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Novel approach for concentrating and harvesting solar radiation in hybrid transparent photovoltaic façade's in Southern Africa.

RH Gevers[1], JHC Pretorius[1] and P van Rhyn[1]

[1] Department of Electrical and Electronic Engineering
University of Johannesburg, Engineering Faculty
Campus of Auckland Park, Johannesburg – (South Africa)
Phone/Fax number: +27 84 657 6675,
E-mail: rhgevers@mweb.co.za jhcpretorius@uj.ac.za mvmafrica@mweb.co.za

Abstract. Electrical consumption and the price thereof is rapidly increasing in South Africa. Finding alternatives to the current grid-tied electricity supply in the country is a prodigious concern to the South African economy due to historic unreliability. The national power grid and the South African economy can extensively benefit from utilizing solar energy as an abundant clean and renewable energy source.

This paper considers and further investigates power generation utilising a novel approach to transparent solar façades (windows). Harvesting solar energy is consequently included in the building envelope, which improves building efficiency while reducing demand on the national electric grid.

The impacts, design, modelling and results of this novel approach to Photo Voltaic (PV) systems, is further examined in this paper. These systems are aimed to be used in the commercial and residential market. Factoring in the location, design and installation of the solar façade, geographical conditions relevant to South Africa were used to evaluate the transparent façade's performance. The generated power from a façade depends on solar irradiation, orientation, (Azimuth and Zenith angles); climate conditions such as temperature and rainfall; and other solar constraints. These factors were incorporated using average values from meteorological data.

Keywords

Transparent solar cell, Solar, Solar energy, Solar panel.

1. Introduction

During the past half-decade, South Africa has seen its cost of electricity supply double in price **[1]**. The reliability of this supply has also been strained with frequent load shedding. Current proposals see the price of electricity doubling once again in the next 5 years **[1]**. This has had a direct effect and a pronounced slowing in economic growth within the area. More reliable sources could help mitigate the threat of another blackout which costed an estimated \$5,000 million during the forced blackout in 2008 **[2]**. Blackouts on this scale have reoccurred in 2011 and 2013.

Therefore the need for additional energy from renewable energy sources is crucial to the sustainability and reliability of South Africa's energy needs **[3]**. As Eskom and the National Energy Regulator of South Africa (NERSA) look for innovative ways to sustain the grid, the use of solar energy plays an increasingly important role to help achieve this. South Africa has an abundant amount of solar energy, with various regions in S.A. having some of the best Global Horizontal Irradiation (GHI) in the world. Most parts experience in excess of 6kWh/m^2/day; an annual equivalent of 2200kWh/m^2 (Fig. 1) **[4]**.

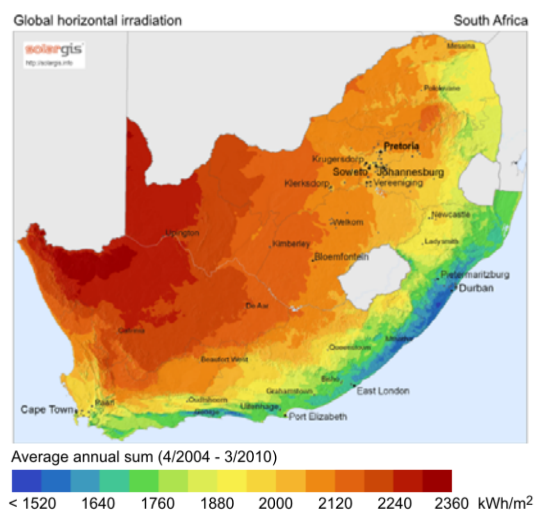

Figure 1: Global Horizontal Irradiation for South Africa (annual sum, 2004-2010) **[4]**.

The utilisation and integration of solar panels into the building envelope, and especially installations in the form of windows (façades), creates sufficient opportunity to harness this energy. Coupled with the naturally high incidence of solar radiation within South Africa, the feasibility of transparent solar façades technology is strengthened.

With the extensive use of glass in modern buildings due to aesthetic and design considerations as well as the drive for greener and zero carbon buildings. Significant economic benefit exists if these glass surfaces had energy-generation capabilities **[5]**. Though many possible solutions currently exist in the market, most of the cost effective solutions involve mono-crystalline, polycrystalline or thin film Photo Voltaic (PV) cells and panels which are still "Black" in colour, and obstruct views through the glass windows.

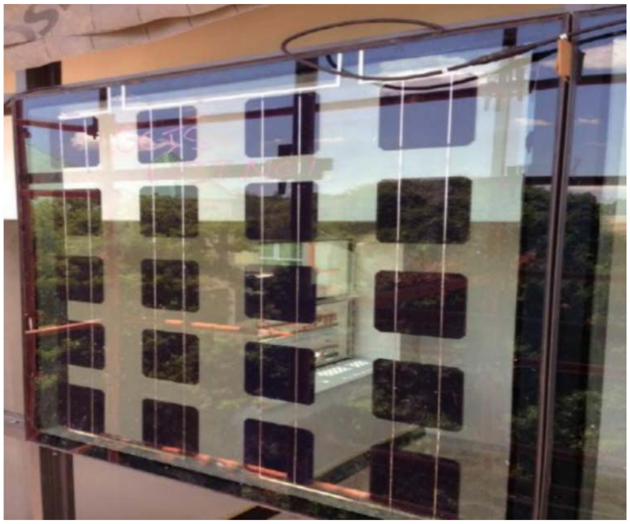

Figure 2: Photo of current installed solar façade illustrating the "old" technology. Photo taken at the Government Commination and Information Systems building in Pretoria South Africa, (GCIS) **[6]**

The recent advancement in the Thin-Film PV now allows researchers the ability to create near and fully transparent photovoltaic cells and transparent collectors/concentrators that generate power. Richard Lunt and Vladimir Bulović, through MIT and MSU **[7] [8] [9]**, have developed such a transparent solar cell. Concurrently the Edith Cowan University (ECU) **[10]** and TropiGlas Technologies **[11]** in Australia have developed an alternative product. This paper will not debate the differences or similarities between the two and other forms of this technology but will primarily focus on the electrical results and radiation attributes of the TropiGlas & ECU sample provided to the University of Johannesburg **[12]** (Fig 3).

To improve energy efficiency within buildings currently, various types of window glazing and coated-type windows are used within the commercial and residential environment worldwide. These offer indoor thermal improvements, heating, ventilation and air-conditioning (HVAC) energy savings, and ultraviolet (UV) protection.

A hybrid technology (PV and glazing) could have a positive impact on the electrical demand and economy of South Africa. These impacts will be discussed in this paper using a test site installation at the GCIS building (Fig 4).

Figure 3: TropiGlas, transparent solar panel (200 x 200 mm).

Figure 4: Installed solar façade at GCIS, six 200 x 200 mm panels (Clear Standard Glass - left. Transparent TropiGlas Façade – Right).

2. Investigation and Case Study of the TropiGlas Transparent Solar Panel

In addition to the power the TropiGlas panel generates, the glazing of the panel provides shielding from solar radiation and assists in improved thermal comfort within the building. This is achieved by incorporating luminophore materials into lamination interlayers and using a spectrally-selective thin-film active luminescent functionalized interlayer that provides photo-induced re-emission of the absorbed photons. Some of these luminescent material types used for interlayer functionalization that individually and in combinations are excited at different wavelengths include: Y_2O_3 co-activated with several rare-earth ions and sensitized with Yb_3^+, YPO_4:Nd, (Zn, Cd)S:Cu and ZnS:(Ag, Tm) **[5]**.

The light that falls on the surface of the panel is reflected and concentrated to the edges of the frame, by utilising these interlayers and a thin-film coating. On the edges of the frame are a number of 5 W $CuInSe_2$ thin film solar cell modules, cut to size, that convert the concentrated irradiation to electricity.

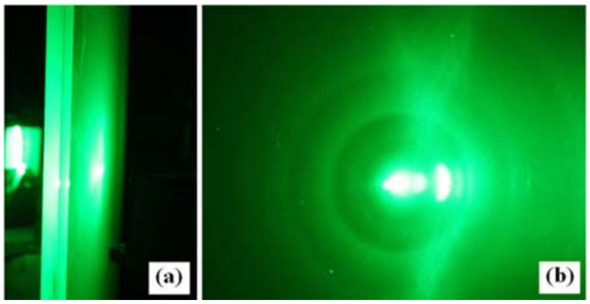

Figure 5: Light diffusion throughout the concentrator volume observed when illuminating a 200 x 200 mm sample with a narrow (1–2 mm) collimated beam from a 532 nm laser source at normal incidence. (a) Diffused light rays reaching the sample's edge; (b) circular fringes of Young type observed within the diffraction halo formed across the glass panel surface originate from the interference of multiple scattered and diffracted rays propagating inside glass panel structure which contains a lamination interlayer loaded with a quasi-random distribution of Luminophore particles **[5]**.

The sunlight striking the panel (Fig 6) is selectively split up into three distinctive electromagnetic regions, namely:

- Ultraviolet (UV) (wavelength of 10nm – 380nm)
- Visible Light (Vis) (wavelengths of 380nm – 700nm)
- Near, Medium and Far Infrared (NIR, MWIR & FIR) (wavelengths of 700nm – 1mm)

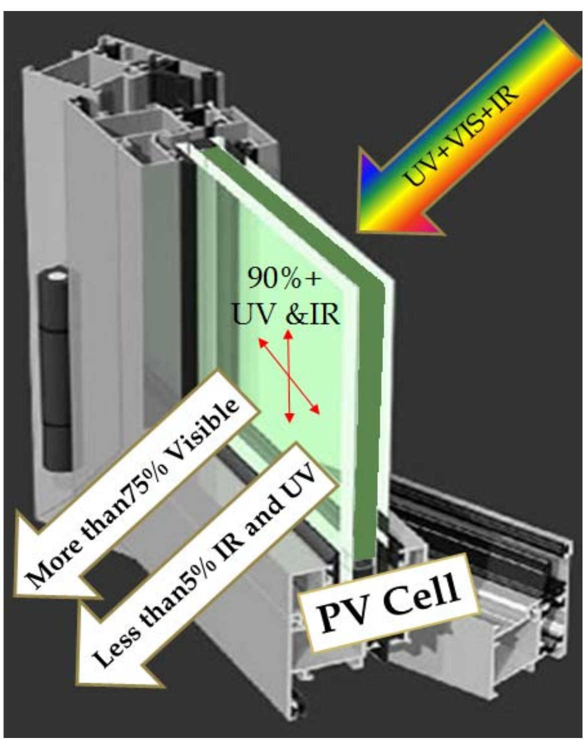

Figure 6: Operation and light characteristics of the transparent solar panel.

Of these 'three' wavelengths (UV, Vis and IR) only the visible spectrum is allowed to pass completely through the panel (Fig 6). The UV and IR wavelengths are reflected and refracted internally to the edges of the panel (Fig 7). As the surface area of the panel that the solar irradiation strikes is larger than the side walls where the solar irradiation is harvested, the waves are concentrated towards the walls of the panel. This approach achieves greater conversion of solar to electric energy using conventional solar cells located on the sides of the panel. However, this also causes the cells to operate at higher temperatures.

A newer 1x1m façade model has been developed by TropiGlas Technologies that not only concentrates the solar irradiation to the edges of the panel but utilises energy harvesting within the length of the panel. This has produced results of up to 40W/m^2 for standard irradiance on a horizontal surface.

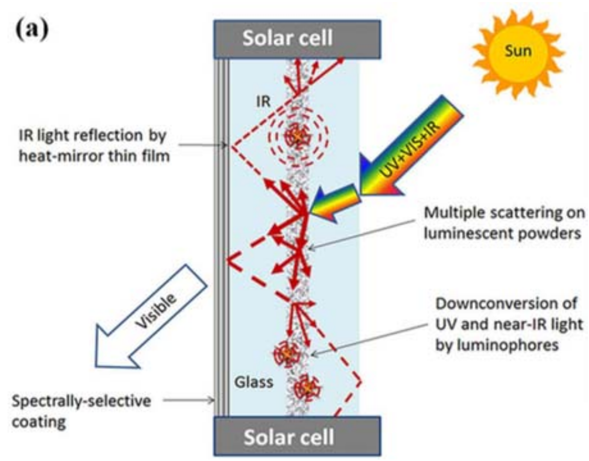

Figure 7: Internal light characteristics of the transparent solar panel **[5]**.

As seen in figure 8 and 9, more than 90% of the UV and IR waves are trapped within the panel's structure, being concentrated to the sides and rejected back into the atmosphere away from the inside of the building, providing possible HVAC energy savings.

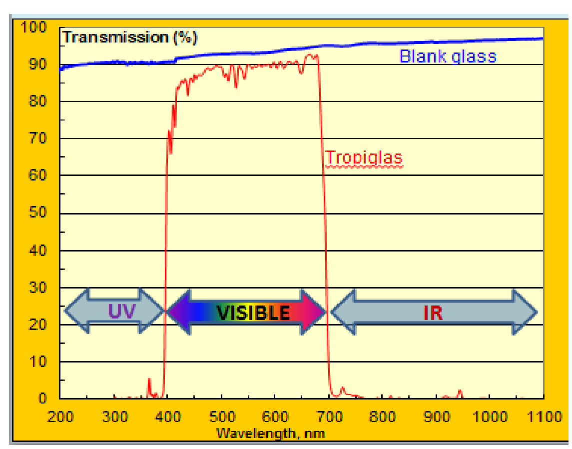

Figure 8: "Electromagnetic spectrum" simulation results of transparent solar panel [adapted from 5].

Further laboratory tests did show that more IR waves are allowed through the panel then initially designed for (Fig 9).

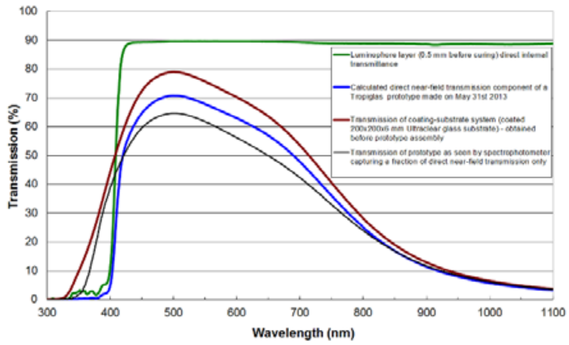

Figure 9: Measured electromagnetic spectrum results of transparent solar panel **[5]**.

There were initial concerns due to the fact that the solar panels were to be installed vertically. This meant that full direct irradiation at the optimal tilt (latitude degrees) was not possible. However the diffused and albedo irradiation that is present close to ground level does influence the radiation that strikes the panel, as depicted in figure 10.

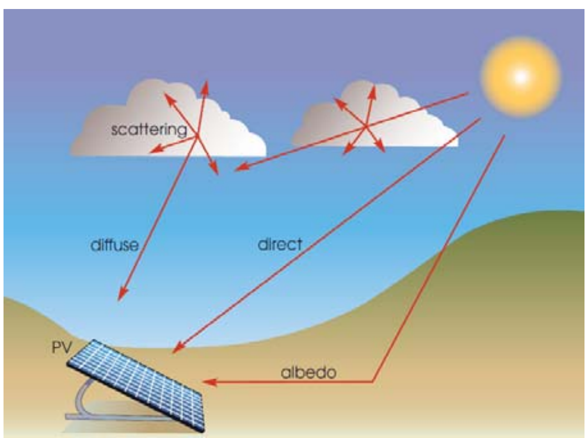

Figure 10: Direct, Diffused and Albedo Radiation **[13]**

Considering the installation of the vertical panel, as in the case with a window, and that not all the direct solar irradiation will fall on the panel. The sun path for South Africa was investigated. During a year the sun will be most high in the sky (highest solar noon) in summer and at a lower angle in winter (Fig 11). However due to the lower angle of the sun during the winter periods, the irradiation that falls on the vertical installed façade is not completely obscured by the building as in the summer months. The possible generation during winter, therefore actually increase slightly for the vertically (90°) installed solar façade.

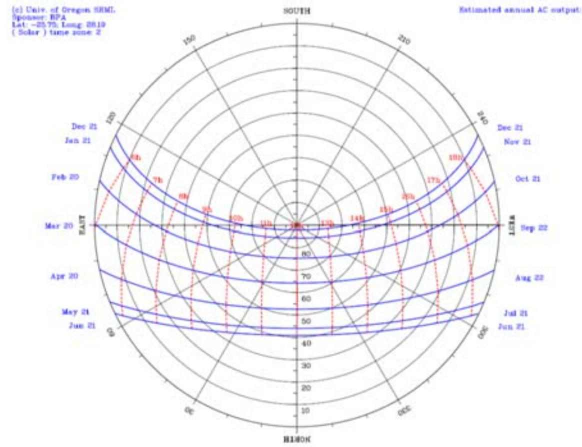
Figure 11: South Africa's Sun Path **[14]**

Therefore the amount of direct irradiation and power generation on a southern hemisphere, vertical - north facing solar façade increases slightly in winter when the son is at a lower angle to the horizon. Additional efficiency effects such as temperature of the panel, and climate conditions (rain/clouds) are taken into account. The less cloud cover and rain (clearness index) during winter and the cooler the cell, caused better efficiency and overall performance of the solar façade. The following theoretical conclusion can be drawn.

Due to the latitude of the fixed installation (S 24° [deg]) the annual solar irradiation graph in Figure 12 can theoretically be drawn with the top four bands in the figure representing the different tilted angles of 0,10,25,40° and the bell-shaped curve (no marker) the solar glass façade (angled at 90°). As the GCIS site had no physical irradiation measurements, NASA data [15] was firstly used to ascertain the viability of the installation.

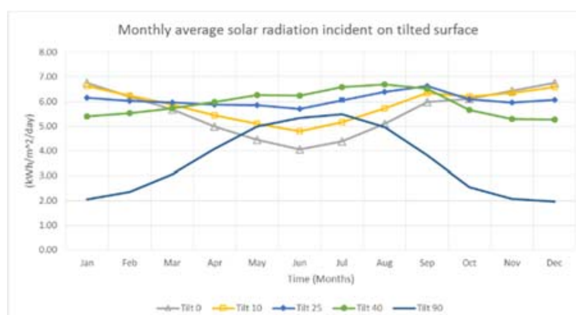

Figure 12: Ave. direct and diffused solar irradiation on a tilted surface. Graph obtained from data provided by NASA **[15]**

It can be seen from data obtained and from theoretical calculations that in the case of the installation at GCIS, the peak period for this installation would be the southern hemisphere winter months.

3. Results

For a 200x200mm (0.04m^2) a maximum power of 900mW is designed for by TropiGlas Technologies. During the winter months the average measured power in South Africa was 250mW (Sunlight hours).

The IV curve shown in Fig. 13 was measured during near-peak outdoor radiation (+-800W/m^2) with one vertically-placed 200by200mm panel, producing an open circuit voltage (V_{oc}) of 15.3V and short circuit current (I_{sc}) of 26mA.

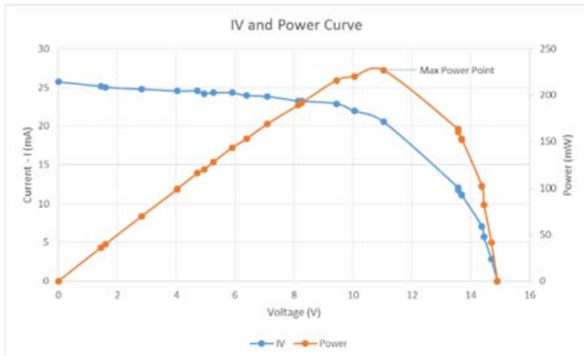

Figure 13: Current-Voltage and Power characteristics (IV & P Curve) of the transparent 200x200mm solar panel.

At the installation test site, the GCIS building management system is supplied power by 3 façades consisting of a total of 18, 200by200mm panels, it was recorded that the power generated for the month of May2014 was 770.04Wh.

Figure 14: TropiGlas three Installed Façades (3x6x200mm x 200mm solar panels) at GCIS building.

Figure 15 below shows the average daily V-I vs. Time profile for the one month.

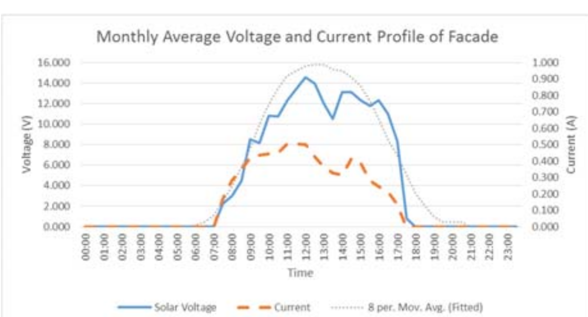

Figure 15: Voltage & Current curve vs. Time for the solar façade installed at the GCIS building.

As seen in the above figure, there is interference from possible sources of shading, from an arch on the building or another source that influences the system at an exact time of day.

Though the result obtained from practical tests was lower than theoretical results. The advancements in the panel construction and the ever increasing efficiency of solar cells, it is clear that any possible power that can be generated is a definite benefit, not previously utilised. A new 1-by-1 meter panel (Fig 16) will be tested and the results will be published at a later stage.

Figure 16: TropiGlas 1x1m transparent solar panel **[11]**.

Table I: Initial Specifications for the 1x1m TropiGlas panel

Standard Electrical Data:	
Maximum Peak Power Per m² [Watt]	40
Max. Power Voltage Per m² [V]	46
Max. Power Current Per m² [A]	0.9
Peak Open Circuit Voltage Per m² [V]	65-70
Peak Short Circuit Current Per m² [A]	0.9-1.0
U Value [W/(m2 K) (within an IGU unit)	1.8
Solar Heat Gain Coefficient (SHGC)	<0.41
Visible Light Transmission (VLT)	>70%
Light-to-Solar Gain	>1.7
Output Power Tolerance (due to components/assembly)	±5%

The above results reflect measurements reported by TropiGlas under laboratory conditions.

For a standard office building as in the example of the GCIS building, the minimum requirement of fenestration for a LEED **[16]** and SANS 10400 **[17]** green building is 15%. This means that the average window to floor area is 1-to-0.15, so an 100m^2 floor would give 15m^2 window surface which when utilizing the 1x1m panel would lead to peak power generation of up to 600Watts. With the GCIS building having a Gross Floor Area: 18 010m² **[18]** and following the same principle this would lead to a total possible generation of 108.06kWp, and if all the glass windows utilised the 1x1m TropiGlas technology this would lead to an annual generation of approximately 197.209MWh.

In a typical modern day skyscraper which are mostly covered with a glass exterior, such as The Empire State Building, it would be beneficial to use this technology. The Empire State building consists of more than 6,500 glass windows (195096m^2) **[19]** and a floor area of 208,879m^2 which could translate to +-8MWp (x10^6) of power, from a previously “unused” source of energy.

The 1x1m panel’s whole unit is totally inorganic and has an estimated lifetime in excess of 25 years. The costs for this panel including the frame and electrical connections is currently $400.00 **[11]** (This is prior to mass production).

Though the life time and reliability of solar panels have greatly improved as the technology has, the reliability in short term testing is hard to quantify. Of the many possible reliability impacts, the ones predicted to have the greatest effect on the panels will be the subjection to extreme environmental effects such as

- Wind stresses;
- Cyclic thermal stresses caused by day to night;
- Thermal stresses caused by summer and winter.

During the experiment, it was noted that panel shading was the primary cause of lower than expected results. Panel shading during the tests included, dark cloud cover and the biggest impact was caused by building shading, where there is no direct irradiation on the panels.

4. Conclusion

It can be clearly seen that this innovative technology has a clear advantage over the current solid (black) solar façades. This approach can assist spectrum selection and block harmful solar irradiation, which also assists in moderating heating and cooling of a building leading to further energy efficiency.

This technology can be used to generate electricity with no additional footprint, (area or real-estate), as currently needed when compared to roof top or awning type installations.

As seen in the example of the GCIS building in South Africa, if all glass material was made from this technology then 197MWh of electrical power could be generated.

Acknowledgement

Special thanks to TropiGlas Technologies, the manufacturers of this product. GrowthPoint Properties, for the use of their buildings to implement this project and Concius Consultants for their management of the large scale implementation of this project.

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