LOW CONCENTRATING PHOTOVOLTAIC GEOMETRY FOR RETROFITTING ONTO EUROPEAN BUILDING STOCK

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Abstract

The most appropriate Low Concentrating Photovoltaic (LCPV) technology suitable for European buildings located in mid-high latitudes under both maritime and continental climatic conditions has been identified as the Asymmetric Compound Parabolic Concentrator (ACPC). To date there is no published experimental data at different latitudes on the long-term performance of these systems at these latitudes nor how location would modify the optical characteristics of deployed systems. Previous theoretical research by the authors has demonstrated the superiority of the ACPC with this additional work experimentally confirming the robustness of the design. To investigate how seasonal and locational variations affect their measured technical performance 2 identical ACPC-LCPVs were installed, instrumented and monitored at two different climatic locations (Uxbridge, UK, and Vevey, Switzerland) from May 2020 to September 2020. A valid comparative performance investigation characterizing two geometrically equivalent ACPC based LCPV systems using real-life experimental data collected is presented in this paper. Locations at higher latitudes experience greater transverse angles more frequently compared to locations nearer the equator making ACPC geometries more appropriate than symmetrical concentrator configurations for building retrofit. This is shown in this paper over a latitudinal expanse of 31.35° for 4 separate locations; Tessalit (20.19° N, 1.00° E; Mali), Timimoun (28.03° N, 1.65° E; Algeria), Uxbridge (51.54° N, 0.48° E, UK) and Vevey (46.6° N, 6.84° E, Switzerland).

Keywords

Asymmetric Compound Parabolic Concentrating (ACPC), Compound Parabolic Concentrating (CPC), V-Trough and Buildings.

1. Introduction

Electricity is playing an increasingly important role in consumers' lives, and for an increasing number of households, it will be the primary source of energy for all of their day-to-day needs, including transportation, cooking, lighting etc. Electricity's reliability, accessibility and pricing are projected to become ever more important in all aspects of people's lives and well-being [1]. The buildings in the European Union account for approximately 40% of the total annual energy consumption and 36% Carbon Dioxide (CO_2) emissions [2]. Renewable energy generation technologies and energy efficiency are the only plausible solutions for fulfilling global energy demand for a sustainable economy, in the view of the current state of technology. Even though economies shrank under the pressure of the Covid-19 restrictions in 2020, clean energy sources like wind and solar Photovoltaic (PV) technologies continued to expand faster than the other renewable energy generation technologies. In 2020, the global installation capacities of wind and solar PV increased by 22.3% and 14% respectively [3]. Prices for solar PV modules have been variable since mid of 2020; especially mono- crystalline silicon solar modules which increased by 40% from August 2020 to November 2021 [4]. Supply chain disruptions, supply and demand imbalances, and levies imposed by various governments are the main causes of rising solar panel prices [4]. The economic recovery from the Covid-19 epidemic has begun, but it is uneven and prone to reverting to the pre-pandemic levels in terms of excessive carbon emissions. The change in gas trading markets from long term to spot contracts whilst improving the interconnectivity of the market means that supply and demand shocks in one region now has global implications for the cost of natural gas. The instabilities in global energy supply in 2022 confirms this point further. A new sustainable energy economy complying with net zero emissions is emerging because of policy initiatives, technological innovation, and the growing urgency of the need to address climate change by developing technologies for energy generation that don’t emit Greenhouse gases during operation.

In the EU and UK, buildings consume almost half of the total annual energy demand. To reduce the use of fossil fuels, PV systems have been deployed on building facades, windows, walls, and roofs. The ability to significantly minimize the cost of electricity generated from PV, is achievable by integrating specifically designed concentrating optical elements with PV panels. Under concentrated radiation, solar cells generate more energy per unit area enhancing their commercial viability. Concentrators with a geometric concentration ratio (C_g) of < 3x can harness a significant proportion of diffuse component of solar radiation without solar tracking. This makes them more attractive for installations onto buildings. The usable solar spectrum of a silicon solar cell is 400 nm to 1100 nm, and the remaining solar spectrum is converted into the heat accumulated on solar cells [5]. The heat generated from optical concentrators can be used to supply thermal energy demands. Although, the heat recovered from the concentrator may not be at the desired temperature, it can still supply preheated liquid for boilers and heat pumps displacing a significant amount of fossil fuels in several situations. Employing optical concentrators with higher geometric concentration ratios can easily deliver heat at 60 °C. However, higher operating cell temperatures can deteriorate the electrical efficiency of the solar PV modules [6]. Research by Rabl [7] reported that non-imaging concentrating optics are the most effective means of delivering fixed non-tracking solar energy collectors.

Prior to the discovery of non-imaging optical systems, it was accepted as fact that no useful concentration of solar radiation could be achieved without the use of an active tracking mechanism. Winston [8] describes the Compound Parabolic Concentrator (CPC) as an ‘ideal’ non-imaging light concentrator due to the unique optical properties of these systems. Non-imaging optics are not subject to the same constraints as imaging systems, enabling designs that can attain or almost achieve the maximum geometric concentration for a particular angle of view. The principle underlying the conceptualization of non-imaging optics considers the propagation of light terms based on energy flow patterns and/or phase space quantities. Non-imaging optical surfaces are designed to collect the extreme angular rays within the field of view instead of axial rays; these can still collect rays near the axis but do not focus them. Well-designed non-imaging systems can almost reach and in certain situations attain the thermodynamic limit for concentration making them ideal for building retrofit.

Several experts are exploring the possibility of substituting traditional flat PV panels with fixed Low Concentrating Photovoltaic (LCPV) systems for the building retrofit market [9–14]. A stationary asymmetric compound parabolic concentrator (ACPC) offers a wider range of ray acceptance angles as well as variable geometric concentration ratios as compared to symmetric LCPV geometric configurations [15]. Due to the asymmetricity of half acceptance angles, truncated ACPC reflectors are the most suitable designs to increase energy collection at higher latitudes. At these latitudes, seasonal variation of the Sun increases which implies a greater difference in solar zenith angles (θ_z) impacting the collectable annual energy. Due to the optical properties of the ACPC concentrator, for the purpose of analysis it is generally assumed that all rays, incident within the half acceptance angle are received at the absorber. This implies that the rays incident at angles beyond the half acceptance angle are rejected. A previous investigation by the authors [16] showed the effect of increased variability of the angles of incidence on the optical efficiency of the concentrator through ray trace simulations. Lu et al. [11] reported using phase change materials cooled mono-crystalline solar cells in conjunction with a truncated ACPC (2x) producing 10% more electrical energy than a concentrator with no heat sink at rear end. Li et al. [17] have studied the curtain wall based dielectric ACPC system for building integration through outdoor experiments in Chengdu, China. The results showed that the developed prototype generated a greater energy yield in winters than summers where it is more useful. Similarly, Xuan et al. [18] have studied the angular acceptances of a dielectric ACPC for building retrofit through indoor and outdoor experimentation conducted in Hefei. Indoor experiments have shown that the short circuit current generated by ACPC was 87% higher than a similarly sized non-concentrating PV panel over a range of angles of incidence. Outdoor experiments have demonstrated that the short circuit current generated by the prototype was 57% higher than a flat PV panel. Roshdan et al. [19] compared performance of an ACPC Photovoltaic-Thermal (PVT) hybrid systems deployed at different latitudes through numerical and limited in-lab investigations. Their numerical predictions have shown that ACPC PVT panels outperformed CPC PVT and Flat PV panels at locations such as London (UK) and Bergen (Norway), though the performance of CPC and ACPC PVTs was found to be comparable in Abu Dhabi. These studies highlighted the advantages of LCPV systems in terms of their higher electrical energy generation, the optimal usage of roof space and easily transformable designs. These publications and/or logical detections have demonstrated the potential technical superiority of the ACPC design for deployment at higher latitudes. However, it is important to understand and establish the long-time behavior of LCPV systems under realistic conditions to demonstrate the robustness of design, demonstrate repeatability and investigate empirically how seasonal or locational variations affect their measured technical performance.

This study compares the real-life performance of 2 identical LCPV systems installed at two different locations to investigate and characterise their performance in terms of optical efficiencies under realistic conditions. Additional laboratory work using a physical ACPC model operated under a solar simulator is also described. Extensive experimental results for two geometrically identical ACPC panels, one located in Uxbridge (UK) in northern maritime weather and the other in Vevey (Switzerland) exposed to a continental climate, have been used in conjunction with previously collected data [16,20]. Data was collected for 5 months at both outdoor test facilities under real life conditions. System performance indices such as generated energy output, performance ratio and optical efficiency are presented. A diagram of the strategic methodology outlining the new research undertaken, why it was carried out, how it was carried out and its evaluation is shown in Fig. 1. The methodology used was a synthesis of a differentiation and focus based strategic approach for further investigating the LCPVs.

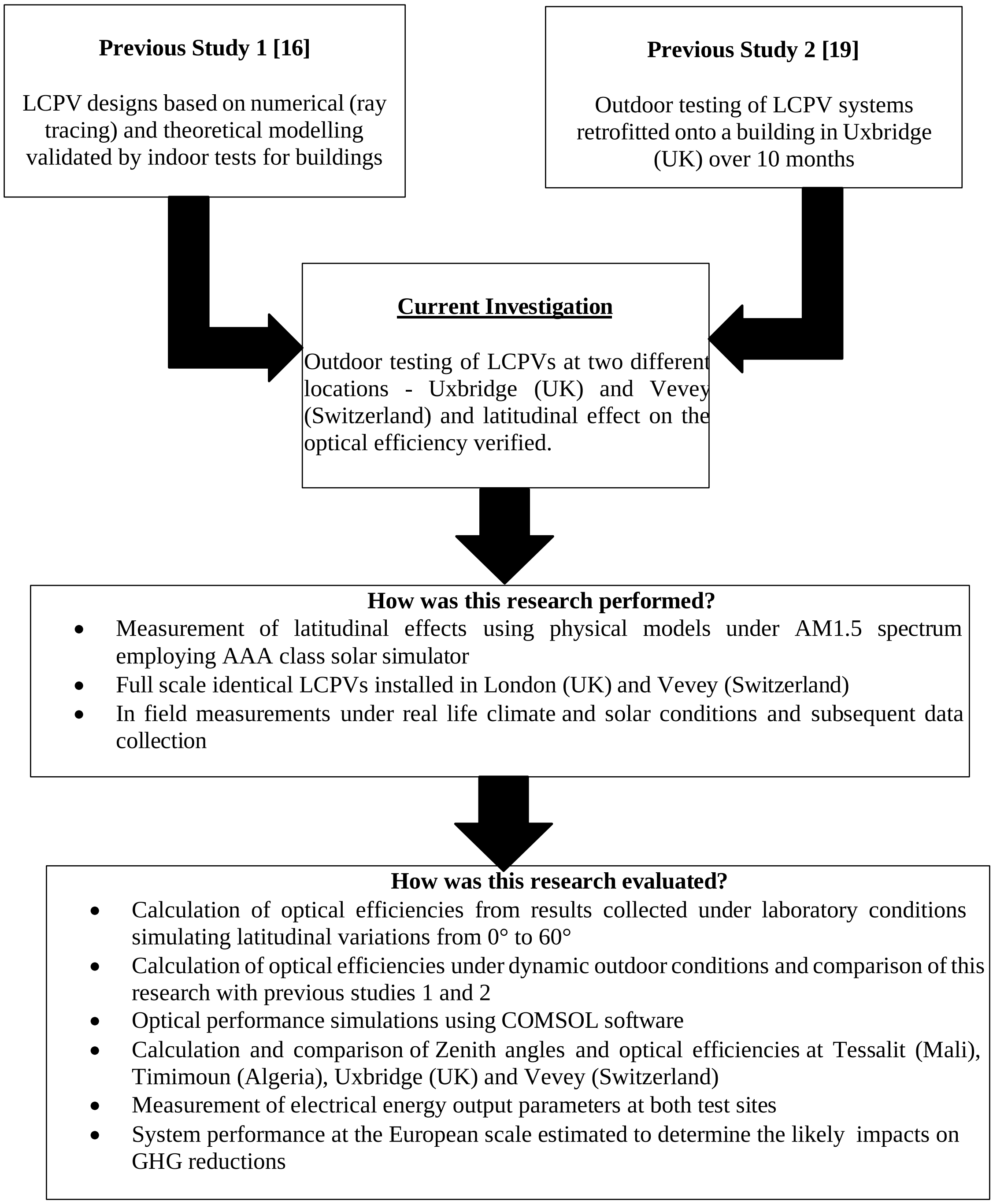
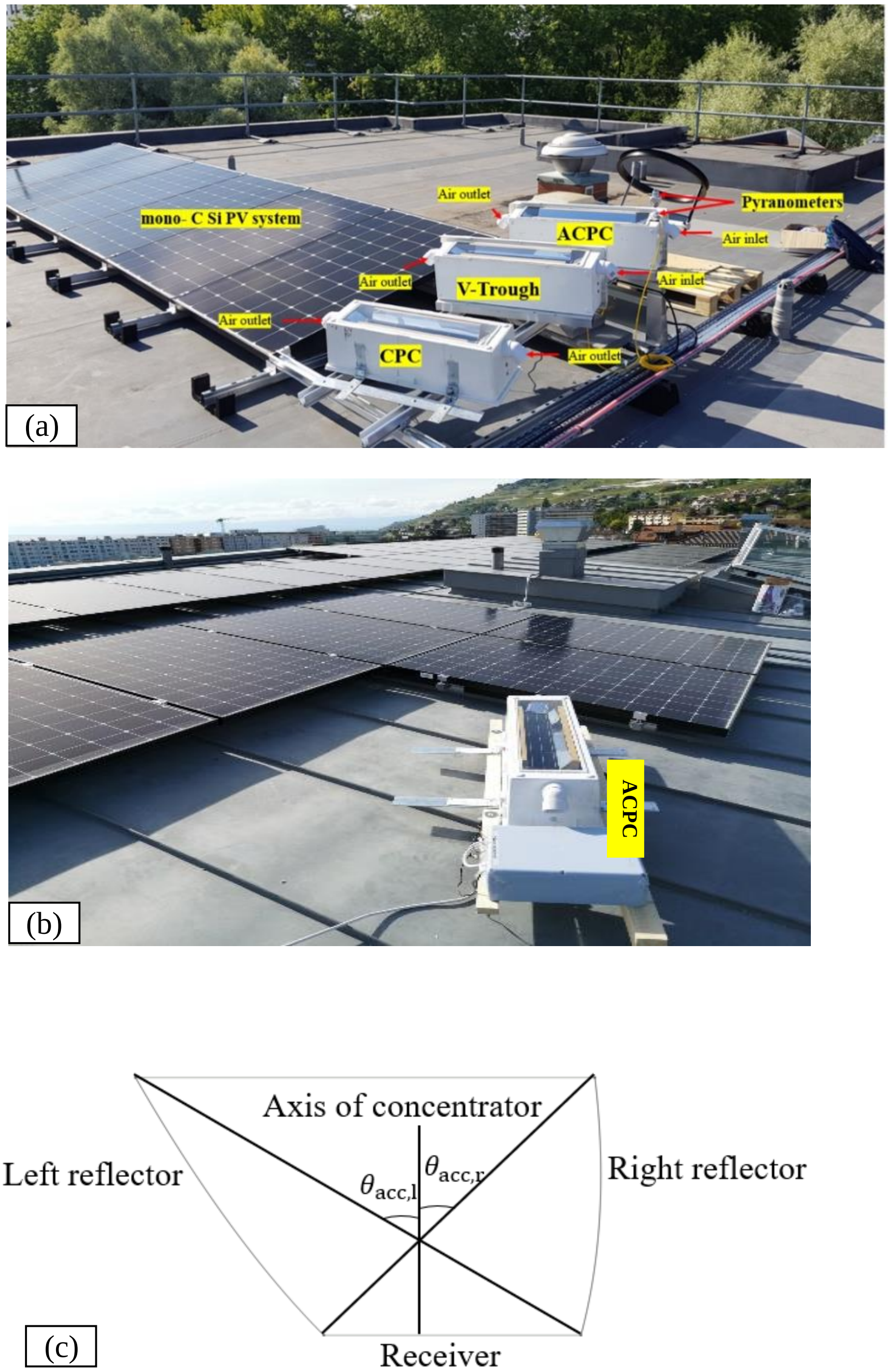


Fig. 1. Outline of strategic methodology of current investigation

From the two previous studies Parupudi et al [16, 19] it was clearly demonstrated that the ACPC design was the most effective choice of LCPV for mid to high latitudes at the test site used at Uxbridge. The designs, geometric features and performance of candidate LCPV systems are described in detail in these two studies which underpin the current research. The ACPC was the obvious candidate for this new research, which considered the latitudinal effects on the optical efficiency, and concludes the previous research providing further measured data from outdoor testing and is extrapolated to a wider range of latitudes.

Data was generated under steady state laboratory conditions by simulating a latitudinal variation of 0° to 60° using a physical ACPC laboratory model. Outdoor deployment testing and measurement provided further data on the dynamic operation of the ACPC. Further rational behind the deployment of the same design at a secondary location was that the durability of this design under different climatic conditions could be further empirically demonstrated in the field making the most efficient use of the resources and time available for this work. The outputs were evaluated using the collected data to determine the impact of latitude variations in several ways. The optical efficiency was calculated using the collected data from the laboratory and outdoor experimentation. Comparisons were made with the previous studies and electrical energy outputs and the performance ratio at both test sites calculated.

COMSOL software was used for the optical simulations. A calculation and comparison of Zenith angles and optical efficiencies at Timimoun (Algeria), Tessalit (Mali), Vevey (Switzerland and Uxbridge (UK) was undertaken. Finally, the impact of these systems at the European scale was estimated to determine the likely impacts on GHG reductions.


mono- C Si PV system
Air outlet
ACPC
Pyranometers
Air inlet
Air outlet
V-Trough
Air inlet
Air outlet
CPC
Air outlet
(a)
ACPC
(b)
Axis of concentrator
Left reflector
$\theta_{acc,l}$
$\theta_{acc,r}$
Right reflector
Receiver
(c)

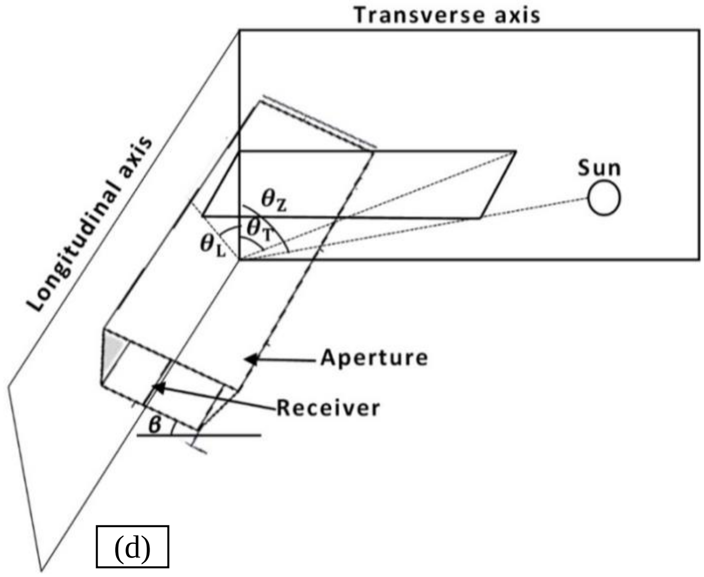


Fig. 2. View of the LCPVs being tested; (a) Uxbridge (UK) and (b) Vevey (Switzerland). (c) Cross sectional view of ACPC system where $\theta_{\mathrm{acc,l}}$ is the acceptance angle for left parabolic reflector and $\theta_{\mathrm{acc,r}}$ for right parabolic reflector and (d) schematic showing a sample LCPV collector tilted at an angle β under longitudinal (θ_L) and transverse (θ_T) projected angles of solar radiation

2. Design and construction of the LCPV panels

The design and manufacturing procedure of the ACPC modules employed in this study have been described in detail in [20]. Fig. 2 shows ACPC design at two sites: (*a*) Uxbridge (*b*) Vevey. In Uxbridge, three single troughs (one each of ACPC, CPC and V-trough geometry) and in Vevey, one single trough of ACPC panel was used. Aperture area of ACPC panel was 114.7 $mm^{2.}$

The geometric and physical details of the ACPC panels are summarized in Table 1 which is adapted from [20].

As seen in table 1, the only difference between the systems besides locations was the angle of tilt at which the systems were installed.

Table 1. Details of the ACPC panels tested.

Parameter	Uxbridge	Vevey
PV cell dimensions (mm)	75 x 490	75 x 490
Length of the concentrator (mm)	500	500
Full height geometric concentration ratio	2.82	2.82
Truncation ratio	1/3	1/3
Geometric concentration ratio after truncation	1.53	1.53
Half acceptance angles (°)	0, 60	0, 60
Angle of tilt (°)	10	5
Latitude and longitude	51.5 °N, 0.47 °W	46.4 °N, 6.8 °E

Single troughs in which solar PV cells were cooled by ambient air that passed naturally through a channel located underneath the solar cells were used. The highest monthly average temperature of solar cells during the months of June, July and August was recorded to be 33 °C in Uxbridge. However, if several of such troughs cooled by the same air passing from one trough to another, the cell temperature is likely to shoot much higher, which will have detrimental effect on the cells' power conversion efficiency. The measured average temperature of panel was < 40 C during the monitoring period. In present study, the cell efficiency was not significantly impacted because a low cell temperature was maintained by comparatively cooler ambient air in London. The increased concentration of solar radiation easily compensated for this factor. However, this can be an issue in hotter/warmer environments requiring well designed cell cooling systems. Standard OAI Trisol Class AAA solar simulator able to deliver AM1.5G and spectral match from 400nm to 1100nm in 100nm wavelength increment with a temporal distribution of <0.5% and spatial non-uniformity of < ± 2% was used. The half collimation angle of the simulator is better than < ±2%.

3. Global and diffuse solar irradiation at the outdoor test facilities

The monthly averaged global solar irradiation (I_G), diffuse solar irradiation (I_d) and average diurnal ambient temperature (T_{amb}) for test locations, Uxbridge and Vevey, are shown in Fig.3.

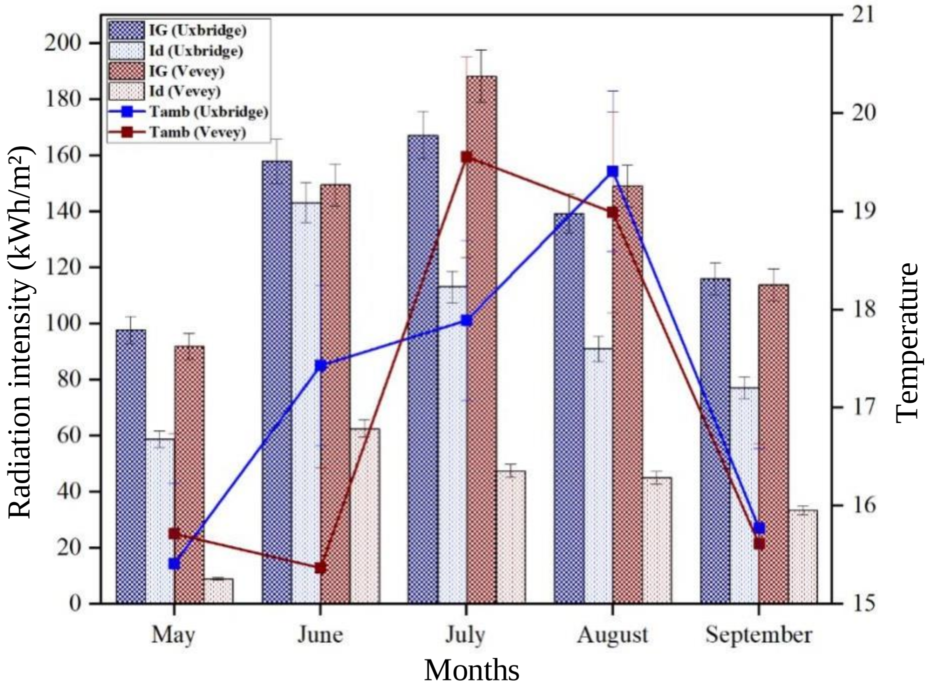


Fig. 3. The monthly averaged global solar radiation (I_G), diffuse solar radiation (I_d), and the ambient temperature (T_{amb}) over the monitored period at outdoor test facilities in Uxbridge (UK) and Vevey (Switzerland) in the year 2020.

The meteorological data of Vevey was adapted from the Solcast real-time weather database [21]. The quarter-hourly data collected was averaged over an hourly period and subsequently analysed. The data presented in Fig. 3 was averaged over diurnal hours during the monitoring period between May 2020 to September 2020. It is observed that Vevey received a relatively a higher proportion of beam radiation compared to Uxbridge. The diffuse component of incident solar radiation at Uxbridge is noticeably higher than Vevey which has a noticeably different patterns in incident solar radiation.

4. Optical performances of the developed LCPV panels

The optical efficiency of the LCPV panels can be determined by the longitudinal (θ_L) and transverse (θ_T) angles of incidence of beam solar radiation, as described by Hertel et al. [21].

The optical efficiency (η_{opt}) of concentrating systems is a product of the optical efficiency at normal incidence and the biaxial modification factors, given by Eqs. 1 and 2 [22].

$$\eta_{opt}\ (\theta_i) = \eta_n\ K(\theta_L, \theta_T) \tag{1}$$

$$K(\theta_L, \theta_T) \approx K_L(\theta_L, 0)\ K_T(0, \theta_T) \tag{2}$$

Where, $K(\theta_L, \theta_T)$ is the function used to calculate the biaxial modification factors; K_L and K_T respectively represent the longitudinal and transverse incidence angle modifiers; θ_i, is the angle of incidence of beam radiation; η_{opt} is the overall optical efficiency of the concentrator and η_n is the optical efficiency at normal incidence for a single glass cover concentrator.

The relationship between the actual, longitudinal (θ_L) and transverse (θ_T) angles of incidence is calculated using Eq. 3 [23].

$$\tan^2 \theta_i = \tan^2 \theta_T + \tan^2 \theta_L \tag{3}$$

The optical efficiency measurements of the developed LCPV panels were performed using OSRAM SFH 203 P photodiodes with a OAI Trisol flash solar simulator. The validated optical performance of the LCPV panels under investigation was calculated for transverse angles of incidence ranging from 0° to 60°. A tilting table was used to mimic the diurnal and seasonal passage of the Sun. The daily variation was simulated by modifying the longitudinal axis. The seasonal variation was replicated to provide further experimental data on modifying the transverse axis. Fig. 4 shows the variation of measured optical efficiencies along the projected longitudinal and transverse angles of incidence.

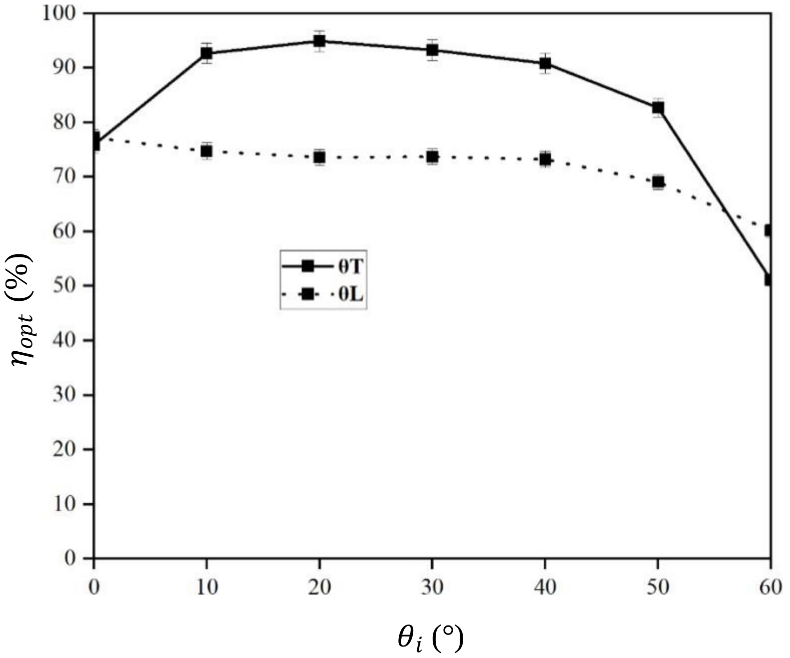


Fig. 4. The measured optical efficiency at various transverse (θ_T) and longitudinal (θ_L) [16] angles of incidence of the developed ACPC module shown respectively as solid and dotted line.

These were compared to the results of ACPC performance in London published earlier by the authors in Parupudi at al. [16] and further information was provided through measurement~~s~~ of the longitudinal angles. From Fig. 4, the optical performance of ACPC based LCPV systems deployed at different locations is more dependent on latitudinal variations.

The ACPC panel achieved lower optical efficiencies when θ_L was varied 0° to 60° having the greatest decrease in performance from 77.2% to 60.1%. The ACPC panel achieved a higher optical efficiency over a wider range of the transverse angles of incidence. The results show the transverse angle has a greater impact on the optical efficiency than the longitudinal angle. This phenomenon should evidently be considered while designing standalone LCPV geometric configurations.

5. Zenith angle and achievable optical efficiencies of the developed LCPV systems

The angle between the vertical direction and the direction of beam solar radiation on a horizontal surface is the zenith angle and is calculated using Eq. 4 – Eq. 10 [24].

$$\theta_z = cos^{-1} (cos\phi \, cos \, \delta \, cos \, \omega + sin\phi \, sin \, \delta) \tag{4}$$

Where ω and δ are the hour angle and declination angle respectively, which were calculated using Eq. 5 and Eq. 6.

$$\omega = (t_{true} - 12.00) \times 15 \tag{5}$$

$$\delta = 23.45 \, sin \, [\frac{360}{365} (284 + n)] \tag{6}$$

Where t_{true} is solar time determined based on the movement of the Sun and calculated using Eq. 7 and Eq. 8 [25].

$$t_{true} = t_{local\ mean} + t_{offset} \tag{7}$$

$$t_{offset} = EOT - 4L + 60 \, t_{zone} \tag{8}$$

where $t_{local\ mean}$ indicates the local time, L is the longitude of the location (East positive, West negative), t_{zone} is the number of hours of the local time zone from GMT (East positive, West negative) and EOT is the equation of time expressed in minutes and is calculated using Eq. 9 and Eq. 10.

$$EOT = 229.2(0.000075 + 0.001868\, cos\beta - 0.032077\, sin\beta - 0.014615\, cos2\beta - 0.04089\, sin2\beta) \quad (9)$$

$$\beta = (n - 1)\frac{360}{365} \quad (10)$$

where function β is calculated using n, the day number.

Estimated monthly variations of the solar zenith angle (θ_z) at solar noon and achievable optical efficiencies of the developed LCPV panels installed in Uxbridge and Vevey were calculated and are shown in Fig. 5.

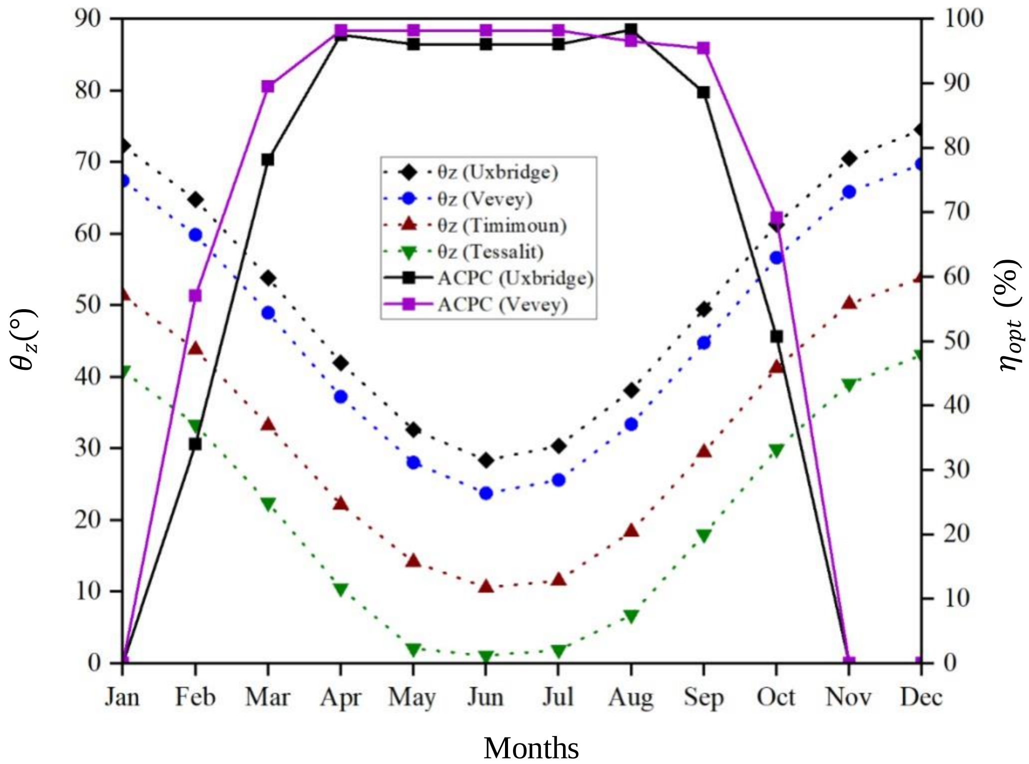


Fig. 5. The predicted monthly solar zenith angles (θ_z) occurring at solar noon at Uxbridge (51.54° N, 0.48° E), Vevey (46.6° N, 6.84° E), Timimoun (28.03° N, 1.65° E; Algeria), Tessalit (20.19° N, 1.00° E; Mali) and panels' optical efficiencies.

In the northern hemisphere, the solar zenith angle (θ_z), reaches its minimum in June and maximum in December on the summer solstice and winter solstice respectively. Annual θ_z in Uxbridge varies between 32° and 75° and in Vevey between 28° to 68° on the solstices respectively. The annual variation of θ_z at solar noon in Timimoun (Algeria) and Tessalit

(Mali) was predicted using the same method from the results collected from the laboratory-based experiments. Predictions show that in Timimoun, θ_z varies between 10° to 51° whereas in Tessalit it ranges from 1° to 40° on the solstices. It can be seen that the variation of θ_z over the year is larger in Uxbridge (43°) than that of Vevey (40°), Timimoun (41°) and Tessalit (39°). From Fig. 5, it is observed that Timimoun and Tessalit experience $\theta_z <$ 30° for longer periods compared to the locations at higher latitudes. This indicates that concentrators designed with half acceptance angles ≤ 30° produce more electrical energy over the course of a year at Timimoun and Tessalit. These results clearly show that latitudinal effects which impact θ_z must be considered at the design stage to ensure maximum performance for building retrofit using LCPV systems.

The half acceptance angle of the ACPC based LCPV panels were 0° and 60°. During the period from March to September, Uxbridge's transverse projection angle varies between 19° and 62°. Peak performance under the UK climate is seen during this time period. The ACPC concentrator installed in Vevey achieved a higher optical efficiency than the ACPC concentrator deployed in Uxbridge from March 2020 to September 2020. During this time period, the incident θ_T of beam solar radiation was less than the θ_{acc} for the ACPC system thus all incident rays were accepted. During the same time period, θ_T of Vevey varied between 13° and 57°. Clearly, the period between March to September yields the highest optical performance for the ACPC concentrator; see Fig. 6. The influence of latitude is clearly shown in the extended collection period of the system located at Vevey. The impact of θ_T on the optical efficiency on ACPC with different geometric concentration ratios was predicted and the results are shown in Fig. 6.

Fig. 6 illustrates data predicted by bespoke COMSOL Multiphysics based ray optics model, results were collected at 10° intervals because the half acceptance angle of the concentrators is 0° and 60°. In Fig. 6, the four ACPCs have similar geometry with the exception of concentration levels and truncation levels.

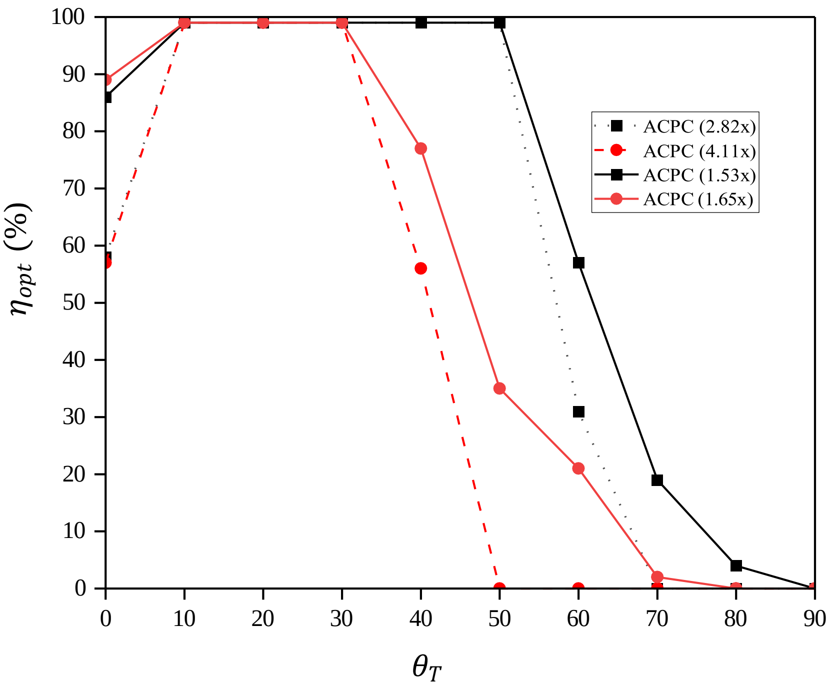


Fig. 6. The predicted optical efficiencies of full height and truncated ACPC concentrator at various angles of incidence.

The predicted optical efficiencies of the ACPC geometric configurations at various angles of incidence are clearly observed in Fig. 6. The optical simulations of the full height ACPC concentrators with C_g of 2.82x and 4.12x was undertaken using the ray optics module in the COMSOL Multiphysics software package. These concentrators were then truncated to 1/3rd of their full height and further optical simulations performed. A detailed description of the design, boundary conditions, and the validated optical performance of the ACPC concentrator with C_g of 1.53x was published previously [16]. From Fig. 6, it is seen that the full height ACPC concentrator with C_g of 2.82x achieved a higher optical efficiency than the concentrator with C_g of 4.12x over the range of angles of incidence shown. After truncation, the optical efficiency of both concentrators was higher than the full height systems even though a proportionate reduction in C_g occurred. Furthermore, the ACPC with C_g of 1.53x achieved a higher optical efficiency than the ACPC with C_g of 1.65x. The LCPV systems with lower C_g can maximize the energy collection at higher latitudes as they achieve higher optical efficiencies over a wider range of incidence angles. The yearly collectible solar irradiation by ACPC panel for relevant transverse angles of incidence of beam radiation at solar noon at Uxbridge and Vevey are shown in Fig. 7.

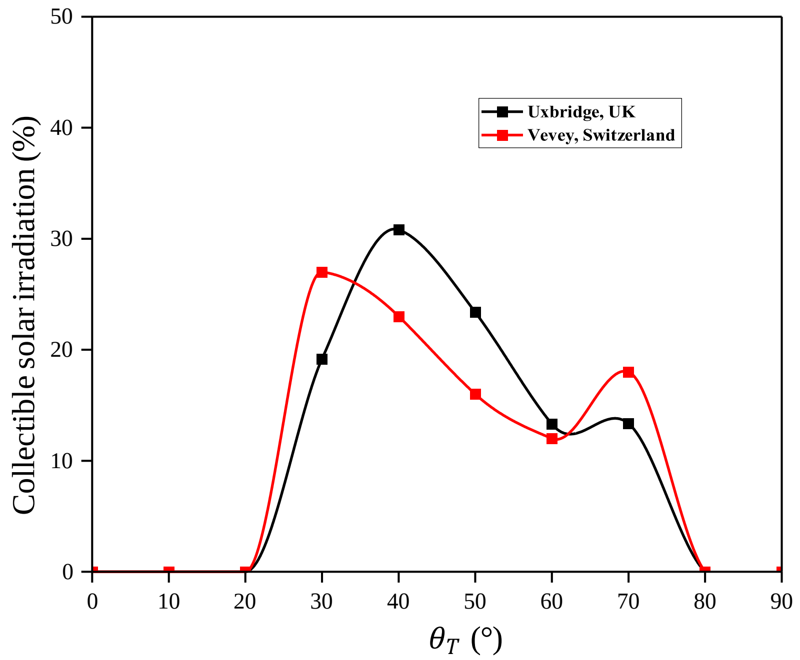


Fig. 7. Transverse Angle and the predicted yearly collectible solar irradiation at solar noon.

As shown by Fig. 7 the projected transverse incidence angle is significant as it is the angle at which direct irradiation in stationary concentrators is accepted or rejected. Solar radiation data of a typical metrological year of 2 sites were adopted from Energy Plus weather datasets [26] to understand the impact of seasonal variations of solar irradiation on the performance of the LCPV systems over longer periods of time. The solar irradiation distribution of Vevey shows two distinct spikes during the solstice months, whereas the winter peak is hardly visible for Uxbridge, see Fig. 7. This is due to larger solar zenith angle subtended by direct radiation during the winter months in Uxbridge, which increases the absorption of direct radiation by the atmosphere. It's clear from Fig. 7 that for the two locations studied it will be advisable to have smaller half acceptance angles for East-West orientated ACPC panels to maximise the collected solar irradiation as the yearly collectible solar irradiation is also asymmetric.

6. Generated energy output and Performance ratio

The measured electrical energy output of the developed LCPV panels is shown in Fig. 8. It should be noted that the efficiency of the solar cells used at STC was 17.62%. The ACPC panel deployed at Vevey generated 174 kWh/m^2 during the monitored period.

The ACPC panel generated 143 kWh/m^2 at Uxbridge. During the monitoring period, the variability of the projected transverse angle remained within the acceptance range of the ACPC concentrator. A higher beam solar irradiation resulted in a higher energy yield at Vevey. Furthermore, the ACPC concentrator at Vevey generated a higher energy output as compared to the ACPC concentrator at Uxbridge, where the sky was overcast for significantly larger number of sunshine hours than Vevey. This result clearly supports the deployment of ACPC panels on Europe's existing building stock in locations experiencing a higher cloud cover and are located at latitudes of testing. These results compared well with those published by Roshdan et al. [19] who have reported ACPC PVT producing 50% higher energy in high latitude countries (UK, Norway). The information provided by Fig. 5 showed that the best performance of the ACPC was achieved when the transverse projected angle is lower than the half acceptance angle incident on the aperture of concentrator during the months of March and October. It is worth mentioning Fig. 3 presents the monthly averaged global solar radiation (I_G) and diffuse solar radiation (I_d) over the monitored period at outdoor test facilities in Uxbridge (UK) and Vevey (Switzerland) in the year 2020. The data shown in Fig. 8 for electrical energy produced and performance ratio should be read in conjunction with that in Fig. 3.

The performance ratio (PR), a dimensionless number indicating the overall effect of losses on the system output, was determined using Eq. 11.

$$\mathrm{PR} = \frac{\mathrm{Y_{Ar}}}{\mathrm{Y_R}} \tag{11}$$

Where $\mathrm{Y_{Ar}}$ and $\mathrm{Y_R}$ are array yield and reference yield respectively. The measured monthly performance ratios of the developed LCPV panels are shown in Fig. 8.

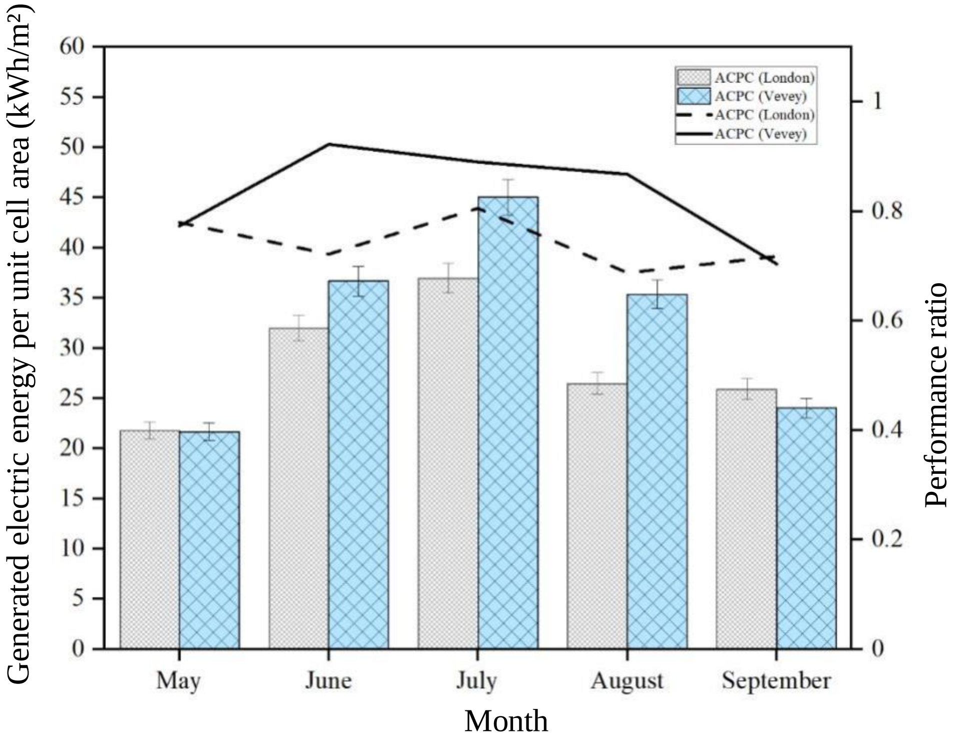


Fig. 8. Performance ratio and the generated energy output per unit cell area of the LCPVs studied. Note: the primary y-axis is for bars which show generated electric energy per unit cell area and the secondary y-axis is for solid and dashed lines showing performance ratio.

Fig. 8 shows a comparison in output between the two systems with the same concentration ratio of 1.53x (after truncation) located in Uxbridge (UK) and Vevey (Switzerland). The difference in performance is caused by the combined effect of factors such as latitude, local ambient and solar climates and tilt angles.

From May 2020 to September 2020, the ACPC concentrator at Vevey generated more energy with an average PR of 0.83. The average PR of the ACPC concentrator installed in Uxbridge was 0.74 over the same time period. The ACPC module deployed in Vevey achieved a higher PR as compared to that for the ACPC panel deployed in Uxbridge as observed in Fig. 8. Furthermore, the PR of the ACPC panels deployed in Uxbridge and Vevey were compared to Compound Parabolic Concentrator (CPC) and a V-trough concentrator developed and tested by the authors in [20]. The CPC module only achieved a higher optical performance around the summer solstice where the ACPC maintains its performance advantage throughout the year.

By 2030, the EU has proposed a set objective of at least a 40% reduction in domestic Green House Gas (GHG) emissions compared to 1990 levels. To achieve the goal of the Paris Agreement on GHG emissions, the EU parliament voted to increase clean energy generation to 35% by 2030. Consequently, the renewable energy generation capacity would need to be in the range of 1200 to 1250 TWh to achieve this target. Solar power is expected to contribute 380 TWh, requiring an increase the solar PV installation capacity particularly rooftop installations to 350 GWp by 2030 [27]. However, LCPV technology would require a total installed capacity of roughly 237 GW_p to generate 380 TWh of electricity.

7. Conclusion

Stationary LCPV panels were designed, fabricated and simultaneously tested under real-life climatic conditions at Uxbridge (UK, northern maritime climatic conditions) and Vevey (Switzerland, continental climatic conditions) in conjunction with commercially available mono-crystalline silicon solar cells. The secondary outdoor test at a different latitude confirmed the previous results simultaneously demonstrating the repeatability and robustness of the ACPC design. At both test facilities, the transverse projection distribution function based on collectible energy showed an asymmetrical trend, demonstrating that the performance characteristics of reflector geometries vary with latitude. It has been shown that the ACPC configuration yields the best optical performance at the latitudes where the seasonal variation of the Sun is significant such as the UK. This new investigation has shown the improvement in optical efficiency with an increase in the amount of beam radiation and decrease in latitude. The ACPC based LCPV panel achieved the highest performance ratio of 0.84 at Vevey whereas the ACPC, CPC and V-Trough panels deployed in Uxbridge had performance ratios of 0.74, 0.72 and 0.63 respectively. Results clearly show that latitudinal effects which impact zenith angle must be considered at the design stage to ensure maximum performance for building retrofit using LCPV systems. Consequently, from the results presented truncated ACPC based stationary LCPV panels ($C_g < 3$) have been recommended for installation at higher latitudes for building retrofit. These panels can be easily mounted on the same supporting frame as that used for flat PV panels making these attractive for building retrofit purposes.

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Abbreviations

ACPC Asymmetric Compound Parabolic Concentrator

CPC Compound Parabolic Concentrator

GHG Greenhouse Gas

LCPV Low Concentrating Photovoltaic

PV Photovoltaic

Nomenclature

C_g Geometric concentration ratio

EOT Equation of time

I_G Global solar irradiation (W/m^2)

I_D Diffuse solar irradiation (W/m^2)

L Longitude

K_L Longitudinal biaxial modification factor

K_T Transverse biaxial modification factor

η_{opt} Optical efficiency (%)

η_{η} Optical efficiency at normal incidence (%)

t_{true} Solar time

T_{amb} Average diurnal ambient temperature (°C)

Greek Symbols

β function for equation of time (deg)

θ_L Longitudinal angle of incidence (deg)

θ_T Transverse angle of incidence (deg)

θ_z Zenith angle (deg)

ω Hour angle

δ Declination angle (deg)

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