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The Assembly of Embedded Systems for Integrated Photovoltaic windows in Rural Buildings (E-IPB)

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Abstract. Embedded PV systems are required to help improve the synergy of renewable energy and smart buildings. A novel concentrator photovoltaic (CPV) system embedded as a window for integration into buildings is presented. The system is made up of crossed compound parabolic concentrators (CCPC), Talesun Silicon solar cells and glass panes. The materials and manufacturing methods are presented along with their advantages and disidvantages. Two sized prototypes are presented, 7cm by 7cm and 20cm by 20cm. The maximum power obtained was 3.53 Watts for the larger prototype. The glass CCPC optics produce more power but plastic alternatives are only 44% the weight of the glass optics. The best performing plastic optics were made of Topaz and injection moulded. The cell soldering and alignment method is explored and in particular silver tracks printed on glass are analysed for their resistance, aesthetics and benefit to the assembly process. Using plastic optics for CPV technology is a relatively new area of research, and the combination of silver tracks printed on glass could make this innovative design revolutionary in its field.

Keywords: solar; energy; optics; concentrator photovoltaics; building integration;

1. Introduction

Concentrator photovoltaic (CPV) systems reduce the requirement of photovoltaic materials needed in a system installation [1]. This in turn reduces the carbon footprint of making this type of solar energy technology and can also reduce the cost of the system whilst maintaining or even increasing the solar cell efficiency. For example, the record solar cell efficiency at present is 46%, held by Fraunhofer and Soitec for a four-junction solar cell under high concentrated sunlight [2]. Despite these advantages, CPV costs limit the technologies competitiveness with flat plate silicon panels. Applications where space is limited and energy demand is high, such as for domestic use, are where CPV technology may contend, especially if more interesting, aesthetically pleasing designs are required. CPV technology also has the advantage of being flexible in its size, shape and transparency. Recent market research suggests that for CPV to succeed alongside standard flat plate PV, niche applications such as building integration, using embedded systems, need to be developed [3,4]. There is a lot of potential for smart integrated solar windows [10,11] with many designs, materials and manufacturing processes in need of investigation. Thus we present an embedded crossed compound parabolic concentrator (CCPC) plastic optic, arrayed within double glazed windows as a means to provide both electricity and natural sunlight to a building (Figure 1).

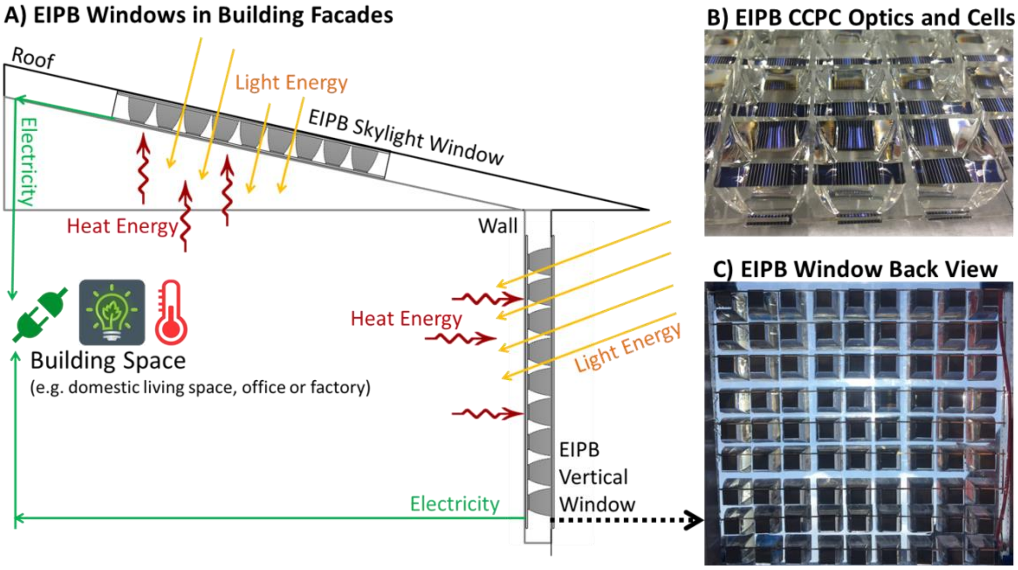

Figure 1. A) Example of roof and wall installations of EIPB window and the transfer of light, heat and electricity for a building space. B) Glass Crossed Compound Parabolic Concentrator optics optically coupled to tabbed silicon cells. C) Back view of 20cm by 20cm prototype showing light passing through module.

The weight of such a design however should be minimised to aid application to any kind of building façade, especially those on roofs and skyscraper buildings. Glass, although a very reliable and high performing material, adds weight to devices and in a window, is already being used for the front and back sheets. Plastics such as polymethylmethacrylate (PMMA) and Polycarbonate (PC) are popular alternative materials in CPV's with lower weight but also lower transmittance values [5–7]. For photovoltaic technology embedded into building facets and windows, plastic materials are an evident alternative to reducing weight, cost and handling difficulty [8,9] however more materials need to be investigated. The proposed embedded system as an integrated photovoltaic window in buildings (E-IPB) utilizes highly transparent Topaz plastic for the CCPC optics inside the windows (Figure 2). This improves the power to weight ratio of the window in comparison to glass optics as can be seen from figure 2.

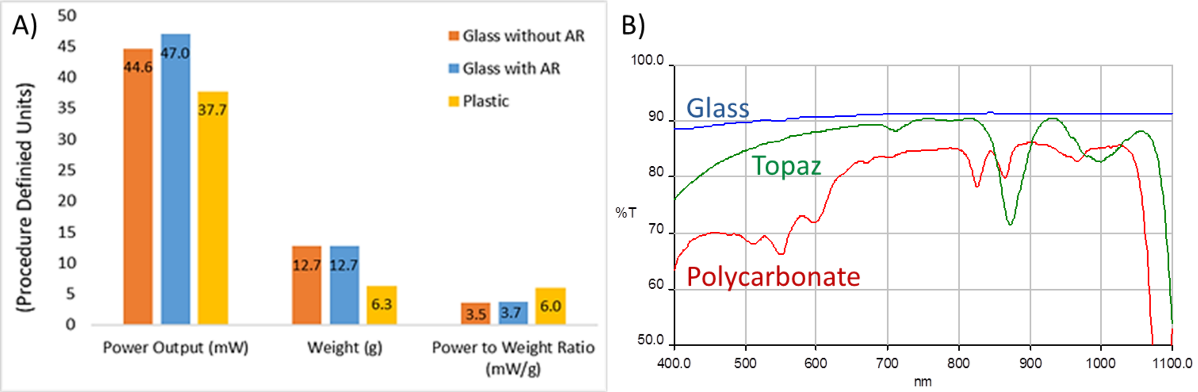

Figure 2. A) Power and weight comparison for glass and plastic CCPC's. B) Transparency spectra of Glass, Topaz and Polycarbonate.

2. Design components and manufacturing methods

One of the key challenges in this type of embedded system, as an integrated photovoltaic for building structures, is the manufacturing and assembly process. Cost effective large scale manufacturing of arrayed solar cells and optics sealed with wiring in window units requires optimization. Here we present the requirements and options for the different subsystems in the E-IPB window (figure 3a).

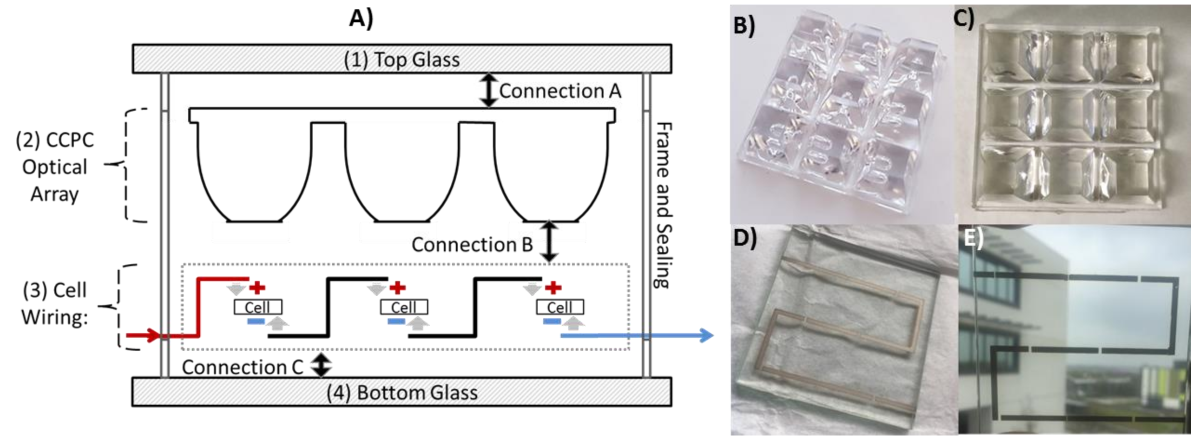

Figure 3. A) Diagrammatic representation of subsystems in EIPB window prototype. B) Injection moulded plastic 3 by 3 optical array with voids and shrinkage. C) Minimized flaws in injection moulded optic by oven cooling after injection. D) Top view of silver tracks printed on glass. E) Back view of silver tracks on glass showing gaps for series connection of cells.

2.1. Top Glass

The top cover glass, which will be the outer pane of the window when installed, should ideally have a high transmittance and an anti-reflective coating which covers most of the solar cell working range (300-1100nm for silicon) for maximum electrical performance of the device. As this is a window required to also be thermally insulating or cooling (location dependent) and perhaps provide certain light filtering (UV or glare for offices with computer screens) these requirements could compromise the exact best coating and material of the top glass. Most coatings are also fragile and cannot be handled or cleaned by ordinary measures which limits these options further for the outer surface which should be able to be installed by non-specialists and cleaned as a regular window. Coatings on the inner surface of the Top and Bottom Glass (1 and 4 in figure 3a) are however a good option but again may be compromised if connection A between the top glass and the CCPC optics is filled with a refractive index coupling material. Optically joining the top glass to the CCPC optics would reduce light loss due to Fresnel reflections as the incoming light passes through the different medium interfaces but adds another processing stage and hence more cost to the assembly.

2.2. CCPC Optical Array

For the CCPC optical array, arrays of optics which are cast as one part allow faster manufacturing, neat placement and alignment. This however also requires the cells to match the spacing. Alignment between the optics and the cells is crucial for maximum performance. Injection molding was the most appropriate, and for some plastics the only option, for manufacturing the designed CCPC plastic optics. Previously, in house casting of plastic crystal clear optics was investigated but the injection moulded parts had superior surface smoothness and optical quality as expected.

However, due to the thickness of the CCPC optics, the bulk material in the center of these optics was found to cool at a much slower temperature than the outer parts of the optics during material injection. This meant the inside of the optics was still in a hot liquid state which contracted and shrunk as it cooled, causing voids (bubbles) or pulling the outer shape inwards (figure 3b and c). This effect could be minimized (figure 3c) by either leaving the optics in the mold until they had fully cooled -a very time consuming and hence costly method in terms of manufacturing large quantities- or by quickly moving the optics into an oven to cool at a slower rate. Ideally this process could be done on a customized lehr (conveyer belt) set up for large scale manufacturing.

Despite this flaw in the optics the Topaz 3 by 3 arrayed optics still achieved a good short circuit current as shown in figure 4c. Glass however maintains the lowest absorbance and hence is still most efficient material, but as seen from figure 2 has the lowest power to weight ratio.

2.3. Cells and electrical connections

The solar cells are Silicon solar cells provided by Talesun following our own metallization and cutting pattern. A single cell (1cm x 1cm) under 1 sun provides ~20 mW of power with an efficiency of 19-20% following an I-V curve as shown in figure 4. The cells have a top contact and bottom contact (component no. 3 in figure 3a) and to be connected in series require tabbing connections as shown in figure 3. This is the most time consuming part of the assembly unless automated tabbing machines can be utilised. Another option for the connection and correct spacing of the cells is to use printed silver tracks on glass (Figure 3d and e). Conductive tracks can be printed onto the bottom glass with the correct spacing for the cells to be soldered onto (Connection C in figure 3a is hence also achieved). Some tabbing would still be required to connect the top contact of the cells to the next conductive track on the glass for our prototyping. Bottom contact cells would benefit most from this type of wiring. One of the disadvantages observed however in these prototyping investigations was the increased chance of misconnections as both the cell and the glass are inflexible allowing slight tilts and uneven soldering to cause incomplete connections along the full length of the cells' bottom contact.

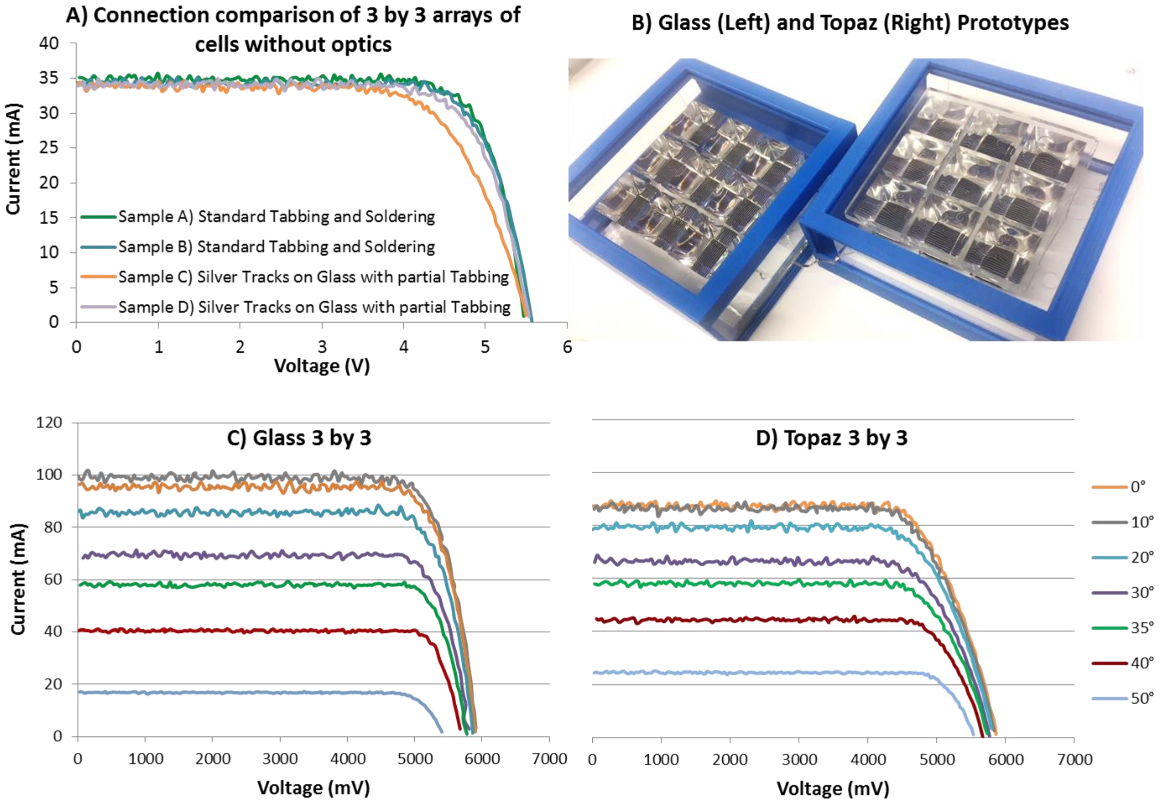

Figure 4. A) Comparison of different connection methods. B) Glass and Topaz prototypes. C) Glass 3 by 3 prototype performance and D) Topaz 3 by 3 prototype performance for different angles of incidence.

2.4. Bottom Glass

As described above, this could be printed with conductive tracks for the cell connections. This also opens up the potential for patterned windows or specific designs which also connects the cells but may be more aesthetically pleasing. Another disadvantage of this however is that it cannot coincide with any special coatings on the inner surface of the bottom glass. For thermal insulation some double glazed windows have low emissivity coatings on the inner surface of the bottom glass which can allow light energy into a room but reduce the heat energy out of the room through that glass (figure 1a). Another consideration is if these printed conductive tracks have increased resistance in comparison to current standard soldering and tabbing methods.

3. Prototype performance

3.1. Conductive tracks on glass

As can be seen from figure 4a, there is negligible difference between the different cell connection methods though as already stated it was more likely to be a fault obtained with the silver tracks on glass and partial tabbing connection method, giving a result such as sample C in figure 4a. With scaled up processes and automated pick and place soldering the chance of misconnections may be minimised.

3.2. Topaz vs. Glass CCPC optics

3 by 3 prototypes utilising glass optics and Topaz optics were made and tested first as shown in figures 4b-d. As expected the glass optics achieved a higher current and fill factor (figure 4c) than the Topaz counterpart (figure 4d). Interestingly the Topaz optics performed better at wider angles of light incidence but this is expected to simply be due to the topaz optics being joined in an array as opposed to the glass optics being individual and separate. The layer of Topaz which joins the 3 by 3 optical units together appears to act as a method of light trapping, but this is to be understood clearer in further investigations.

3.3. 9 by 9 arrayed Prototype (20cm by 20cm)

A larger 20cm by 20cm module consisting of 9 rows of 9 glass optics was developed (figure 5a) next but with standard tabbed cell connections. The maximum power output obtained was 3.53W with a fill factor of 0.722 as shown in figure 5b. These results although good can be improved with more accurate automated machinery and customised conveyer systems to align the cells and optics with repeated accuracy as opposed to the in house manual placement done for this prototype. Since the cells were connected in series, one lower functioning cell or slightly misaligned optic will limit the total output. As can be seen from figure 5b, the cover glass reduces the short circuit current by 8.55mA and power output by 0.28W. AR coatings and an encapsulate such as sylgard between the optics and cover glass (connection A in figure 3a) would reduce this but also add cost and time to the manufacturing process.

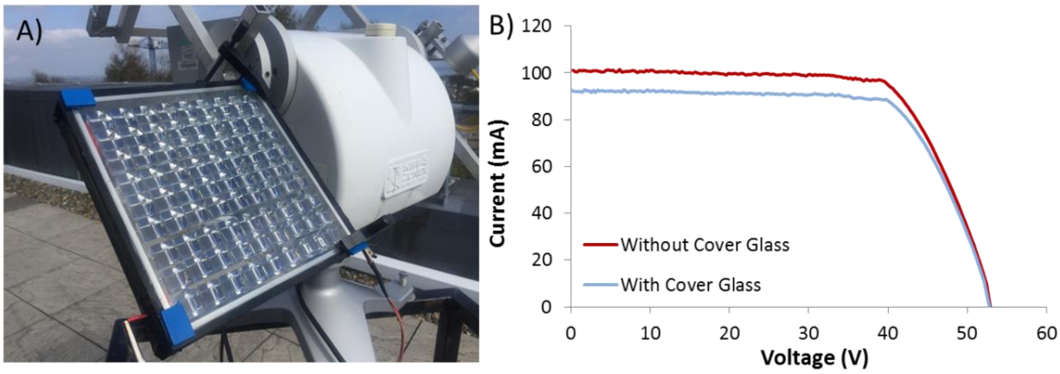

Figure 5. 20cm by 20cm prototype outside mounted on tracker at the Environment and Sustainability Institute, University of Exeter, Penryn, UK. B) I-V Outputs of prototype with and without cover glass.

The 20cm by 20cm prototype is the thickness of a standard double glazed window, framed and sealed by Cornwall Glass in Penryn, UK. This means integrations of this type of system into a wide selection of commercially available window frames should be easily achieved but consideration of the wiring and electrical connections needs to be carried out and will be investigated next as part of the EIPB project.

4. Conclusion

Plastic optics made of such materials as Topaz have serious potential for replacing glass optics in concentrator photovoltaic products to improve their power to weight ratios beyond glass and expand their applications for building integrated skylights and windows. The durability, aesthetics and electrical connection of these windows within a building have to be investigated further but the findings presented here confirm feasibility and assembly optimisation utilising Topaz injection moulded optics and silver tracks printed on glass cell connections. The Topaz optics achieve a power to weight ratio almost double that achieved by the glass optics and are best manufactured using a lehr such that the newly injection moulded arrays can be cooled slowly to minimise air voids and surface shrink back flaws. Silver printed on glass conductive tracks is more aesthetic, scalable and does not add extra resistive losses to the system. AR coatings and extra optical coupling between the optics and glass cover would reduce Fresnel losses but may also reduce the light trapping effect seen by the Topaz 3 by 3 arrays and add another stage and cost to the manufacturing system.

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