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Innovative Cast Glass Surfaces for Improved Photovoltaic Efficiency in BIPV Systems

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Declaration

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Abstract

This thesis investigates the current state of the Building Integrated Photovoltaics (BIPV) industry and identifies an area of potential product design for vertical facades, using cast glass textures over standard photovoltaic solar panels to maximise light capture efficiency and to improve on the visual aesthetic of the solar panels.

To simulate the angle of the Earth to Sun, this research involves the production and testing of a selection of sample cast glass profiles using solar simulator in laboratory to record the light capture and energy generation. Each sample is made in the kiln using heat and gravity to mould the glass in to lens shapes and other textures for testing. In order to visually assess the difference between standard photovoltaic solar panels and the cast glass product, an experimental test station is to be set up to view the idea on full scale proportion.

The market for BIPV glass products at present shows many glass products using opaque inks or laminated interlayers to offer a coloured solution to the flat monotone black standard solar panel. These products lose a considerable amount of energy by blocking the light.

The glass panels developed in this research (to be called PVGlass) are made by using low iron Opti clear glass with the design on the surface to remain clear to maximise light and to redirect light from changing angles on to the solar cells. This is the principle of the Fresnel lens used in lighthouses to maximise the light outwards for navigation. PVGlass work in the reverse; the light is captured from the sun and directed inward on the vertical building façade to create energy for the building. The texture of the cast glass surface becomes the visual difference and by using clear glass the obstruction of natural light is minimised.

For aesthetic improvement, the light is broken on the surface giving a visually dynamic moving surface that disguises the monotone dark solar panel while achieving 95 % of efficiency of standard solar panel.

Acknowledgements

I would like to acknowledge the encouragement and support of Professor Sarah McCormack to turn an idea into reality.

I extend my gratitude to Dr Anita Ortega for her hard work setting up the solar glass experiments and patience explaining the scientific process to me.

I would also like to thank Irish Lights for invaluable information on the Fresnel lenses of Irish Lighthouses and the solarisation of the lighthouses.

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Nomenclature

G	Irradiation	W/m^2
I	Current	A
P	Power	W
R	reflectivity	%
T	Temperature	°C - K
t	time	s
V	Voltage	V
Ø	diameter	mm
Δ	variation	
M_{pp}	Power output at maximum power point	W
I_{mpp}	Current at maximum power point	A
V_{mpp}	Voltage at maximum power point	V
BIPV	Building integrated photovoltaics	

Chapter 1 Introduction

1.1 Background

The concern for energy supply in 2025 is continuing to focus more on renewable energy and away from fossil fuels for commercial and residential use. The primary source of energy for the future is electricity and there is a growing shift to wind and solar energy supply. Solar farms are currently established and continue to be developed across Ireland and wind farms out at sea and on land are also on the increase. Figure 1.1 presents a solar farm installed in County Meath, Ireland.

Figure 1. 1 Neoen Solar Farm, installed in County Meath, Ireland

This research focuses on generating electricity form the built environment and in the vertical façade of buildings. In the industry this is referred to as BIPV (Building Integrated Photovoltaics) (IEA, 2020). All building design for new and refurbished building must now contain a justifiable element of energy consumption awareness within the design and if possible, integrate a renewable energy source into the building energy rating (BER) B1 or B2 (SEAI, 2024).

Sustainable Energy Authority of Ireland, SEAI, has introduced the Nearly Zero Energy Building standard (NZEB) which requires all buildings in future to be designed with a " very high energy performance, the nearly zero or very low amounts of energy required should be covered to a very significant extent by energy from renewable sources, including energy from nearby sources produced on site or nearby" as defined by Energy Performance in Buildings Directive (EPBD) (European Commission, 2018; SEAI 2024).

The key phrase for this research is "energy produced on site or nearby." Building design is moving toward a source of energy that does not require costly infrastructure to deliver the energy from source to the user. Solar panels have been used extensively on roof spaces, but the potential of vertical building surfaces and walls is not fully utilised to install an additional source of energy (IRENA, 2023).

This is a part of the energy solution which also includes improved insulation to walls, windows, and roofs. This contributes to the overall drive for decarbonisation on the built environment and a sustainable energy solution for the future (IPCC, 2022). Figure 1.2 illustrates the ongoing facade construction at Trinity College Dublin (2024), highlighting the extensive integration of fenestration elements. The design incorporates a high ratio of glazed surfaces, emphasizing natural light optimization, energy efficiency, and architectural transparency within the building envelope.

Figure 1. 2 Building Façade work in progress at TCD 2024

Rooftop solar panels are widely adopted and considered a standard technology. The reference panel used in this study is the Longi Hi-MO X6 450 W photovoltaic module, which produces between 450–470 W under optimal efficiency conditions and ideal orientation to sunlight. The panel has approximate dimensions of 1.8 × 1.1 m, a weight of 21 kg, and features a 3.2 mm anti-reflective toughened glass front layer (LONGi Solar, 2025). As of June 2025, the cost per panel is approximately €69 (excluding VAT), which is lower than the cost per square metre of many conventional building surface materials (PV Marketplace Data, 2025). A summary of cost reductions over time is presented in Figure 1.3.

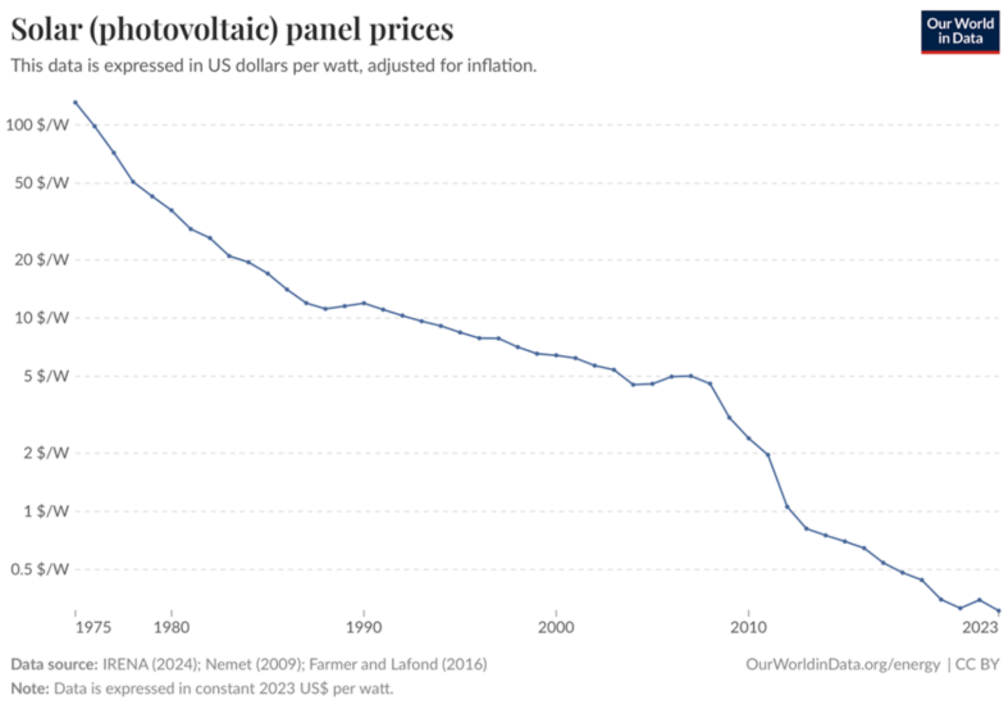


Figure 1. 3 Graph Showing cost reduction per MW in solar industry (Our World in Data, 2024)

The advancing solar cell industry continues to improve the wattage output per square metre and per panel over time. Mass production has contributed to a reduction in cost per panel, while ongoing improvements in solar cell efficiency further enhance performance. This development provides a more economically viable option for energy generation (IEA PVPS, 2023; IRENA, 2023). Figure 1.4 presents a standard 460 W monocrystalline photovoltaic (PV) panel commonly used in residential solar installations.

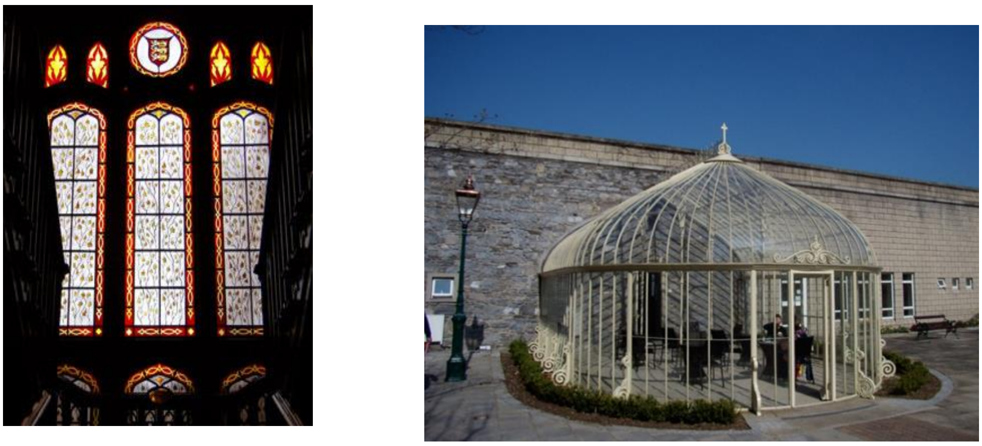
Figure 1. 4 Standard Monocrystalline PV Panels 450 W for domestic installation

Urban density has led building design to increase in height, and while roof space offers an area for solar panels at an optimum angle to the sun, there is a large vertical façade area upon which solar panels may be installed to generate additional energy (IEA PVPS, 2023). In general, architects are often reluctant to specify black solar panels on façades, as their visual appearance may not align with the desired aesthetic of the design. This has led to the development of BIPV (Building Integrated Photovoltaics) (International Energy Agency [IEA], 2020).

The background of this work lies in visual design, with extensive collaboration with interior designers and architects to enhance architectural aesthetics using glass in various forms, including stained glass, cast glass, and lighting solutions. McGuire Glass Studio, established in 1997, has specialised in bespoke glasswork, with a recent focus on casting flat glass in kilns at high temperatures exceeding 800 °C (McGuire Glass Studio, n.d.). This process enables the melting of glass into moulds, imprinting textures onto its surface to create unique artistic and architectural elements. A distinctive casting method has led to the development of botanically imprinted glass, where leaves and foliage are directly used to produce intricate surface textures. These one-of-a-kind glass pieces have been incorporated into architectural and landscape designs across Ireland, the UK, Europe, the Middle East, and the USA. Additionally, many cast glass pieces are silvered on the reverse side, creating a reflective quality suited for interior wall-mounted installations. A notable recent commission involved the installation of custom glasswork at Lansdowne Place, a luxury apartment complex. Historically, this site served as Trinity College Dublin's botanical garden until 1966, playing a significant role in botanical research for medicinal studies, further reinforcing the connection between glass design and natural elements in architectural applications. Figures 1.5 show a selection of examples of work.

The primary source of energy for glass artwork is light. This research aims to apply aesthetic design principles at a practical level, using light both as an artistic medium and as a source of building energy generation.

Figure 1. 5 a) Traditional Stained Glass Doorway 2015, b) Newport



Church Co Tipperary 2000, c) Dromoland Castle Co Clare 2008, d) Lansdowne Place Dublin 2018, f) Willow, Silvered Cast Glass 2022, g) Europe Hotel Co Kerry, Silvered Cast Glass Panels 2007, h) Restoration Turner Curved Glasshouse Dublin 2009.

1.2 Scope of the research

The focus of this work is on the texture and reflective properties of clear low-iron optical glass as a medium for enhancing solar panel efficiency, achieving up to 95 % energy transmission (Green, 2023). In contrast, many commercially available products show a 40 % reduction in efficiency due to surface modifications (IEA PVPS, 2023). The application of opaque coatings or treatments on the glass significantly reduces the amount of light reaching the solar cells, thereby diminishing overall photovoltaic performance. This research aims to improve glass transparency and surface characteristics to maximize solar energy absorption and efficiency in photovoltaic applications. At acute angles to the sun, the aim is to improve the efficiency by capturing more natural light by diverting maximum light on to the solar cells via lens shapes and texture cast into the glass surface.

The inspiration for this idea goes back to the Fresnel lens developed c1750 by Augustus-Jean Fresnel (Hecht, 2017). Historically, lighthouses were built as a tower with a lit flame on top to give visibility at night to ships navigating at sea. Fresnel designed a faceted glass lens that refracted the light and sending it outward from multiple directions meaning that the eye could see the light from further distances and increase the safety of human life at sea. The light source is not magnified as the light energy cannot be increased, but the direction of light can be multiplied, and the appearance of more light is achieved. As this design developed, a rotating device was added to the glass to send the light out in multiple direction and "flash" at intervals through 360 degrees. Figure 1.6 present different types of Fresnel Lens samples.

Figure 1. 6 Selection of 3 Fresnel Lens samples

Bailey Lighthouse Lens plus other examples of Fresnel Lens. Cast Glass pieces are polished to maximise the amount of visible light to ships for navigation. Faceted glass pieces capture light forms single light source and project light greater distance. Figure 1.7 shows a Fresnel Lens at Bailey Lighthouse relocated to Mariners Museum Dun Laoghaire.

Figure 1. 7 Fresnel Lens, Bailey Lighthouse

If this design concept is reversed, light can be directed inward from multiple angles of sunlight. This research explores glass surface design on solar panels to capture more natural light throughout the day as the Earth rotates and its angle relative to the sun changes (Duffie & Beckman, 2013). Lens shapes and texture are cast in the kiln/furnace to create angles in the glass that redirect light from the sun onto the photovoltaic cell and maximise the energy available throughout the day and throughout the seasons when the light is at lower acute angles.

This research exclusively utilizes clear glass to examine its impact on solar panel efficiency, while also exploring the visual and aesthetic benefits of surface texture. The textured glass not only enhances architectural appeal but also mitigates the monochromatic appearance of black solar panels. While a portion of the incident light is reflected, the majority is transmitted through the glass, with some being scattered to create a dynamic visual interaction with light, enhancing the building's exterior appearance from a pedestrian perspective. The primary objective of this study is to determine the light transmission properties of cast glass, referred to as PVGlass, and its effect on photovoltaic (PV) cell efficiency at varying angles, simulating the Earth-Sun inclination. These results are compared to a reference PV cell under identical conditions. By measuring current and voltage output, this study evaluates the efficiency of various glass samples in directing solar radiation. While it is not possible to create or amplify solar energy, nor to control environmental variables such as cloud cover, temperature, or weather conditions, the study aims to optimize light direction to maximize energy capture—a to the light-focusing principles of a lighthouse lens.

1.3 Research aims

This research aims to prove that a cast glass surface can improve the visual aesthetic of solar photovoltaic panel while minimising the obstruction of natural light capture on the solar cells. Many products on the BIPV market reduce efficiency by 20 to 35 % by using coloured opaque inks or tinted interlayers (IEA PVPS, 2023; Jelle et al., 2012). This research aims to investigate only clear glass textures and lens shapes which are cast into the glass sheet using heat in kilns. By using only clear glass the research aims to use the Fresnel Lens principle in reverse to maximise light capture from the Sun at changing angles to the Earth (Hecht, 2017). At acute angles, this research aims to prove that energy efficiency can be improved by the design of the glass surface.

1.4 Thesis outline

To outline this thesis the following chapters will contain the following:

Chapter 2. State of the Art of Building Integrated Photovoltaics in the Industry at Present.

This reviews a cross section of the BIPV industry investigating the current products on the market and technological advances. A visit to Intersolar Munich to investigate the market was made and the findings are in this chapter.

Chapter 3. Methodology – Glass Manufacture and Experimental Set Up.

A description of the process of glass casting using heat and moulds to create different glass surfaces. An experimental set up in Co Galway was built to visually assess the glass texture over solar panels and to gather preliminary data to refine the research from the results. Two solar module analysers are connected; one to the standard solar PV panel without glass layer; the second analyser connected to the PV panel with cast glass mounted over surface. Results are gathered simultaneously in different weather conditions, and the visual appearance is noted and recorded.

Chapter 4. Results – Indoor laboratory tests.

A detailed report and graph analysis is presented from 6 different glass texture samples using solar simulator in Trinity College laboratory. Images of samples included.

Chapter 5. Conclusion and Recommendation for future works.

This chapter is a conclusion to outline the results of the research covering efficiency, structural considerations, advancing technology in BIPV, visual aesthetic and costing.

1- Efficiency; performance over time with changing light conditions
2- Structural consideration; weight, safety, fixing method

3- Aesthetic; the visual appearance and texture of the surface to clad the façade
4- Cost: this glass will be more expensive than standard PV Modules but there is a high level of consideration to be given to the façade to present to the face of the building to the public.

1.5 Conclusion

This research enhances BIPV technology by modifying clear low-iron glass with textured surfaces to improve solar panel efficiency compared to current options on the market, and architectural aesthetics. Inspired by Fresnel lens principles, the study demonstrates how cast glass textures can redirect light, achieving up to 95 % electrical efficiency. By improving light absorption and diffusion, this approach makes vertical solar facades more viable, offering a visually appealing alternative to traditional black panels while structural integrity and energy performance in urban architecture.

Chapter 2 State of the Art BIPV Industry

2.1 Overview of BIPV Industry 2024

The state of the art of BIPV today is a fast-moving innovative market with advancement solar cell technology allow the design of solar panels to broaden form rigid fixed panels to flexible sheets of solar cells, floating flexible panels on water, and continued research into perovskite, copper and organic photovoltaics (IEA PVPS, 2023; IRENA, 2023). In the visual design of BIPV there are many options available. The problem with many products is the reduced efficiency due to vertical positioning but also due to obstructive quality of printed inks and limited natural light capture of laminated interlayers (Jelle et al., 2012).

This chapter presents research on these products, in particular from a visit to a large trade fair in Munich “Intersolar” which showcases all aspects of the solar industry and a section dedicated to BIPV in line of the halls (Intersolar Europe, 2024). By examining the market, the aim is to identify a gap and fill this gap with a cast glass solution to integrate with solar cell technology. The present-day standard is to make a monocrystalline photovoltaic solar panel in layers. From outside face we have usually:

- 3.2 mm toughened glass layer approximate 1.7 X 1 m
- layer of encapsulant
- arrangement of solar PV cells (approximate 60)
- layer of encapsulant
- back panel of aluminium or second layer of glass (Fraunhofer ISE, 2023).

Figure 2.1 shows the different part of a standard PV panel.

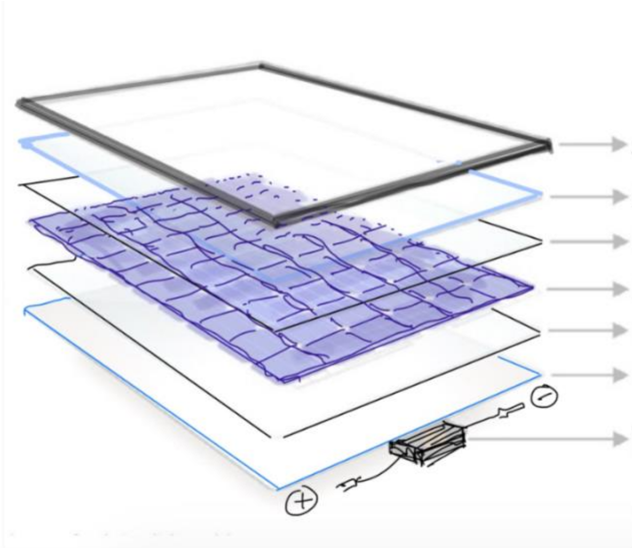


Figure 2. 1 Structure of standard PV panel

- A = Aluminium frame. Approx 30mm deep
- B = Glass layer. Standard 3.2mm anti reflective glass
- C = EVA vinyl encapsulant
- D = Photovoltaic Solar cells connected
- E =EVA vinyl encapsulant
- F= Aluminium back plate of second layer of 3.2mm glass for bifacial PV Module
- G = Electrical box with MC4 positive / negative

The encapsulant acts as a laminating material to bond the unit together. The external face of the glass is treated with anti-reflective surface to absorb maximum light. Reflected light means less light travelling through to the solar cells (Green, 2003). Bifacial PV modules are increasing in use. This is a layer of glass (4 mm or thinner) on each side of the module and solar cells are placed back-to-back and designed to capture extra light on reverse side (IEA PVPS, 2023). The amount of light is much less on reverse side but as the cost of solar cells is falling as production and demand increases, then it is worthwhile gathering this extra light (IRENA, 2023).

Also, from a structural aspect to laminate glass to glass is more stable than glass to aluminium as the material expands and contract at the same rate giving more even conditions of movement for the solar cells and thus causing less stress and less damage/ cracking (Fraunhofer ISE, 2023). Solar cells are made from wafer thin silicon (monocrystalline) and fine wiring so and impact or twisting can damage cells affecting performance.

The cost of solar PV panels has reduced in recent years which suggest it may be more cost effective to use the standard present-day panels to be integrated with the solar PVGlass design (IRENA, 2023). In future as the PV panel technology advances the glass layer may be used within updated solar panels with increased efficiency.

There is ongoing development in technologies such as CIGS (Copper Indium Gallium Selenide) and perovskite solar cells, which are expected to improve efficiency in the future (National Renewable Energy Laboratory [NREL], 2023). However, this research focuses on a comparison between monocrystalline solar panels and monocrystalline panels combined with PVGlass.

It is worthwhile to review the market and the visual options available today, as described below.

2.2 Intersolar Munich 2023

A visit to Intersolar Munich was made to assess the current state of products on the BIPV market and to identify the potential for this project research as a future product for this market The exhibition highlighted various aspects of the solar industry, encompassing battery storage solutions, electric vehicle integration, advancements in solar cell technologies, and innovative solutions to meet the increasing global demand for renewable energy (Intersolar Europe, 2023; IEA PVPS, 2023). A particular emphasis was placed on the BIPV sector, where market research was conducted to assess trends, challenges, and technological developments influencing the adoption of photovoltaic glass in architectural applications (Jelle et al., 2012). For reference, standard monocrystalline photovoltaic panels typically achieve efficiency rates of approximately 19–20 % and remain among the most cost-effective solutions currently available (Fraunhofer ISE, 2023; IRENA, 2023). Figures 2.2 show assorted designs from Intersolar Munich 2023.

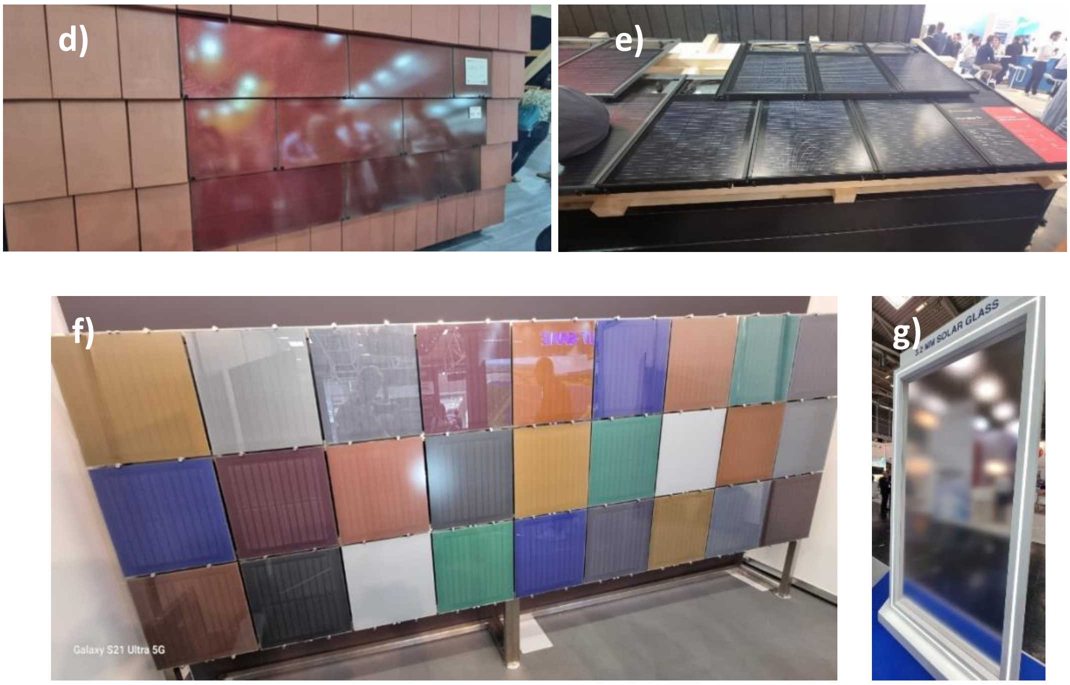


Figure 2. 2 a) Laminated glass with coloured solar interlayer, b) Coloured PV panels for use in roof of wall space, c) Integrated PV solar roof tiles to resemble slate, d) Integrated Roof /Wall tiles terracotta, e) Integrated Photovoltaic Modular Roof tiles, f) Coloured Interlayer with PV Cells in laminate layer, g) Anti Reflective 3.2mm Solar Glass

2.3 Conclusion

From a business perspective, the research aims to develop the design idea and prove its technical performance. It is important not to invent something that already exists on the market and to review the current products with the following outline:

1. Examine the market
2. Find an area where the gap is in the market
3. Fill this gap and develop an economic way to produce and supply the market.

This idea has been developed in the studio workshop and in the Trinity College laboratory. There are many products on offer, coloured panels to match terracotta brickwork, roof tile-type modular panels and interlayers in the vinyl laminate material. This has been researched by the visit to Intersolar Munich and in particular, the BIPV section of the exhibition.

Clear glass option: It was found that there is potential explore and develop a design to produce a clear texture that aims to increase performance and efficiency of solar cells while offering a long term building surface that allows the panels to be accessed to monitor performance and change the solar panels as technology improves on solar cell at a rapid rate. By working with the design of the clear glass texture, we can avoid using opaque ceramic inks to decorate the panel and use the dynamic of shifting light redirected to maximise the available energy from the sun.

Vertical advantages: An added advantage of using vertical installed BIPV panels is that the water can wash down with gravity with greater ease than roof panel installed at 30 or 40 degrees. This avoids dust and debris gathering on the surface and reduces cleaning and maintenance.

Weight consideration: The added weight load can be carried by a substructure fixed to vertical wall and load bearing on the ground. In many refurbishment situations it is likely that a secondary structure will be required to carry the PVGlass / BIPV panels. Access to be considered should the solar panels need to be updated in future as technology advances.

Visual improvement of standard monocrystalline panel: The aim is to develop an attractive aesthetic building envelope that produces energy which works parallel with standard solar PV panels. This allows the option of either retrofit on existing buildings such as industrial warehouses or less visually appealing building. The aesthetic is improved by catching light from many angles and the ever-changing light is reflected on the surface. The glass may be used as an illuminated billboard style public lighting solution. LED lighting uses low amounts of energy and produces very little heat to offer a visual effect using changeable colours etc.

Energy generated onsite used by the building: Many solar panels are added on to building on roof space which is great and out of sight of street level. These panels feed some energy to the building itself, but a large amount of the energy is transferred to the national grid. The national grid buys energy from the building source at a set cost and sells the energy back to the customer at a higher cost. It would make more sense economically if the energy produced on site can be used on site using battery storage options to achieve NZEB, Nearly Zero Energy Buildings, as indicated by the SEAI in recent reports.

Working with industry standard pv panel: By allowing the solar panels to serviced and changed every 5 years or so, we can increase the efficiency of the building on a realistic target of Zero Energy Buildings by 2050. Emerging materials such as perovskite and copper-based solar technologies are expected to increase efficiency in the future. However, this research focuses on currently available and cost-effective technologies, specifically monocrystalline silicon solar cells. The preferred PV module for northwestern Europe is the N-type (TOPCon), which is designed to achieve higher efficiency under regional climatic conditions. By developing a clear glass product designed for use with a wide of angle of solar panels in the future, a product is designed that can be re-used as solar cell technology advances thus reducing the waste of material and avoiding rapid obsolescence. This conclusion highlights advancements in BIPV technology, balancing efficiency, durability, and aesthetics. Innovations such as bifacial modules, anti-reflective coatings, and textured glass improve light absorption while integrating seamlessly into architecture. Insights from Intersolar Munich 2023 show a growing market for custom solar solutions, making BIPV increasingly practical for sustainable building applications.

Chapter 3 Methodology- Glass Manufacture and Experimental set up

3.1 Experimental design using kilns to cast hot over mould shapes and textures.

The textured glass samples are produced using a kiln, with over 30 years of experience informing the process. A kiln is an insulated chamber with a heat source (gas or electric) used to heat glass to temperatures exceeding 800°C, allowing it to soften and form surface textures (Shelby, 2005). Experimental samples are fabricated using 6 mm, 10 mm, and 15 mm low-iron Optiwhite glass. Low-iron glass contains fewer impurities than standard float glass, resulting in reduced light absorption and reflection and enabling greater light transmission to the solar cells (Pilkington, n.d.). In contrast, float glass exhibits a green tint due to its higher iron content, whereas low-iron glass provides improved optical clarity. As the glass is heated and becomes viscous, it conforms to the surface beneath it under gravitational forces. Stainless steel moulds are used to control the texture and depth of the casting. Following controlled cooling and annealing, the samples are prepared for testing with solar cells. Based on the reverse application of the Fresnel lens principle, the surface undulations and lens geometries capture light from multiple angles and redirect it onto the solar cells (Hecht, 2017). To establish this preliminary experiment, the glass samples are positioned over standard PV modules (300 W), and a solar module analyser (SMA) is used to record performance data. The results obtained from the experimental glass (PVGlass) are compared with those from a standard PV module (reference). Figures 3.1 and 3.2 illustrate the electric kiln equipment used for glass casting and the internal kiln setup, showing the process of molten glass forming within stainless steel moulds.

Figure 3. 1 Electric Kiln equipment for casting glass panels

Figure 3. 2 Inside Electric Kiln, glass casting into steel moulds

3.2 Experimental Set Up: Site testing Connemara Co Galway August 2023

Initial site tests were carried out in Connemara, Co. Galway, where standard 300 W solar PV panels were installed to allow comparisons between a 300 W reference panel and PVGlass sample panels, which could be easily interchanged. A radiation meter was used to measure the level of natural light capture, and a solar module analyser connected to each panel enabled data to be recorded on a computer for further analysis. The overall experimental setup of the test station is shown in Figure 3.3, while the connection of the solar module analyser to the test panels is illustrated in Figure 3.4. The arrangement of PVGlass samples alongside the reference panels is presented in Figure 3.5, and the configuration of the solar module analyser connected to both PVGlass, and the reference panel is shown in Figure 3.6. Data were collected over a two-week period under varying weather and daylight conditions. This preliminary experiment provided a visual representation of the concept and enabled monitoring of the performance of PVGlass in comparison with the reference panel.

Figure 3. 3 Preliminary Solar Test Station, Connemara, Co Galway August 2023

Figure 3. 4 Solar Module Analyzer connected to test panels

Figure 3. 5 Solar Test Station Connemara Squarelens samples/ reference panels

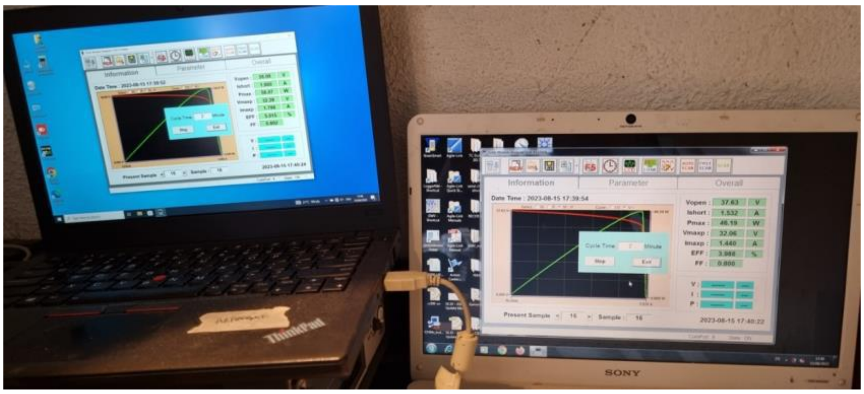


Figure 3. 6 Solar Module Analyser connected to PVGlass and reference panel

A significant increase in panel weight is associated with the addition of cast glass. To accommodate the additional glass layer, a secondary frame is required to sit over the solar panels and be anchored to the vertical façade or supported from the ground. The weight of 10 mm cast glass is approximately 25 kg/m², while the weight of a standard solar panel is approximately 10 kg/m². The secondary frame therefore becomes an integral part of the overall design and must consider the proportions of the building façade. For example, a standard stone block at Trinity College Dublin measures approximately 1000 mm × 300 mm. The experiment highlights two potential design approaches: (A) retrofitting and (B) modular panel systems.

(A) Retrofitting involves cladding the vertical façade with standard solar panels (approximately 1.7 × 1.1 m) and installing PVGlass over them, allowing the solar panels to be upgraded over time as technology and efficiency improve. Current standard panels deliver approximately 420 W.

(B) A modular approach involves designing units that can be fitted to the vertical surface in manageable sizes (e.g., 1 m × 0.3 m or 1 m × 0.6 m), with solar cells integrated into the PVGlass design.

An example of the modular approach is illustrated in Figure 3.7, which shows a 900 × 320 mm PVGlass unit incorporating a flexible 50 W solar panel positioned behind the glass.

Figure 3. 7 900 x 320mm Modular unit PVGlass with flexible solar panel behind 50 W

3.3 Preliminary Test Station: Conclusion

Test station at Connemara proved PVGlass can be mounted over standard PV panel with some low amount of efficiency loss but with improvement to visual appearance. It has proved clear difference between the textured reflective side and glossy non reflective side of the glass, with the textured non reflective better for efficiency by 15 % when tested against each other.

Performance: The findings at this stage indicate that any additional material placed in front of a solar cell affects performance and efficiency. However, the experiment demonstrated that PVGlass panels achieved up to 90% of the performance of the reference panel. In addition, the visual appearance improved as light passed through the PVGlass, creating a dynamic surface that reduces the visual impact of the conventional dark PV panel. These results supported further development of the samples and subsequent testing at a smaller scale in the solar optics laboratory at Trinity College Dublin. Additional considerations identified during this phase include weight, safety regulations for glass in buildings, and heat build-up on solar panels.

Visual aesthetic improvement: The aesthetic value of a full-size PV Module (1.7 x 1.1 m) with PVGlass over the surface has shown how light moves across the glass and gives a stimulating visual effect. The results of this test station are encouraging as a visual design solution using full scale solar panels. Visual Improvement is a key part of the research. The placement of a textured clear PVGlass over the solar panels improves the appearance by breaking the light and creating a moving visual surface which responds to the viewers position as they walk by. Different angle of viewpoint will alter the aesthetic and give life to the surface. A crystal-like prism is created which throws sparkles of colour that change throughout the day. The standard PV Panel is designed not to reflect light and gives a dull black surface to absorb light. If we want to see more solar energy generated on building surfaces the aesthetic must be considered to present the face of the building in a stimulating way. Aesthetic may be a subjective consideration, but it is an important one and the identity of buildings may be reflected in its façade through the choice of surface finish. Colour is an option, but this is even more subjective and likely to tire over time. There is also the added possibility of using the PVGlass panel as a source of artificial light for the street / public lighting if the energy generated is used to illuminate LED strip light within the frame. This presents a low energy usage that can serve a purpose for the building that it is integrated into. This adds visual quality and purpose to the building façade at night.

The design and manufacture of textured glass panels for interior and exterior architecture have been the focus of work practice since establishing McGuire Glass Studio in 1997. The work from the studio includes design and production and installation of bespoke stained glass and cast glass panels from the kiln for a wide range of clients. In recent years the focus has been on the kiln formed glass to produce unique work to compliment the building and this has always been dependant on light to illuminate through the glass or reflect from the glass.

It is the use of heat in very large kilns that produces the glass for use on surface of solar panels. This is an anti-reflective glass surface which maximises the light entering through to the solar cells. This is 3.2 mm glass, laminated to the solar cells to protect the cells and ensure safety if the panel is broken. The texture on glass of standard solar panels is quite fine and barely visible. PVGlass explores the amplification of the surface design to provide visual texture and additional light capture.

A set of transferable skills has been developed, applicable to the renewable energy sector through the design and optimization of glass textures for enhanced photovoltaic performance. The manufacturing process begins with sheet glass, low iron content, 6 mm, 10 mm and 15 mm thickness. Maximum size for one panel during this research is 1000 x 800 mm, which is the size of the kiln floor. Larger kilns are available on the market up to 3 x 2 m. Ideally the glass would be in one section covering the solar panel to avoid any structural steel to obstruct light from reaching the panel and generating maximum energy.

The glass is examined and reviewed after each firing process. The underside gathers texture and therefore is the non-reflective side of the glass panel. The top side is the glossy smoother side but reflects light back and as a result, this reflective side reduces the energy produced by the solar cells.

Based on study of Fresnel lens and Lighthouses a series of stainless-steel moulds to cast the glass into was designed. As the glass is heated it liquifies and gravity pulls the fluid material into the negative spaces leaving a domed shape.

PVGlass panels can enhance localized energy use, storing captured solar energy to power public lighting in urban areas, improving safety, pedestrian wayfinding, and deterring anti-social behaviour.

Additionally, LED strip lights can be integrated along the panel edges for enhanced illumination. This approach mirrors energy storage in Irish lighthouses, where vertically mounted solar panels prevent bird fouling and maximize sunlight exposure. Captured energy is stored in batteries during brighter months and utilized throughout winter to sustain light transmission.

3.4 Thickness of the glass

The glass used on standard PV Modules is usually 3.2mm toughened glass with a non-reflective texture on the side facing the light. This is laminated to the back plate or second sheet of glass in bi-facial panels. The laminating layer is a clear encapsulant which strengthens the panel and protects the solar cells from damage. Sheet glasses of 6 mm, 10 mm and 15 mm thickness was used. The thicker glass means more structural strength and gives more visual substance to the finish material sample. Thicker glass also means heavier material. We are intending to install these PVGlass panels on vertical wall spaces and therefore can be supported from the ground up and all weight is vertical. No additional weight is added to the load of the building. A secondary structure of steel frame may be required to house the glass and anchor to the vertical wall. Each building will have different requirements in this area. Table 3.1 shows weight of glasses with the thickness.

Table 3. 1 Weight of glasses with the thickness compared to other building facades

Material	Thickness (mm)	Weight per m² (kg)
Glass	15 mm	39 kg
Glass	10 mm	26 kg
Glass	6 mm	15 kg
Glass (Standard PV Module)	3.2 mm	8 kg
Concrete Slab	15 mm	~ 28 kg (varies by composition)

Glass is a heavy material, and this needs consideration when designing the structure for PVGlass. A large target sector for the PVGlass is on refurbished buildings which may be concrete built and structurally sound but visually outdated or worn out. PVGlass offers an aesthetic solution to an existing building which has grown tired, yet the buildings skeleton structure remains intact and avoids the need for demolition of concrete structure and replacement with more concrete structure. If the PVGlass is fitted over PV module then there is an opportunity to double glaze the PVGlass over the PV Module. This will assist in reducing the temperature of the PV Modular solar cells and avoid cutting out at higher temperatures above 30 Degree Celsius.

3.5 Profile Shape of glass and mould design

Using sheet glass material to start the production, the glass is placed over a stainless-steel grid mould to allow the heat to melt the glass into the cavities of the mould. Heat is applied over 800 degrees Celsius and when the glass is in liquid form gravity pulls the molten material into shape. When this the required shape is formed in the kiln the glass is “frozen” by rapidly dropping the temperature to 600 ˚C. The glass is then annealed at 540 ˚C for several hours to allow the molecular change in the material to realign and stabilize. The glass is then cooled very slowly to room temperature and can be cut to size when cool. Variations on the mould and temperatures provide different profile of glass sample to test in laboratory. Figure 3.8 shows the schematic design of the glass production process inside the kiln. Figures 3.9 presents the external and internal parts of the kiln respectively and figure 3.10 shows the final product glass.

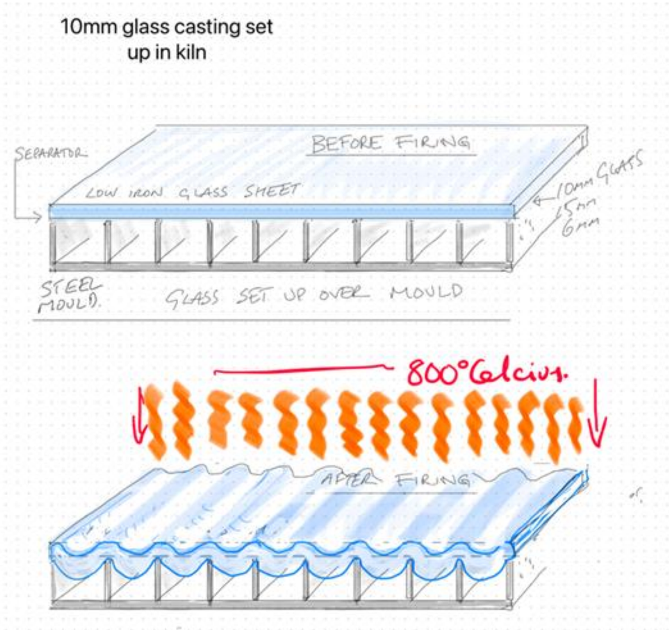


Figure 3. 8 10mm Glass casting set up design, Mould diagram

Figure 3. 9 Internal Gas kiln view for small sample production

Figure 3. 10 Sample of SQ10 over 100 W flexible solar panel 1050 X 615 mm

3.6 Texture of Glass: Reflective vs non-reflective sides

The texture of the glass is an important consideration when measuring the efficiency of glass over solar cells. In standard PV Modules the face of the module is coated in a non-reflective coating. If the glass is reflecting light, then it is light lost to generate energy in the solar cells. The glass becomes soft and liquid when heated and takes a casting of the surface below which can be controlled in process. For example, gritty sand aggregate leaves a deep textured non reflective surface where it contacts the glass at high temperatures of 800 ˚C. The top surface is untouched by any surface and becomes glossy smooth and reflective of light in areas. Laboratory testing conducted at the Trinity solar laboratory examined the performance differences between the non-reflective and reflective surfaces. Any light reflected away from the panel does not contribute to solar cell activation and therefore reduces efficiency. However, from a visual perspective, the reflective surface is more perceptible to the human eye at a distance and contributes to the aesthetic quality of the panel. This highlights the balance between efficiency and visual appearance, which is a central consideration of this research.

3.7 Composition of Glass

Using available sheet glass materials, two primary options are identified:

1. Float glass: This is the most commonly used glass for windows in buildings and is available in thicknesses of 2 mm, 4 mm, 6 mm, 8 mm, and 10 mm. Float glass contains iron, which gives it a characteristic green tint and results in increased light absorption (Pilkington, n.d.).
2. Low-iron (Optiwhite) glass: This type of glass has a lower iron content than standard float glass and is therefore clearer, with reduced light obstruction. It is the preferred material for PVGlass sample production in order to maximise light transmission to the solar cells and improve overall efficiency (Pilkington, n.d.).

3.8 Annealing the glass

The glass is cooled to an annealing temperature of approximately 540°C to allow its molecular structure to stabilise and strengthen the material (Shelby, 2005). This process ensures that the glass performs safely under varying light and thermal conditions. Due to the irregular profile of cast glass, it can be challenging to toughen the material to meet standard safety regulations. Lamination therefore provides a suitable alternative to improve safety performance. Additionally, the use of thicker glass (e.g., 15 mm low-iron glass) can provide sufficient structural strength to meet safety requirements.

3.9 Conclusion

The manufacturing process for PVGlass panels focuses on optimizing glass texture, thickness, and composition to enhance solar energy absorption and structural integration. Utilizing kiln-formed low-iron glass, the study explores heat treatment, annealing, and lamination techniques to maximize light transmission while maintaining durability. The findings highlight the importance of glass texture in minimizing light reflection, ensuring optimal photovoltaic efficiency. Additionally, considerations such as weight distribution, structural support, and thermal management demonstrate the feasibility of integrating PVGlass panels into both new and refurbished buildings, offering an aesthetic and energy-efficient solution for sustainable architecture. A set of transferable skills has been developed, applicable to the renewable energy sector through the design and optimization of glass textures for enhanced photovoltaic performance.

Chapter 4. Results Indoor Laboratory Tests

A series of textured glass samples were fabricated and tested under a solar simulator in the controlled laboratory setting of Trinity College. Each sample, measuring 150 x 150 mm, was designed to cover a single 100 x 100 mm solar cell. An adjustable armature was used to modify the glass inclination in 10-degree intervals, ranging from 0° (vertical to the light source) to 90° (perpendicular to the light source), enabling precise evaluation of light transmission and photovoltaic efficiency at varying angles. The experimental setup used for this testing is illustrated in figure 4.1.

In all tests there was a series of factors recorded for analysis:

1. Texture of glass
2. Reflective or non-reflective sides of glass
3. Radiation measured with Pyranometer

4. Reference solar cell
5. PVGlass over reference solar cell
6. Angle of cell to light source from 0 to 90 Degrees

The evaluation was conducted under a controlled environment using a solar simulator interfaced with a solar module analyser (SMA) for precise measurement of photovoltaic and optical properties.

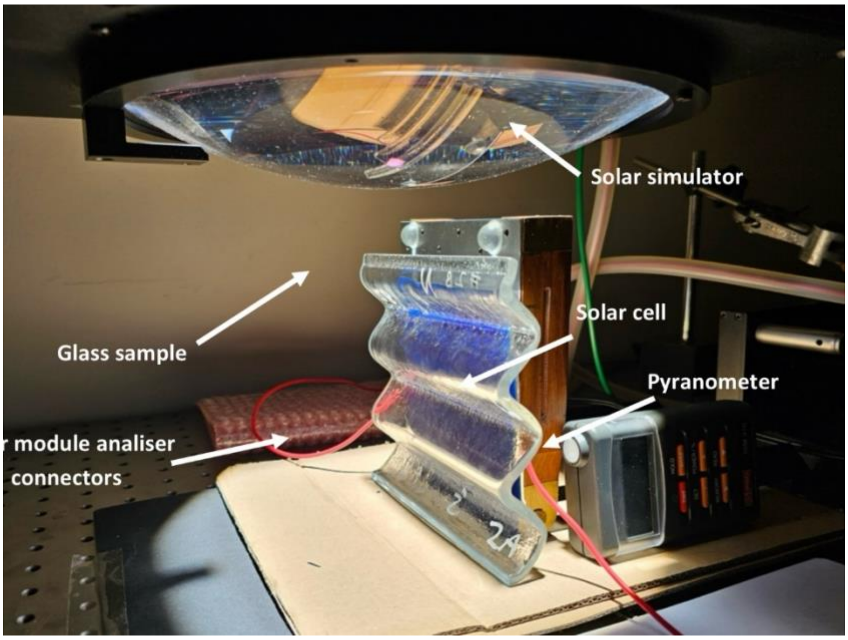
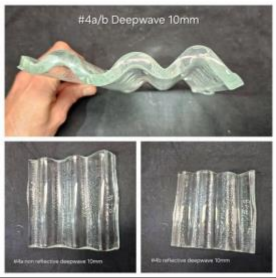
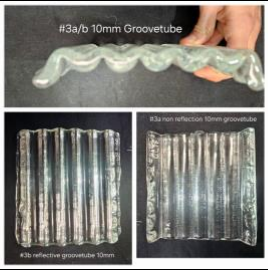
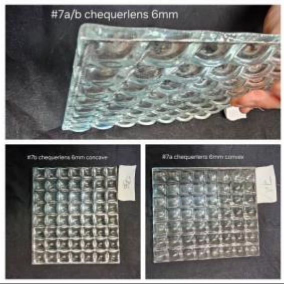
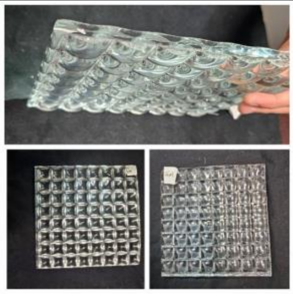


Figure 4. 1 Solar Simulator Lab set up to test samples

The following low-iron Opti Glass variants were tested are showing in table 4.1:

Table 4. 1 Glass variants tested.

Sample Code	Name	Thickness	Description	Picture
DW6	Deepwave	6 mm	A structured glass with a deep sinusoidal wave pattern, designed for light diffusion and aesthetic applications.	

DW10	Deepwave	10 mm	A thicker version of Deepwave glass, offering enhanced structural integrity and deeper wave formations for optical effects.	
GT10	Groovetube	10 mm	A patterned glass featuring parallel grooves, optimizing light redirection and diffusion for specific solar and architectural applications.	
SQ6	Squarelens	6 mm	A textured glass with square-shaped lens structures that focus and distribute light efficiently, improving light transmission.	
SQ10	Squarelens	10 mm	A thicker Squarelens variant providing improved durability and enhanced optical focusing properties for solar applications.	
FW10	Falling Wave	10 mm	A patterned glass with a cascading wave design, enhancing light scattering while maintaining high transparency and aesthetic appeal.	

Figures 4.2(a) and 4.2(b) illustrate the differences between the reflective and non-reflective surfaces of the cast glass samples. The variation in performance is significant, as reflected light is lost and does not reach the solar cells, thereby reducing energy generation. Most PV modules incorporate a non-reflective surface to maximise light absorption. However, such surfaces typically result in a visually subdued appearance, characterised by a dull, matte finish. The non-reflective side of the cast glass samples demonstrates superior performance, as supported by the results presented below. Nevertheless, to achieve a degree of visual enhancement, a balance is required whereby

some reflective qualities are retained to improve surface appearance without significantly compromising efficiency.

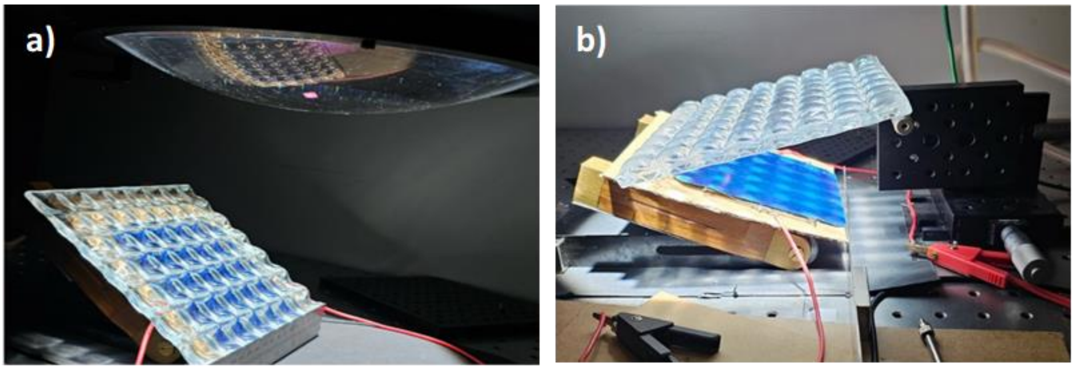


Figure 4. 2 a) Solar Simulator with reflective glass side Squarelens 6mm SQ6, b) Solar Simulator testing non reflective Squarelens 10mm SQ10

4.1 Indoor test results and graph analysis

Testing of 150 x 150 mm PVGlass samples commenced at TCD in November 2023, using a solar simulator to measure radiation from a controlled light source directed at the samples. The setup allowed for adjustable glass positioning over a solar cell, enabling angular testing to simulate the Earth-Sun inclination. Data was collected at angles ranging from 0° to 90°, with measurements taken for both the reflective front surface and the non-reflective reverse side. A control measurement was performed on a solar cell without PVGlass as a reference. 0° corresponded to a vertical orientation relative to the solar simulator, while 90° indicated a flat horizontal alignment, with readings recorded at 10° intervals under constant irradiance conditions. The results were analysed through graphical representation, comparing the efficiency of different PVGlass samples against the reference. The evaluation was based on photovoltaic efficiency, structural integrity and safety, visual aesthetics, cost considerations, and encapsulation feasibility for potential solar applications. Figure 4.2 and 4.3 shows the system setup during the test.

The graphs below present measurements of the reference solar cell (REF) without PVGlass and the solar cell covered with PVGlass, tested on both the Reflective Side and Non-Reflective Side of the glass samples. The black line in the graphs represents the reference solar cell without any glass covering, while the continuous line corresponds to the solar cell with PVGlass placed over it for the reflective side and the dashed line for the non-reflective side. These measurements provide a comparative analysis of photovoltaic performance, highlighting variations in efficiency based on glass type and surface orientation.

Figure 4.3 illustrates the relationship between solar radiation intensity (W/m²) and the angle of incidence on a solar cell, ranging from 0 ° (vertical) to 90 ° (perpendicular). Radiation starts at 107 W/m² at 0 ° and gradually increases with angle, reaching 657 W/m² at 50 °. Between 50 ° and 80 °, radiation levels stabilize around 690 – 720 W/m², before peaking at 806 W/m² at 90 °, where the surface is fully perpendicular to the light source. This trend confirms that maximum energy absorption occurs when solar panels are positioned perpendicular to the light source, highlighting the importance of angle optimization in solar energy applications.

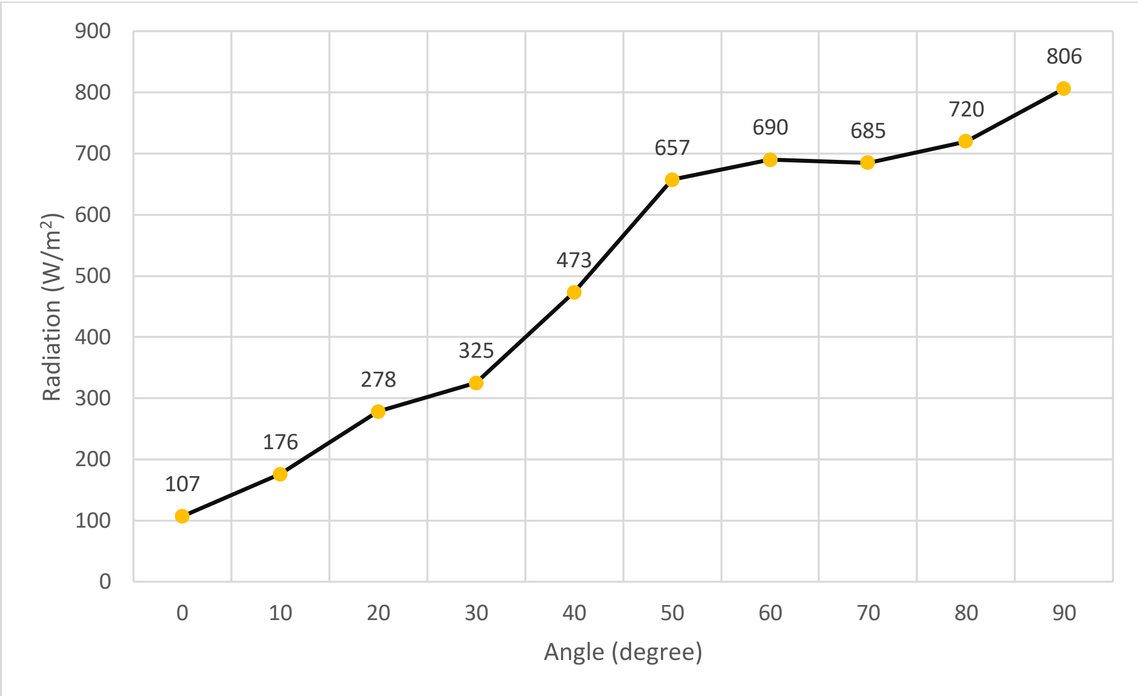


Figure 4. 3 Solar radiation during test

Figure 4.4 illustrates the power output (W) as a function of the solar panel angle (degrees) for three different conditions: Reference (black line), DW6 Reflective Side (DW6-R, solid light blue line), and DW6 Non-Reflective Side (DW6-NR, dashed light blue line). The reference solar cell consistently exhibits the highest power output, reaching approximately 1.65 W at 80 °, while the DW6-NR and DW6-R samples reach around 1.5 W and 1.4 W, respectively, at the same angle. At 0°, all samples produce less than 0.3 W, with the reference panel showing slightly higher values. As the angle increases from 10 ° to 50 °, power output rises sharply, with the reference reaching 1.2 W at 50 °, while DW6-NR and DW6-R reach approximately 1.0 W and 0.9 W, respectively. The non-reflective side (DW6-NR) consistently outperforms the reflective side (DW6-R), demonstrating that minimizing surface reflection enhances light transmission and improves solar cell efficiency. However, both DW6 samples show a power loss of 10 - 15

% compared to the reference, indicating some light absorption or scattering effects caused by the textured glass.

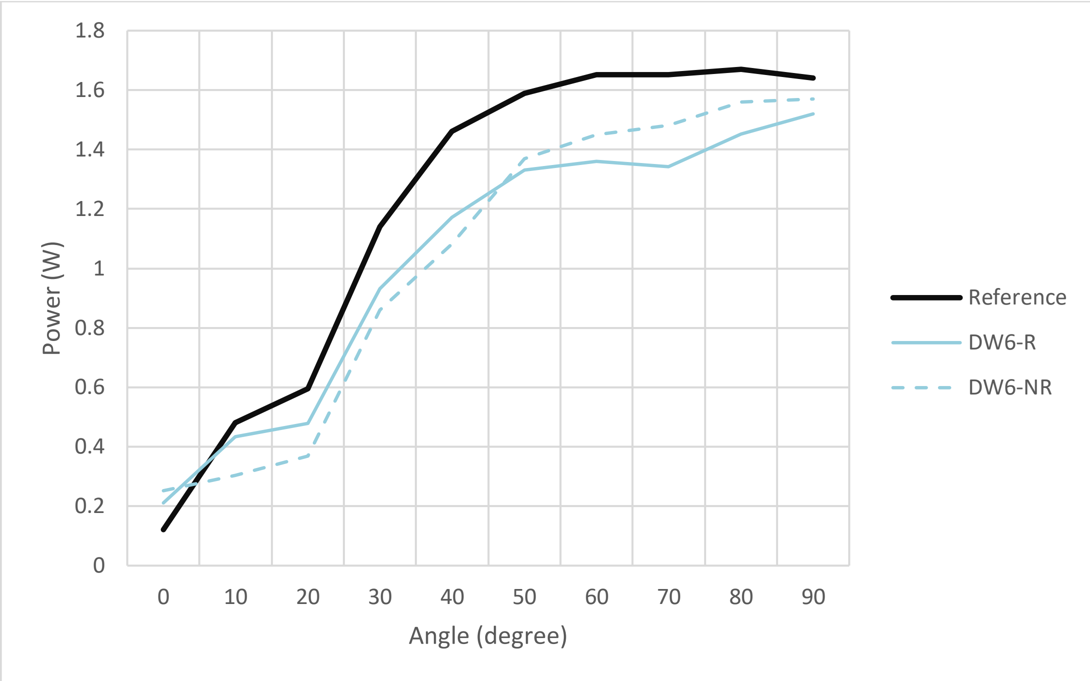


Figure 4. 4 Power production for DW6 sample

Figure 4.5 illustrates the power output (W) as a function of the solar panel angle (degrees) for the sample DW. The reference solar cell consistently exhibits the highest power output, reaching approximately 1.65 W at 80 °, whereas DW10-NR and DW10-R reach around 1.55 W and 1.45 W, respectively, at the same angle. At 0 °, power output for all samples starts below 0.3 W, gradually increasing as the angle rises. Between 10 ° and 50 °, power rises sharply, with the reference panel reaching 1.2 W at 50°, while DW10-NR and DW10-R reach approximately 1.1 W and 1.0 W, respectively. The non-reflective side (DW10-NR) consistently performs better than the reflective side (DW10-R), indicating that reducing surface reflection improves light transmission. However, both DW10 samples show a 5 - 10% reduction in power output compared to the reference, suggesting some light absorption or scattering losses due to the textured glass surface.

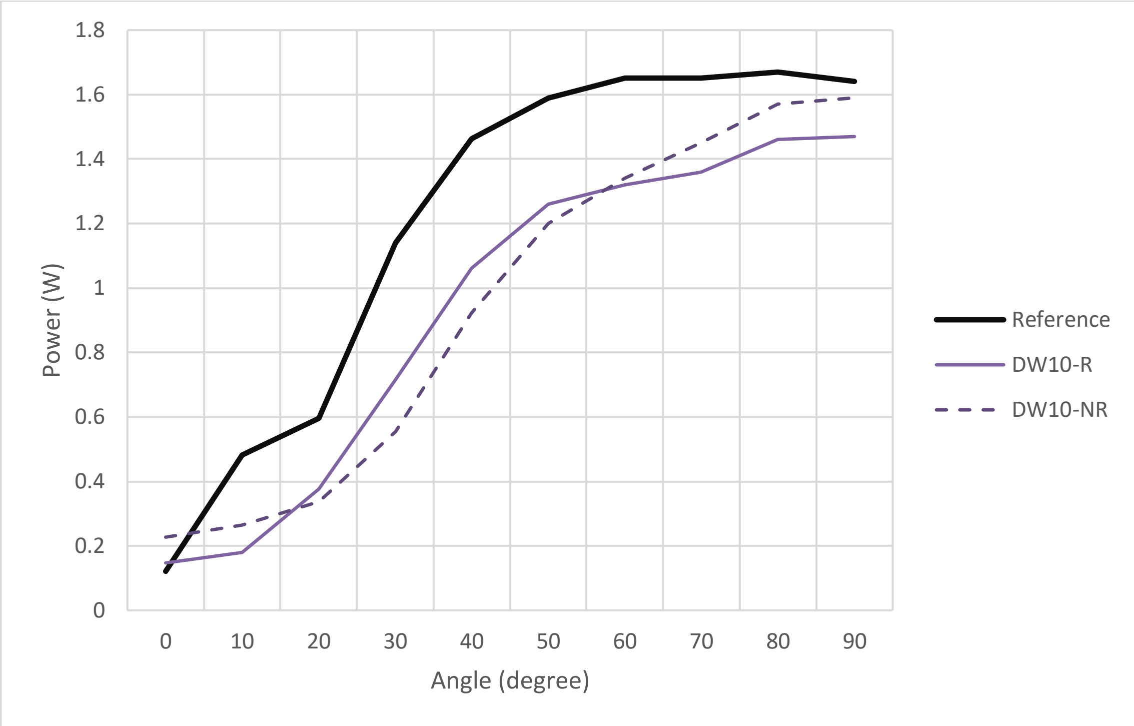


Figure 4. 5 Power production for DW10 sample

Figure 4.6 presents the power output for the GT10 sample. The reference solar cell maintains the highest power output, peaking at 1.65 W at 80 °, while GT10-NR and GT10-R reach approximately 1.62 W and 1.35 W, respectively. At 0°, all samples produce less than 0.3 W, with GT10-NR initially showing lower power (around 0.2 W) than GT10-R (approximately 0.25 W). However, beyond 30 °, GT10-NR experiences a sharp increase in power, reaching 1.0 W at 50 °, compared to 0.85 W for GT10-R at the same angle. Between 60 ° and 90 °, GT10-NR closely follows the reference curve, reaching over 1.6 W at 80 °, nearly matching the reference panel's performance, whereas GT10-R remains lower at around 1.4 W. These results indicate that the non-reflective side (GT10-NR) significantly improves light transmission, minimizing reflection losses and enhancing solar cell efficiency. Conversely, the reflective side (GT10-R) consistently underperforms, confirming that higher reflectivity reduces light absorption. While both GT10 samples show some power loss compared to the reference, GT10-NR demonstrates superior performance, particularly at higher angles, making it a more efficient option for photovoltaic applications.

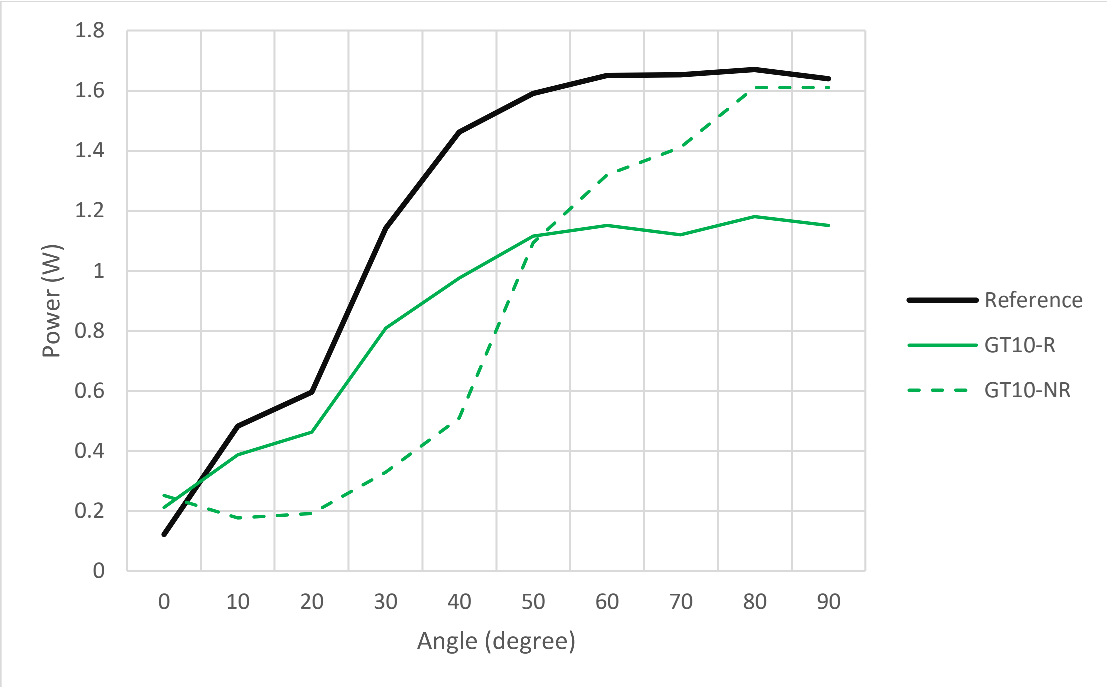


Figure 4. 6 Power production for GT10 sample

Figure 4.7 presents the power output for the SQ6 sample. The reference solar cell initially demonstrates the highest power output, reaching approximately 1.65 W at 80 °, while SQ6-R and SQ6-NR exhibit lower values during the early stages, starting below 0.3 W at 0°. However, beyond 50 °, SQ6-NR sharply increases, surpassing the reference at 80 ° with approximately 1.75 W, making it the highest-performing sample at this angle. Meanwhile, SQ6-R continues to rise steadily, surpassing the reference at 90° with approximately 1.7 W, outperforming both the reference and SQ6-NR at the highest tested angle. These results indicate that the textured non-reflective surface initially enhances light transmission, but at higher angles, the reflective surface (SQ6-R) captures and redirects light more efficiently, leading to superior power generation at 90 °. This suggests that SQ6-R could be particularly effective for vertical solar applications, where the incident light is more oblique.

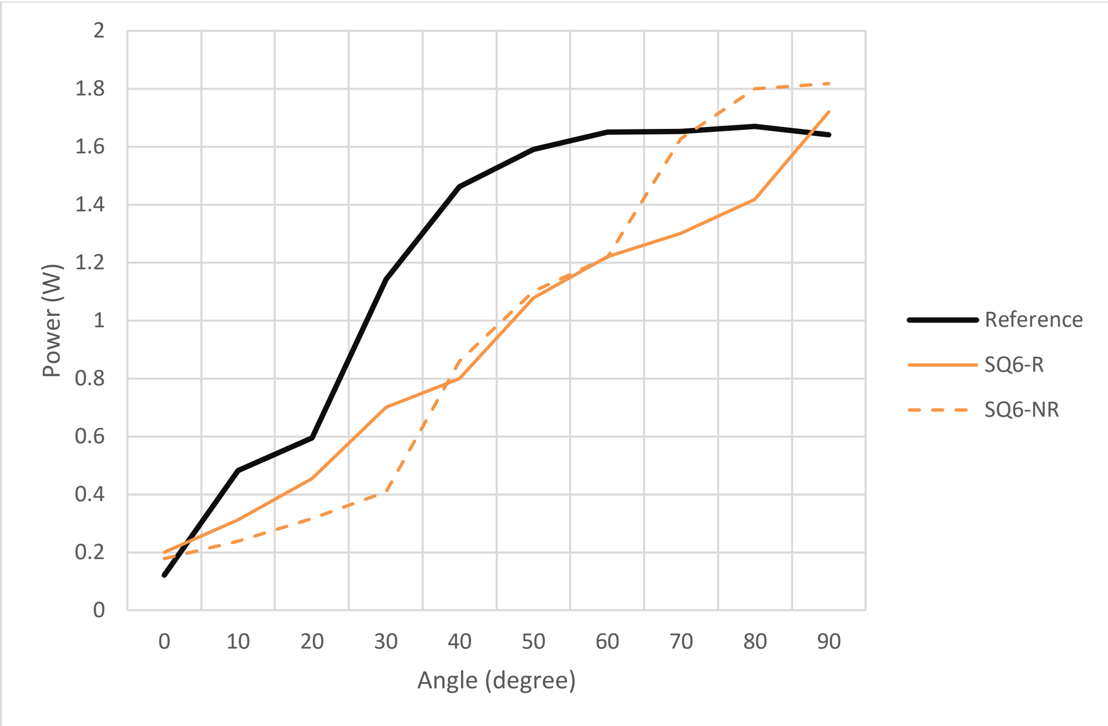


Figure 4. 7 Power production for SQ6 sample

Figure 4.8 shows the power output of the SQ10 sample. The reference solar cell maintains the highest power output, reaching 1.65 W at 80 °, while SQ10-NR closely follows, peaking at approximately 1.6 W, demonstrating its effectiveness in comparison to the reference. In contrast, SQ10-R underperforms, reaching only 1.3 W at 80 °. At 0 °, all samples start with power below 0.3 W, with SQ10-NR and SQ10-R nearly identical. However, beyond 30°, SQ10-NR experiences a sharp increase, surpassing 1.4 W at 50 °, while SQ10-R remains lower at around 1.1 W. Between 60° and 90°, SQ10-NR remains just below the reference, providing strong evidence of PVGlass functionality, while SQ10-R stabilizes at lower values, indicating reduced efficiency due to higher reflection losses.

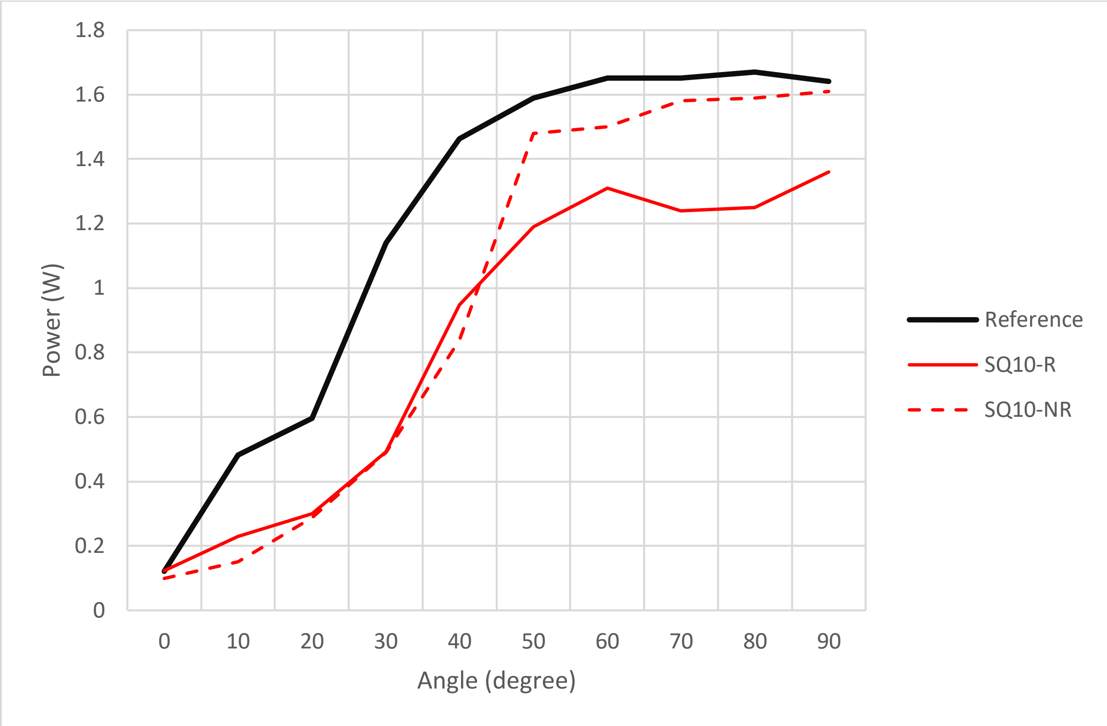


Figure 4. 8 Power production for SQ10 sample

Figure 4.9 illustrates the power output of the FW10 sample. At 0 °, both FW10-R and FW10-NR start with power output below 0.3 W, following a gradual increase. Between 30 ° and 50 °, FW10-R reaches approximately 1.1 W, while FW10-NR follows closely behind at 1.0 W. Beyond 60 °, FW10-NR surpasses FW10-R, reaching 1.5 W at 80 °, while FW10-R stabilizes at around 1.35 W. This indicates that the non-reflective surface (FW10-NR) performs better at higher angles, enhancing light transmission and minimizing reflection losses. Conversely, the reflective side (FW10-R) maintains more stable performance at lower angles, suggesting its ability to direct light efficiently within specific conditions. The results highlight that FW10-NR is more effective in maximizing photovoltaic efficiency at steeper angles, making it a better candidate for applications where light approaches at an oblique angle, such as vertical solar facades.

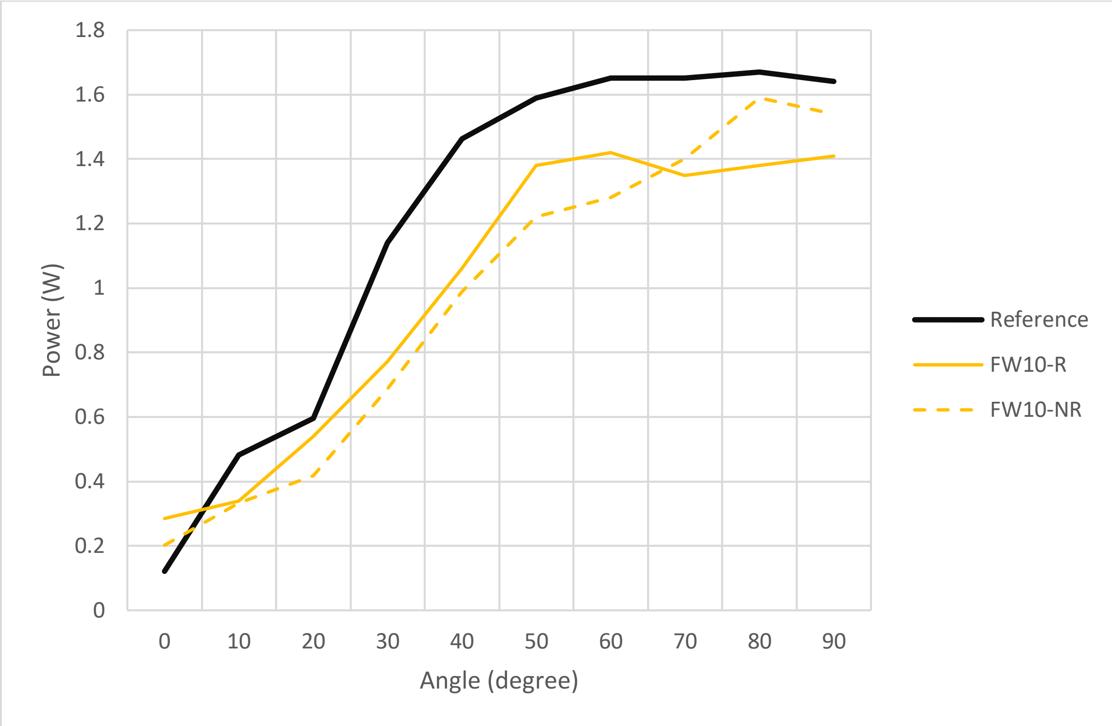


Figure 4. 9 Power production for FW10 sample

Lastly, figure 4.10 presents the efficiency comparison between PVGlass samples tested, with the reference solar cell maintaining the highest efficiency. Among the tested samples, DW6-R and DW6-NR exhibited the highest efficiency values of 13.67 % and 13.32 %, respectively, closely approaching the reference. SQ10-R and SQ10-NR, representing 10 mm low-iron glass, achieved 10.90 % and 10.23 % efficiency, respectively. Additionally, GT10-R (11.80 %) and GT10-NR (10.24 %) showed mid-range efficiency values, suggesting that their grooved texture may cause some light scattering, reducing the overall energy transmission compared to DW6 samples. FW10-R (12.38 %) and FW10-NR (13.40 %) demonstrated high efficiency, with FW10-NR closely rivalling DW6-NR, indicating that non-reflective surfaces perform better by reducing light losses and increasing absorption efficiency.

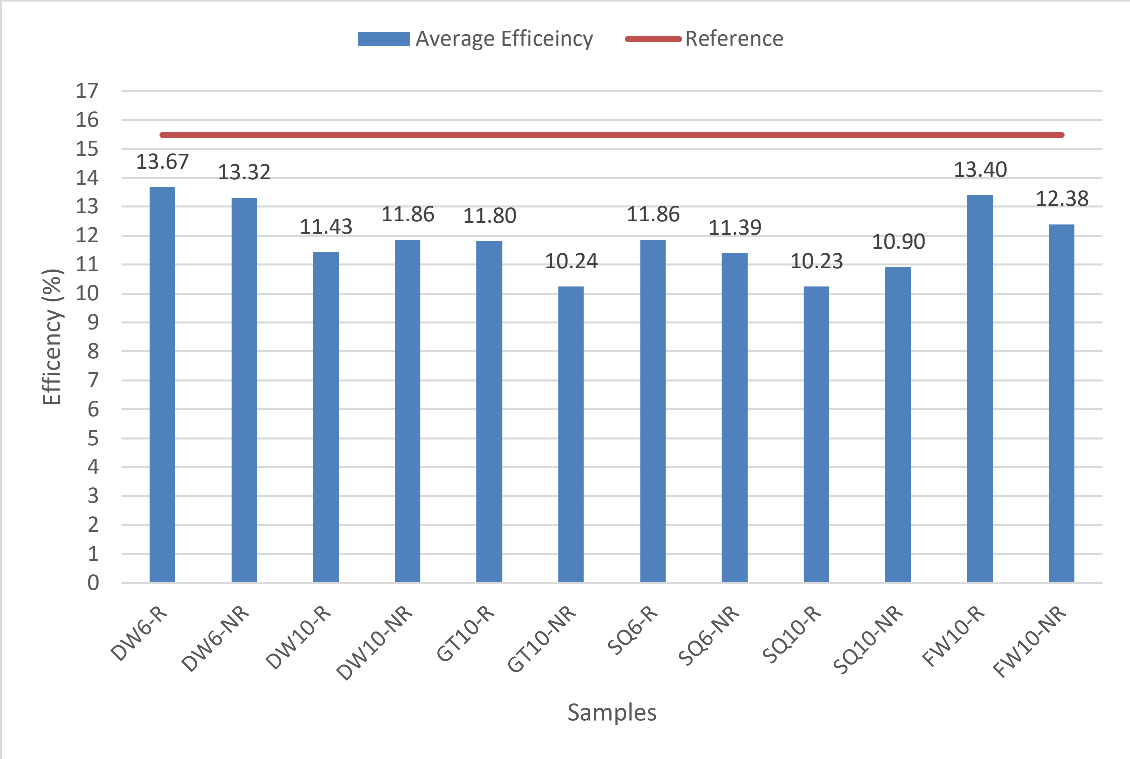


Figure 4. 10 Efficiency comparison between samples

The table 5.1 compares PVGlass samples based on structural safety, visual appeal, economic feasibility, retrofit potential, and encapsulation compatibility. SQ10 ranks highest overall, with 90 % structural safety, and 100 % visual appeal, making it the most suitable candidate for building-integrated photovoltaics (BIPV). Its thicker 10mm low-iron glass ensures stability, durability, and optimal lamination with EVA or resin, creating a structurally safe solar panel for facades. Additionally, its dynamic light interaction enhances architectural aesthetics, making it ideal for both new and retrofit solar applications.

The results indicate that while certain thinner glass samples (such as DW6) offer higher efficiency, thicker glass options like SQ10 provide significant advantages for architectural applications due to their structural integrity and aesthetic appeal. Given these findings, SQ10 was selected as the best-performing PVGlass sample for further testing, particularly for BIPV facade integration. The next stage of research will involve scaling up SQ10 panels for real-world deployment and monitoring over 12 months, evaluating their energy performance under varying seasonal conditions. Furthermore, installing PVGlass panels in sequence will not only optimize energy capture but also enhance the visual impact of solar-integrated architecture, reinforcing the potential for widespread adoption in sustainable building design.

Table 5. 1 PVGlass samples based on different parameters

Sample	Structure Safety %	Visual Appeal	Economics %	Retrofit Option?	Encapsulate Option?
DW6	50	70	40	yes	No
DW10	50	80	40	yes	No
SQ6	80	90	80	yes	Yes
SQ10	90	100	80	yes	yes
GT10	60	90	70	yes	Yes
FW10	70	80	70	yes	No

4.2 Conclusion Indoor Testing

The indoor laboratory testing of PVGlass samples successfully demonstrated the impact of glass texture, thickness, and reflectivity on solar energy transmission and photovoltaic efficiency. By utilizing a solar simulator and a solar module analyser, controlled experiments provided a comparative analysis between various low-iron glass variants and a reference solar cell. Results highlighted that non-reflective surface performed better than reflective ones, enhancing light transmission and improving solar cell efficiency. Additionally, findings confirmed that glass thickness and surface texture significantly influence light scattering and absorption, affecting overall power output. The study also emphasized the importance of angle optimization, showing that maximum radiation absorption occurs when solar panels are positioned perpendicular to the light source (90 °). While the reference cell consistently outperformed all PVGlass samples, the results confirmed that certain PVGlass variants, such as SQ10, offer an optimal balance between efficiency, structural integrity, and aesthetic value for BIPV applications. These findings support further research into full-scale PVGlass panel production for long-term outdoor testing, assessing their performance across different environmental conditions and reinforcing their potential for sustainable architectural integration.

Chapter 5 Conclusions and recommendation for future works

The development and production of PVGlass prototypes involve significant costs; however, once the optimal design is finalized, scaling up production using large-scale manufacturing facilities will be the most economically viable approach. Given that the minimum expected installation area for PVGlass on a building facade is 100 square meters, a dedicated workspace and specialized equipment will be required to achieve efficient mass production. To ensure commercial viability and market competitiveness, it is essential to protect the design and intellectual property, while partnering with BIPV manufacturers to integrate PVGlass with solar panel production lines. If prototype testing over 12 months yields successful results, collaboration with BIPV-specific PV panel manufacturers should be explored to facilitate seamless integration into the existing market. Compliance with building regulations is also critical, particularly concerning safety standards for glass installations in public spaces. Strict regulatory requirements exist to prevent potential hazards associated with broken glass, necessitating adherence to safety protocols in material selection, lamination, and installation methods. Finally, market validation through trade shows will play a crucial role in introducing PVGlass to the BIPV industry. Events such as Intersolar Munich, the largest trade show for solar innovations in Europe, offer valuable opportunities to showcase the product, attract clients and investors, and foster collaborations with industry leaders. Engaging in such events will provide critical market feedback, ensuring that PVGlass meets industry demands and commercialization goals.

5.1 Indoor Laboratory test

The indoor laboratory testing of PVGlass samples provided critical insights into their photovoltaic efficiency, structural integrity, and light transmission properties. By conducting controlled experiments with a solar simulator and a solar module analyser, the study effectively demonstrated the influence of glass texture, thickness, and surface reflectivity on solar energy conversion. Results indicated that non-reflective surfaces enhanced light absorption, while glass thickness and structural properties affected both durability and optical performance. Furthermore, the angle of incidence was confirmed as a key factor in energy capture, with maximum radiation absorption occurring at 90° (perpendicular to the light source). Although the reference solar cell performed at the highest efficiency, select PVGlass variants—particularly SQ10—proved strong potential for integration into BIPV applications, offering a best balance between efficiency, safety, and architectural aesthetics. These findings justify further testing in real-world conditions, where full-scale PVGlass panels will be assessed over 12 months to decide their long-term viability in sustainable building design.

5.2 Contributions to knowledge

The contributions to knowledge for the research are many:

1. Bringing a visual aesthetic to the renewable energy market and thus encouraging specification in architecture.
2. Offering a façade solution to buildings that may be refurbished rather than demolished and avoiding concrete destruction and replacement therefore reducing carbon emissions in building works.
3. Continuing to push the boundary of innovation in architectural surface to present a more stimulating built environment to the public.
4. To provide a sustainable energy solution for the building to be clad in PVGlass to provide indoor and outdoor lighting, hot water and services for the building. It may contribute to the overall energy demand of the building if not supplying all energy needs.
5. Allow a system that can replace PV panels behind PVGlass over time as the advancement of solar cell technology brings more efficient cells to the market. It is likely that in the future we will have 1000 W standard PV panels available at affordable cost
6. Suppling a key product to the rapidly growing solar power industry. There are many BIPV products on the market. PVGlass will be a high-quality surface solution for the face of buildings in the future

5.3 Recommendation for future works

Optimization of PVGlass Design & Efficiency

- Further refine glass surface textures to enhance light transmission and solar cell performance.
- Investigate new coatings or treatments to maximize energy absorption while keeping transparency.

Aesthetic & Architectural Integration

- Develop PVGlass as a visually dynamic facade material, enhancing building aesthetics while generating energy.
- Study the interaction of PVGlass with natural light from different angles to improve visual and energy performance.

Performance at Different Angles & Locations

- Conduct real-world tests in various climates and locations to assess PVGlass performance at different sun angles.
- Expand laboratory testing to confirm how PVGlass outperforms standard PV modules at angles below 20°.

Dust Accumulation & Maintenance

- Evaluate dust and dirt accumulation over a 12-month period to determine its impact on energy efficiency.
- Test self-cleaning coatings or hydrophobic treatments to reduce the need for maintenance.

Heat Management & Thermal Insulation

- Investigate the integration of PVGlass into double-glazed units to create an insulated air gap, improving thermal regulation.
- Study how reduced heat exposure on solar cells affects efficiency and long-term durability.

Structural Safety & Glass Thickness Considerations

- Analyse the use of 10mm–15mm thick glass for improved strength and durability in facade applications.
- Ensure compliance with building safety standards, including toughening or lamination of thinner glass options.

Encapsulation & Lamination of Solar Cells

Explore two encapsulation methods for integrating solar cells with PVGlass:

- Option A: Encapsulating solar cells directly to PVGlass, creating an all-in-one integrated module.
- Option B: Using PVGlass as a protective layer over existing PV modules, allowing future solar panel upgrades without replacing the facade.

Scaling Up Production & Market Integration

- Assess the feasibility of large-scale manufacturing once an optimized PVGlass design is selected.
- Secure intellectual property protection and collaborate with BIPV manufacturers for commercial production.
- Prepare for minimum facade coverage of $100m^2$ per installation, requiring suitable manufacturing facilities.

Compliance with Building Regulations

- Ensure that PVGlass meets safety standards for public installations, preventing hazards related to breakage and sharp edges.
- Develop lamination and reinforcement techniques to enhance impact resistance and durability.

Trade Shows & Market Validation

- Showcase PVGlass at major BIPV industry trade shows, such as Intersolar Munich, to attract clients, investors, and partners.
- Conduct live demonstrations to gather industry feedback and explore collaborations for large-scale implementation.

Long-Term Monitoring & Performance Testing

- Install PVGlass panels in real-world conditions and monitor energy output for at least 12 months.
- Evaluate how PVGlass can be integrated into smart buildings, improving on-site energy consumption instead of relying on the national grid.
- Test sequential panel installations to analyse scalability, durability, and economic feasibility for widespread use.

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