. Die heb je nodig in de winter. En dan is er geen zon. Zou mooi zijn als je het kan bewaren.

M: Kunt u meer vertellen over uw indruk van BIPV oplossingen.

H: Ik zag een startup uit Delft die het wil verwerken in de ramen.

M: [uitleg Physee], nog niet rendabel.

H: Het is dus nog heel erg in het begin.

M: ramen wel, gevelbekleding is opkomend. Maar adoptie door architecten is laag. Daar probeer ik iets aan te doen.

H: Dat is denk ik iets heel goeds. En jij denkt dat het naast goed ook mooi moet zijn?

M: inderdaad [Ceramic laten zien]. Wat is uw indruk van deze samples. Hardop nadenken.

H: Als je dit materiaal dat dit materiaal zover krijgt dat het stroom opwerkt, dan zou ik investeren in jouw bedrijf. Ik vind het vrij briljant. Het ziet eruit als keramisch materiaal. Dat wordt al gebruikt. Het ziet er ook hoogwaardig uit. Strak en netjes.

M: Wat maakt het strak en netjes?

H: Je hebt patroontjes enzo. Het lijkt een beetje op tegelmateriaal. Het nadeel daarvan is dat het vaak vlak oogt. Maar met deze structuren krijg je juist dat het tactiel wordt. Het valt of staat wel bij de naden, esthetisch gezien. Het moet niet lijken of de gevel beplakt is met panelen. Het moet eruit zien alsof de gevel gemaakt is van dit materiaal.

M: wanneer is iets naadloos?

H: Ik neem aan dat het kwetsbaar is en dat ivm. Schaduw het hoger toegepast wordt dus dan maakt een naadje niet uit. Een gebouw moet er stevig uitzien. Zoals met de klemmetjes of met de frames. Dan ziet het gebouw eruit alsof het behangen is met zonnepanelen. Dan moet je voorkomen dat het eruit ziet alsof het behangen is. Dat is met natuursteen bekleding ook. Dat ziet eruit alsof het helemaal van steen is. (Als esthetisch wel het belangrijkst is). Het leuke aan je product is dat het een nieuw soort esthetica zoekt.

H: Als ik dit zou mogen gebruiken. En je hebt een proefopstelling van zeg 100m2 nodig. Dan zou ik daar graag gebruik van maken.

M: Welke zou dan de voorkeur hebben?

H: Het gaat erom hoe het bevestigd wordt. [haalt Equitone tevoorschijn]. Dit vinden ze zelf fantastisch. Dit is een bedrijf dat maakt (best wel lelijk) plaatmateriaal. Dat maakten ze dan vast met schroeven. Dat geeft een goedkoop sociale woningbouw gevoel. Nu kunnen ze dat blind bevestigen en hebben ze er een structuurtje in gemaakt. Dit is nu een hip en duur materiaal. En dan heeft het geen andere functie dan gewoon een jasje zijn. Weet je wat jouw oplossing nu kost?

M: Hangt helemaal van de schaal af.

H: Je moet wel de som maken wat het per m2 kost en hoe het zichzelf terugverdient.

H: Als je erin slaagt om dit in productie te krijgen, ben ik er van overtuigd dat dat kan slagen. Ik denk ook dat in de toekomst er alleen nog maar zal worden gewerkt met materialen die energie opwekken. Waarom zou je het niet doen als je eenmaal het trucje door hebt.

H: Wij maken ook tools die berekenen wat je energiekosten zijn als je naar een nieuw huis gaat. Door extra investeringen wordt de energierekening een stuk lager.

H: Waar ik nog wel problemen zie, is de efficiëntie. Je zit wel met de richting van de panelen en met schaduwen in de gevel.

M: Ongeveer twee keer een factor 0.8 door de coating en het verticaal plaatsen.

H: Je hebt ook projectontwikkelaars die graag naar de toekomst kijken. Je ziet veel ontwikkelingen daar. Die zouden dit denk ik ook graag toepassen. Die willen een duurzaam, zelfvoorzienend gebouw. Dat is een soort holy grail waar ze naar op zoek zijn. Top. Ik hoop dat je ermee doorgaat.

Appendix I - Design concept validation

M: solar mirror + canale sample laten zien.

H: Dit is een high end materiaal. Dat zou je verwachten bij een sterren restaurant of een bank. Of een appartement in Milaan bij rijke mensen. Ik weet alleen niet zeker of de aanname dat esthetica het probleem is klopt.

M: Wat is wel het probleem?

H: Ik denk dat je niet een gebouw gaat volhangen met een product waarvan je niet zeker weet of het 25 jaar mee gaat. Certificering is belangrijk. Hoe weet ik of het over 25 jaar nog steeds functioneert? Als daar twijfel over is, wordt het heel makkelijk om er iets op af te schieten. En wie garandeert mij die opbrengst? En wat gebeurt er als er een vogel tegenaan vliegt? Of als het bedrijf failliet gaat en er moet iets vervangen worden? Wat gebeurt er dan? Je hebt bijvoorbeeld een tegenfabriek die heel populair is omdat ze sinds de jaren 50 dezelfde tegels maken en daardoor makkelijk dingen kan vervangen.

H: Wat ook belangrijk is, bijvoorbeeld met een bepaald type nep natuursteen. Dat wordt heel goed geplakt maar af en toe valt het naar beneden. Daarom mag het vanaf bepaalde hoogtes niet meer gebruikt worden in Rotterdam. Andere steden hebben eigen regels daarvoor. Je platen moeten niet bekend staan als onveilig. Ik kan me ook voorstellen dat bij kantoorgebouwen met grid gevels, je daar dit ook in zou kunnen stoppen. Waar nu het gewone (opaak) glas in zit. (Vliesgevel)

M: [introductie solar mirror + helder + uitleg hoe techniek werkt met kleuren] en dichroic.

H: Er zijn heel veel architecten die wild worden als ze dit zien. Die vinden het heel gaaf als je verschillende dingen kan zien. Esthetisch zit het wel goed. Dat geloof ik direct dat daar markt voor is.

H: Een terugverdientijd van 13 jaar is hartstikke goed. BENG glas bijvoorbeeld, is ook heel duur maar het wordt ook gewoon verkocht. Dus ik ben niet zo bang voor de kosten.

M: Als u terugdenkt aan project uit het verleden, zou een van de producten er dan tussen passen?

H: Ik vind het zo interessant dat ik het zeker zou pushen. Ik denk dat het meer geschikt is voor grotere projecten, bijvoorbeeld appartementencomplexen of kantoorgebouwen. Ik zou dat er bij bijna ieder project proberen erin te krijgen.

M: welk type zou dan de voorkeur hebben?

H: Esthetisch zit het wel goed. Dat hangt van het project af. De ene keer moet het terughoudend zijn en een andere keer mag het meer disco zijn. Dit (ceramic) is een heel overtuigend product. Dat zou je zo op de bouwbeurs kunnen verkopen.

M: Wat maakt dan het verschil tussen een gewoon gekleurd zonnepaneel en dit materiaal tegen een gebouw zetten.

H: Vooral de manier van bevestigen. [verwijst naar equitone]. Dit zou je ook moeten bewijzen. Dat je zoiets kan maken. Zonder RVS klemmetjes in het zicht. Ik zou inzetten op blinde bevestiging. En maatwerk bieden met passend kunnen maken. Je moet anderen ervan overtuigen dat het hassle free, zoveel jaar kan blijven zitten. Met een hoge prijs kan je wel wat early adopters overtuigen zodat je het over de streep kan trekken.

Solar material design — project title

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

start date 11 - 12 - 2022 | 07 - 04 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

As we are moving away from fossil energy sources, photovoltaic (PV) materials are becoming more widely used in our surroundings. When you think about solar panels, the black/blue sheets on top of houses or in fields are the first thing that comes to mind. This is just the beginning though. Instead of the standard solar panels as we know them, interest is growing in customized PV materials that integrate more seamlessly into buildings, products, and other objects.

Efforts from the European Commission to make buildings "nearly-zero energy buildings" (NZEB)1, and the plan to integrate PV panels where possible in 35 million building renovations show the importance of PV in the energy transition. Another area where PV material is becoming more common is electronic products.

In the past three years, I have worked at Van Dijken Glas Beleving B.V (VDGB), a family-owned flat glass processing company. Here I gained experience in the possibilities of glass processing and became knowledgeable in working with colors. With this knowledge, a collaboration was formed with solar panel manufacturer Kameleon Solar (KS). They specialize in custom solar panel production. This collaboration resulted in two PV products/materials that are currently at technology readiness level (TRL) 5.

Next to the current products, I see more opportunities to design aesthetic PV materials that can be seamlessly integrated into products and buildings. Therefore I am going to set up a startup company that does PV material/product development and translates that into concepts. It functions as an R&D and consultancy unit that brings together material/product development, glass craftsmanship, and solar technology.

The main stakeholders at this moment are listed below. Next to the current stakeholders I want to increase my network in the PV world to become active stakeholders in the project I am setting up.

1. Solar panel manufacturer (Kameleon Solar)
By offering a range of BIPV solutions they want to be "the candy store" for architects looking to apply BIPV materials. Intellectual Property is an important topic for them because they do not want their know-how to become public. Their contribution to my graduation is technical know-how and their knowledge in the world of BIPV.

2. Glass processing company (Van Dijken Glas Beleving)
It is specialized in high-end glass projects. Over the years they have gathered a large portfolio of projects in collaboration with renowned designers. Their know-how of colors and glass structures, and manufacturing is one of the main contributors in the development of the startup.

To illustrate the businesses of the stakeholders involved, two images are added on the next page.

The entire process of testing a new type of solar panel is rather long. Therefore the developments of my graduation project will probably not surpass TRL 5. Another limitation is the cost and effort in making working solar panels. This will mean that many prototypes will not be fully functioning. This does not have to be a problem though as long as the performance, look, and feel will be similar to the real deal. Eventually, the most promising prototypes can be remad

space available for images / figures on next page

image / figure 1: Projects to illustrate the type of business of the stakeholders involved.

image / figure 2: BIPV facade realized by Kameleon Solar

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Architects and designers need more options to integrate photovoltaic materials into their designs because current solutions offer limited to no design freedom. Furthermore, they often have little knowledge of how the materials can be adapted to their liking and implemented in their designs.

The scope of the project consists of four topics. The first topic is PV material development. The issues that are addressed include analyzing PV technology and manufacturing processes, material tinkering, and benchmarking. The second topic is concept development with the materials from the previous topic. With the qualities of the material as a starting point, the concepts are developed and evaluated on feasibility, desirability, and viability. The third topic is intellectual property (IP) management. IP is an important topic for all stakeholders. An issue to be addressed is to find an IP solution that satisfies all stakeholders. The fourth and final topic is building a network of active stakeholders with different areas of expertise. This includes identifying relevant experts, companies, and other organizations. Furthermore is a way of keeping the network interested, informed, and active, needed as well.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

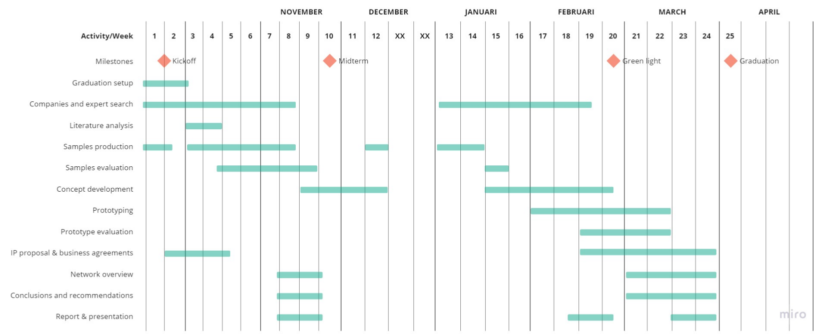
The assignment is to develop unique/aesthetic PV material compositions that can be integrated into buildings and/or products. Build a network of relevant and active stakeholders and make sure that IP is managed in a fair way.

The outcome of the assignment will be a series of PV material compositions (3 to 5 prototypes). Each material will be accompanied by one or two design concepts that are evaluated on feasibility, desirability, and viability. Along with this, I will deliver a proposition for IP ownership and an agreement for future development and going to market. Finally, an overview of the network including people and organizations that are relevant for future development and market strategy will be presented as well.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and 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 activities.

start date 11 - 12 - 2022 7 - 4 - 2023 end date



The project starts with a diverging phase. Here I will gain an understanding of the available PV technologies, manufacturing processes, and design possibilities. After the initial converging, I will start to converge and select material compositions to take into the second phase. The second phase is about developing concepts with the material compositions from the first phase. At first, diverging again to explore different concepts and directions, and finally converging and crystallizing the concepts with prototypes and visuals. Parallel to the "design" work of the project I am actively building a network of stakeholders and experts. Their input will be highly valuable for creating a final result that has the potential to become successful in the market.

The total project will take 25 weeks because I will spend one day a week working my job.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

This project enables me to combine every reason why I chose to study industrial design. It includes material science, concept development, embodiment design, and business to create sustainable value. I want to prove myself in the areas of concept development, embodiment design, and entrepreneurship. Following AED and ACD was great practice. It will be interesting to combine both these subjects into one project. Next to that I can apply what I have learned during Material Driven Design and Build Your Startup.

My ambition is to become an entrepreneur in a company that combines creativity with technology. I can still grow in project management, planning, and communication subjects. Because of the multidisciplinary nature of the project, this will become a challenge that will teach me a lot. Another important area in which I want to grow is IP management. The multitude of stakeholders makes IP a delicate subject in this project. A solution needs to be found that can satisfy all stakeholders to keep them on board. These skills will be essential if I want to make it as an entrepreneur.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Initials & Name M van Dijken Student number 5435196

Title of Project Solar material design