Applied Energy 300 (2021) 117412

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Long term performance analysis of low concentrating photovoltaic (LCPV) systems for building retrofit

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HIGHLIGHTS

- Three LCPV panels were fabricated and tested at Brunel's outdoor test facility.
- Performance indices such as energy output and payback period have been presented.
- LCPV systems were compared against the flat PV systems in terms of energy output.
- The best LCPV system for the UK's climate is presented.

ARTICLE INFO

Keywords:
Low concentrating photovoltaics (LCPV)
Asymmetric Compound Parabolic Concentrator (ACPC)
Compound Parabolic Concentrator (CPC)
V-Trough
Buildings
Diffuse radiation

ABSTRACT

Low concentrating photovoltaic (LCPV) systems offer viable solution for generating higher energy output per unit cell area compared to a typical flat PV panel, making them potential candidates for building retrofit. However, the best LCPV geometry for a given location is yet to be identified. The current study investigates the technical, economic and environmental feasibility of three geometrically equivalent LCPV designs installed at a building within Brunel University London (UK). The studied LCPV systems comprised of Asymmetric Compound Parabolic Concentrating (ACPC), Compound Parabolic Concentrating (CPC) and V-Trough optical concentrators with the post-truncation geometric concentration ratios of 1.53, 1.46, 1.40 respectively. The performances of the prototypes have been monitored every 15 min over 10 months and analyzed on hourly, daily, and monthly basis. Performance parameters such as reference yield, array yield, performance ratio, electrical conversion efficiency and the generated energy output per unit area have been derived and presented. Payback periods have been estimated in two separate scenarios. Measurements have showed that the ACPC integrated LCPV achieved the highest annual optical efficiency generating the highest amount of electrical energy per unit cell area of 246.2 kWh/m^2 compared to CPC-LCPV, V-Trough-LCPV and conventional flat modules which produced 224.6 kWh/m^2, 196.1 kWh/m^2 and 185.4 kWh/m^2 respectively. One particular conclusion of the study is that the ACPC based LCPVs perform better in locations where diffuse component of solar radiation is predominant as in the case of the UK. Consequently, ACPC based LCPV modules are recommended for the building retrofit in such locations.

1. Introduction

Buildings are responsible for one-third of the total energy consumption in Europe, are amongst the top energy consuming sectors and more than three quarters of existing buildings in Europe are over 50 years old [1]. Historically, buildings have not been constructed by considering energy efficiency and thermal comfort factors. Research into nearly Zero-Energy Buildings (NZEB) is becoming increasingly important to alleviate the impact of climate change. nZEBs have significantly reduced energy demand that locally deployed renewable energy systems are able to supply. Over the last decade, engineers and architects have learned the impact of their design choices and have begun to construct buildings that consume less energy using energy-efficient components and/or integrate renewable energy generation technologies for energy generation [2,3]. This is supported by European Union's Directive 2012/27/EU which encourages decarbonizing the buildings from generating clean electricity for powering their energy demand [4]. The UK government is supporting low carbon power generation through the Smart Export Guarantee to ensure that small scale electricity suppliers (i.e. households who have installed solar PV < 5 MW) will always be paid for any electricity exported to the grid [5].

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https://doi.org/10.1016/j.apenergy.2021.117412
Received 5 May 2021; Received in revised form 18 June 2021; Accepted 7 July 2021
Available online 17 July 2021

Nomenclature

A	area (m^2)
C	concentration ratio
d	day
E	energy (Wh)
h	hour (h)
I	irradiation (W/m^2)
T	temperature (°C)
W	width (mm)
Y	yield
y	year

Abbreviations

ACPC	asymmetric compound parabolic concentrator
amorphous-Si	amorphous silicon
CPC	compound parabolic concentrator
CO_2	carbon dioxide
CH_4	methane
EVA	ethylene vinyl acetate
LCPV	low concentrating photovoltaics
MPPT	maximum power point tracker
m- C Si	mono crystalline silicon
N_2O	nitrous oxide
poly-C Si	poly crystalline silicon
PR	performance ratio
PV	photovoltaic

Greek symbol

η	efficiency
θ	angle
ϕ	profile angle

Subscripts

Ar	array
acc	acceptance
amb	ambient
D	diffuse
dc	direct current
e	electrical
f	final
G	global
g	geometric
i	incidence
lt	left
p	peak
R	reference
r	receiver
rt	right
T	tough
t	total

Since at least 75% of the existing buildings in the UK will be still standing in 2050 [1], easily fit-able solar photovoltaic (PV) modules are being increasingly proposed to achieve a low carbon intensive building stock [6]. Deploying roof mounted or wall mounted PV modules additionally reduces transmission losses (thermal) when the generated energy is locally consumed.

Conventional non-concentrating flat PV panels cannot meet the total energy demand of a typical building, domestic or other, due to a limited power/cell area ratio and a narrow mounting area available on roof and/or walls. Optical concentrators can reduce the high surface area requirements of flat PV panels by increasing the availability of solar radiation on the surface of the solar cells, thereby increasing the energy output. Those with geometric concentration ratio (C_g) > 10 require to track the sun which increases capital, complexity of operation and maintenance costs and therefore cannot be easily installed on the rooftop of a building [7]. Furthermore, these systems can only be installed in the regions experiencing high beam component of solar radiation. On the other hand, low concentrating systems with $C_g < 10$ are simple in design requiring nil or minimal solar tracking making them suitable to develop LCPV panels. Additionally, LCPV with $C_g < 3$ can harness both beam and a significant proportion of diffuse component of solar radiation (depending on concentration ratio) making them suitable for maritime and semi-maritime climates such as the UK [8].

Despite decades of research into solar cells for the non-concentrating and concentrating solar PV technologies, LCPVs entered the market in mid-2000s [9]. Although a considerable market growth in large scale installations (MW level) has been recorded in recent years, LCPVs still represent a relatively new technology as compared to conventional flat PV panels. Low uptake can be attributed to a lack of reliable data on the LCPVs' technical and economic performance.

Baig et al. [10] reported a three-dimensional CPC (3.6x), which produced 2.67 times greater power as opposed to a comparable flat PV panel. Sangani et al. [11] reported a 44% higher energy output by a seasonally tracked V-Trough integrated PV panel (2x) than a flat PV panel. Mallick et al. [12,13] have experimentally characterized ACPC integrated PV modules producing 62% greater power than a flat PV panel. Whilst these studies have highlighted the advantages LCPV systems offer in terms of higher electrical conversion efficiency, the effective usage of roof space and easily transformable designs to maintain the module temperature, these are limited to lab scale experiments failing to report any long-term performance data collected under real-life climate and solar conditions, which is critical to validate the superior performance promise of LCPV systems.

This study compares the real-life performance of three in-house developed low concentrating PV (LCPV) technologies considered as potential candidates for building application (new-build or retrofit). Systems have been tested outdoors for 10 months at Brunel's outdoor test facility. Regardless of the progress achieved in LCPV technologies reported in the literature, this study is unique in that a reliable comparative performance assessment based on the data obtained from real life outdoor experiments is yet to be published. System performance indices such as generated energy have been measured and payback period estimated using realistic interfering factors. LCPVs have been compared among themselves as well as with an accompanying flat PV panel system. The paper clearly identifies the best LCPV technology for the UK's climate characterised by partially cloudy sky for a significant sunshine hours per year. The results are valid for several other global locations

2. Design and construction of the LCPV panels

Ray trace models have been developed in COMSOL MULTIPHYSICS to predict the angular acceptance of the different geometries. The parametric equations used to design the reflectors of CPC and ACPC panels [14] are described in Eqs. (1) and (2). A V-Trough concentrator consists of two flat reflector profiles that are inclined at an angle ($90^{\circ} + \theta_T$) to the axis normal to the either sides receiver as shown in Fig. 1.

$$y = \frac{2W_r(1 + sin\theta_{acc})sin(\phi - \theta_{acc})}{1 - cos\phi} - \frac{W_r}{2} \quad (1)$$

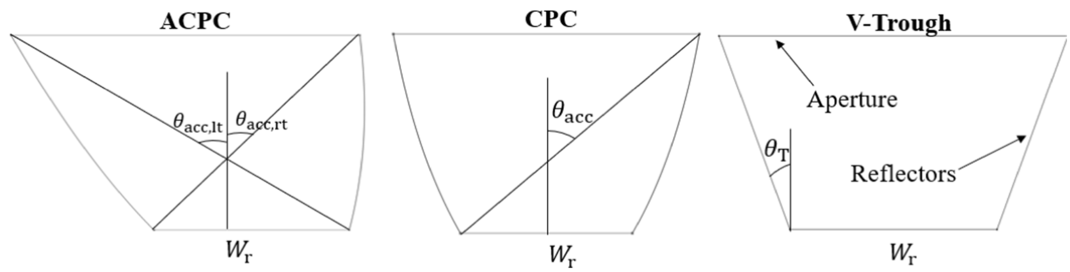

Fig. 1. Cross sectional view of the optical concentrator geometries studied.

$$Z = \frac{2W_r(1 + sin\theta_{acc})cos(\phi - \theta_{acc})}{1 - cos\phi} \quad (2)$$

θ_{acc} is the half acceptance angle, W_r is the receiver width, and ϕ is the profile angle whose value vary as $2\theta_{acc} \le \phi \le \pi/2 + \theta_{acc}$.

Three concentrator geometries designed for illuminating 75 mm wide PV cells were designed to have a concentration ratio varying between 1.4 and 1.53. For example, a full height ACPC concentrator with a full-height geometric concentration ratio (C_g) of 2.82 was truncated to one-third of its height resulting into a final C_g of 1.53, see Fig. 1(a). The ACPC reflectors with the half acceptance angles of 0° and 60° for the left ($\theta_{acc,\ lt}$) and right ($\theta_{acc,\ rt}$) reflectors were considered respectively. A CPC with a half acceptance angle of (θ_{acc}) of 30° and $C_g = 2$ truncated to one-third of its full height with a resulting final C_g of 1.46, shown in Fig. 1(b), and a V-Trough concentrator with C_g of 1.40 and trough angle (θ_T) of 20°, shown in Fig. 1(c), were studied as well. The receiver width (W_r) of each concentrator was kept at 75 mm. The details of the concentrator geometries are detailed in Table 1.

The substrate walls for reflective sides with specific profiles were manufactured on a CNC milling machine from high-density polyurethane board. MIRO-SILVER 4200 AG [15] sheets with a total reflectivity of 0.98 in the visible range were glued to the machined substrate surfaces to form the walls of the concentrators. The transmittance of the glass cover depends on the radiation wavelength, the angle of incidence of solar radiation and its thickness. A glass with low ferric oxide absorbs less solar energy incident on its surface [16]. Therefore, a 3 mm thick low iron glass cover was used.

Commercially available Aoxuan 5BB mono-crystalline silicon (m-C Si) PV cells [17] were cut to 120 mm × 75 mm using a rotary cutter. Each LCPV panel consisted of 4 such solar cells connected in series. Cells were encapsulated using Ethylene Vinyl Acetate (EVA) and placed on the copper base plate with a thermal interface material sandwiched between them. A heat sink made from rectangular copper channel was located on the underside of the copper base plate. Any air gap between the EVA created due to the presence of the tabbing wire and the thermal interface material was reduced by using a thermally conducting paste. A cross-sectional view of a typical LCPV panel developed is shown in Fig. 2.

3. The PV system

The developed LCPV panels were installed at the outdoor test facility at the Brunel University London in Uxbridge (UK) located at a latitude of 51.53 °N and longitude of 0.473 °W. Additionally, a m-C Si PV cell based 4 kW_p system (12 panels of 340 W_p each) consisting of a cell area of 17.52 m^2 and an overall panel area of 22 m^2 was installed. There are no trees and buildings obstructing or shadowing the incoming solar radiation on the LCPV and flat PV panels. LCPV and flat panels were installed at the same angle of tilt of 10° and orientated towards True-South direction with a solar azimuth angle of 0°.

The schematic, of the developed LCPV prototype and the associate monitoring equipment installed are shown in Fig. 3a. The electrical energy output of the LCPV panels were monitored using PASCO wireless voltage and current sensors with their thermal performance recorded using Grant data loggers. Fig. 3b shows the locations of the thermocouples on the underside of the PV cells. In order to cool the cells to within 30 °C, two DC fans (5 W each) with a flow rate of 33 m^3/h were installed at the inlet and outlet of the copper channel (heat sink) located under the solar PV cells in each LCPV panel.

The deployed LCPV panels and conventional flat PV panels are shown in Fig. 4. The conventional flat PV consisted of an inverter unit to convert DC into AC and an Emlite ECA2 single phase meter was used to measure their electrical energy output in kWh.

The monitoring equipment and instrumentation used are detailed in Table 2. Two pyranometers were used to record the in-plane solar insolation (global and diffuse) and k-type thermocouples were used for measuring air inlet temperature and the ambient temperature. The thermocouples were connected to the Grant data logger. The data collection frequency was set at 15 min interval with the data averaged over one-hour during diurnal hours. Similarly, the PV system parameters (current and voltage) were sampled every 15 min and averaged over one-hour intervals. The electrical consumption data of the building was recorded on monthly basis.

Table 1
Geometrical details of the concentrators developed.

Parameter	ACPC	CPC	V-Trough
Receiver width (mm)	75	75	75
Length (mm)	500	500	500
Geometric concentration ratio	1.53	1.46	1.40
Half acceptance angle (°)	0, 60	30	20

4. Global and diffuse solar irradiation at the test site

The quarter-hourly data collected at site was averaged over an hour and used for the analysis. Fig. 5 presents the monthly averaged global solar irradiation (I_G), diffuse solar irradiation (I_D) and average diurnal ambient temperature (T_{amb}). The data presented in Fig. 5 was averaged over diurnal hours during the monitoring period between February 2020 to November 2020. The highest global irradiation was measured in the month of May (210.73 kWh/m^2) with the lowest recorded in February (156.60 kWh/m^2). The highest and lowest value of diffuse irradiation was recorded in May (188.18 kWh/m^2) and February (12.65 kWh/m^2) respectively. Between the months of February and November, T_{amb} varied from 8.1 °C to 19.41 °C. Fig. 6 shows that the total hourly in-plane insolation incident on the aperture of the solar concentrators at 11:00 AM, 12:00 PM and 1:00 PM remains relatively constant thus the collectors will be operating at close to their maximum optical efficiency. Any deviations encountered will be as a result of the reflector profiles.

The daily normalized frequency distribution of I_G and I_D over the monitored period is shown in Fig. 7. Each set represents the percentage of the total monitored days that I_G and I_D ranged between 0 kWh/m^2 to 11 kWh/m^2. Nearly 38% of the total monitored days, I_G was less than 1 kWh/m^2 and I_D was less than 1 kWh/m^2 for 37% of the total monitored days. The daily total I_G exceeded 5 kWh/m^2 for 19% of the total monitored days. The data shown in Fig. 7 for the test location demonstrate

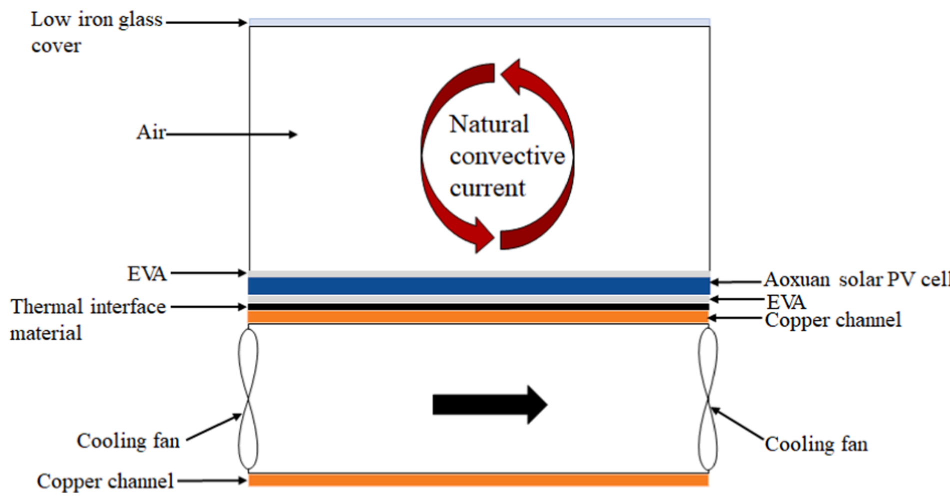

Fig. 2. A cross sectional view of the developed LCPV panel.

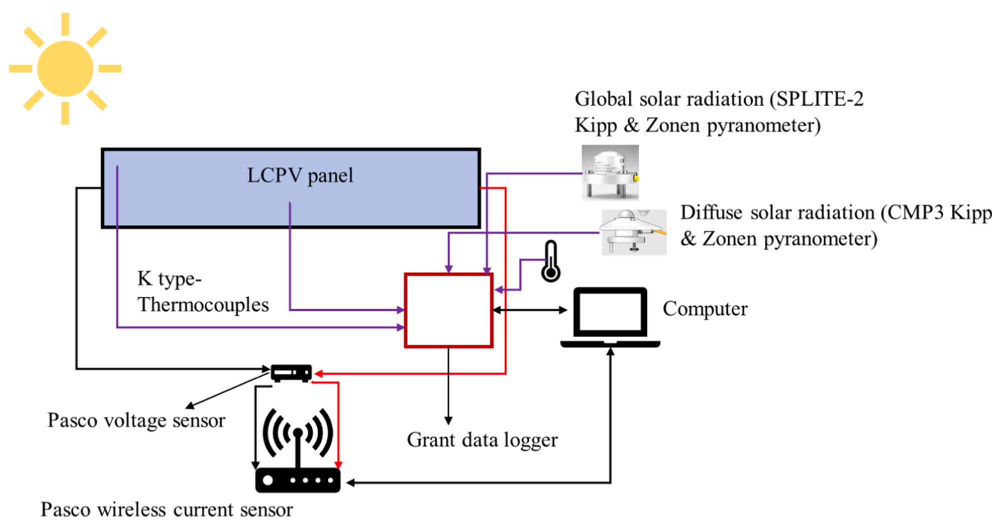

Fig. 3a. The schematic of the developed LCPV panel with the monitoring equipment.

that it receives low levels of solar radiation with 38% having less than 1 kWh/m^2/day incident.

5. Comparison of the operating cell temperature of the LCPV panels

The monthly average cell temperatures and T_{amb} measured during the diurnal hours are shown in Fig. 8. In the months of June, July and August, the recorded monthly average of LCPV module temperatures varied from 20 °C to 33 °C, and the ambient temperature ranged between 15.4 °C and 19.4 °C. From Fig. 8, it can be seen that the operating cell temperature of the CPC based LCPV was higher than that for the other two concentrators due to a higher optical concentration achieved by the CPC from 9:00 AM to 12:00 PM as demonstrated in Fig. 9. Conversely, the ACPC based LCPV concentrator achieved a higher optical concentration than the CPC and V-Trough based LCPVs between 12:00 PM and 5:00 PM. The optical concentration ratio of the LCPV concentrators shown in Fig. 9 were predicted using a ray trace based analytical model published earlier by the authors [24]. This model [24] was validated against the indoor experiments conducted using OAI AAA solar simulator. Between 12:00 pm and 5:00 pm, the ACPC concentrator gained maximum optical concentration due to higher ray acceptance, which is attributed to asymmetry of its half acceptance angles ($\theta_{acc,\ lt}$ and $\theta_{acc,\ rt}$). CPC and V-trough concentrators achieved higher optical concentration around noon time due to a higher ray acceptance when angle of incidence is well within their respective half acceptance angles. However, the average cell temperature of CPC was higher than ACPC and V-Trough concentrators due to a higher optical concentration in the early hours of sunshine. V-Trough concentrator achieved the lowest optical concentration over the full monitoring period.

6. Comparison of the energy generated by the developed LCPV panels

The measured energy output of the developed LCPV panels is shown in Fig. 10. Each LCPV panel had a cell area of 75 mm × 480 mm. The measurements shown in Fig. 10 demonstrated that the CPC generated a higher energy output as compared to the ACPC and V-Trough concentrators in the months of June and July. Over the full duration of the test (February to November), the ACPC generated 8.9 kWh as compared to CPC and V-Trough panels' 8.1 kWh and 6.9 kWh respectively. Clearly, ACPC concentrator generated 9.2% higher energy output than CPC and 26.6% higher than V-Trough concentrator.

The hourly frequency distribution of the energy generated by the LCPV panels over the monitored period is shown in Fig. 11. Approximately 42.0% of the total number of hours of energy generation, the

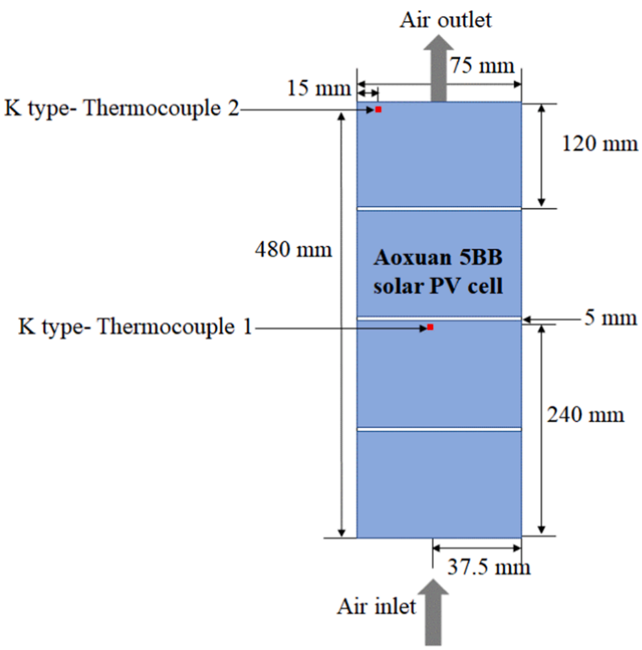

Fig. 3b. Location of the thermocouples under the solar cells.

Fig. 4. The in house developed LCPV panels and conventional flat PV panels installed at the outdoor test facility within Brunel University London.

Table 2
Monitoring equipment.

Equipment/Sensor	Parameter	Accuracy	Supplier
k-type thermocouple	Cell temperature and Ambient Temperature	±0.5 °C	[18]
Grant SQ 2010 Data logger	–	±0.1%	[19]
SP Lite2 Pyranometer	Global solar radiation	±0.5 μV/W/m^2	[20]
CMP3 Pyranometer	Diffuse solar radiation	±0.5 μV/W/m^2	[20]
Pasco wireless Voltage sensor	Voltage	±1.0%	[21]
Pasco current sensor	Current	±1.0%	[21]
Emlite phase meter	Energy	±5.0%	[22]
Solis 4.0 kW 5G Dual MPPT	Inverter and maximum power point tracker (MPPT)	±3.0%	[23]

ACPC concentrator generated < 1 Wh followed by the CPC and V-Trough with 37.2% and 37.6% respectively. For 17.8% of the total number of daytime hours, LCPV concentrators generated maximum energy output of 5–10 Wh indicating that the installation site is a low solar insolation location.

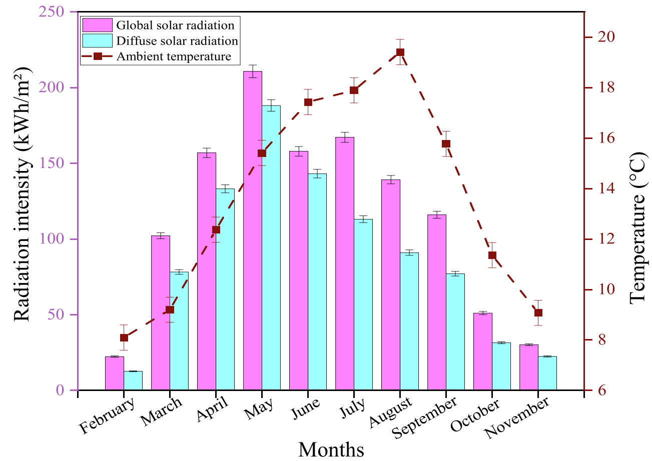

Fig. 5. The monthly averaged global solar radiation, diffuse solar radiation, and the ambient temperature over the monitored period.

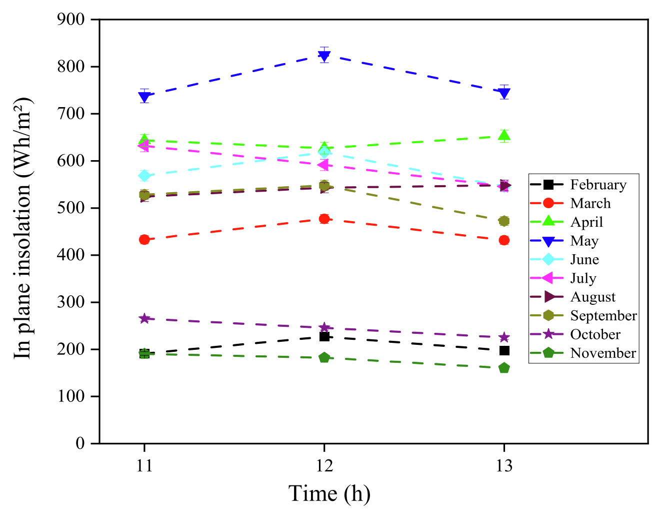

Fig. 6. The in-plane isolation incident on the aperture of LCPV panels at 11:00 AM, 12:00 PM and 1:00 PM.

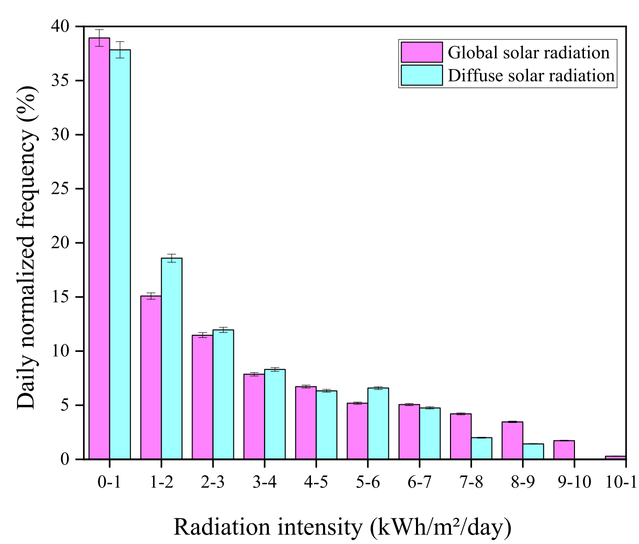

Fig. 7. The daily normalized frequency distributions of in plane insolation (global and diffuse) at Brunel University London.

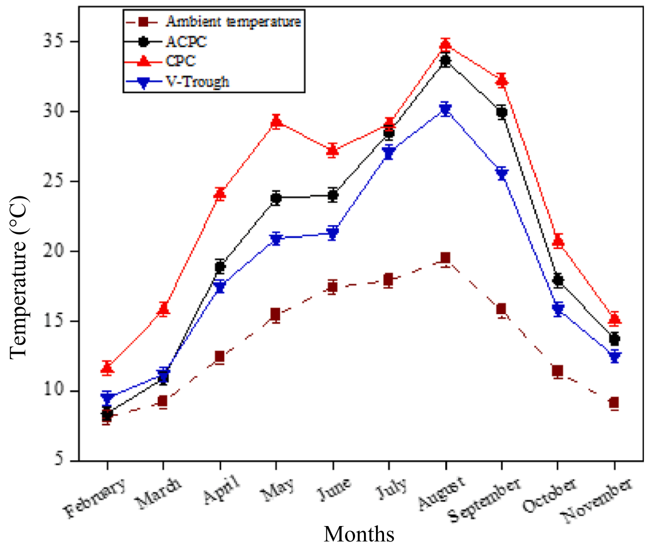

Fig. 8. The monthly average of hourly operating cell temperature of the LCPV panels and the ambient temperature.

7. Electrical conversion efficiency of LCPV panels

Electrical conversion efficiency (η_e) was calculated as the ratio of the measured energy output (kWh) to the product of hourly total incident solar irradiation (kWh/m^2) and cell area (m^2) as described in Eq. (3).

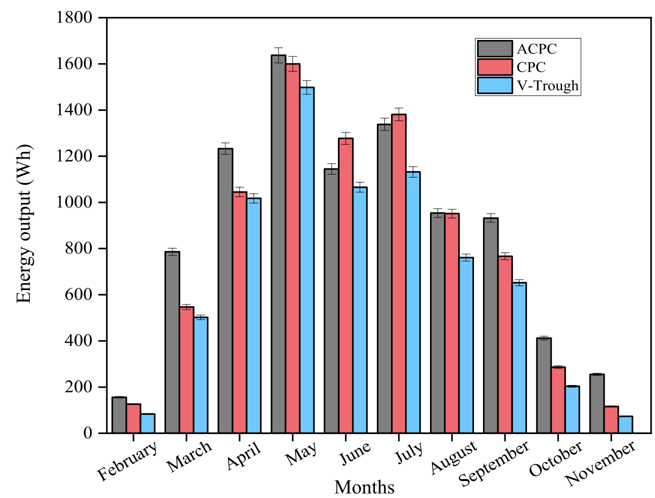

Fig. 10. The measured electrical energy output of the LCPV panels developed.

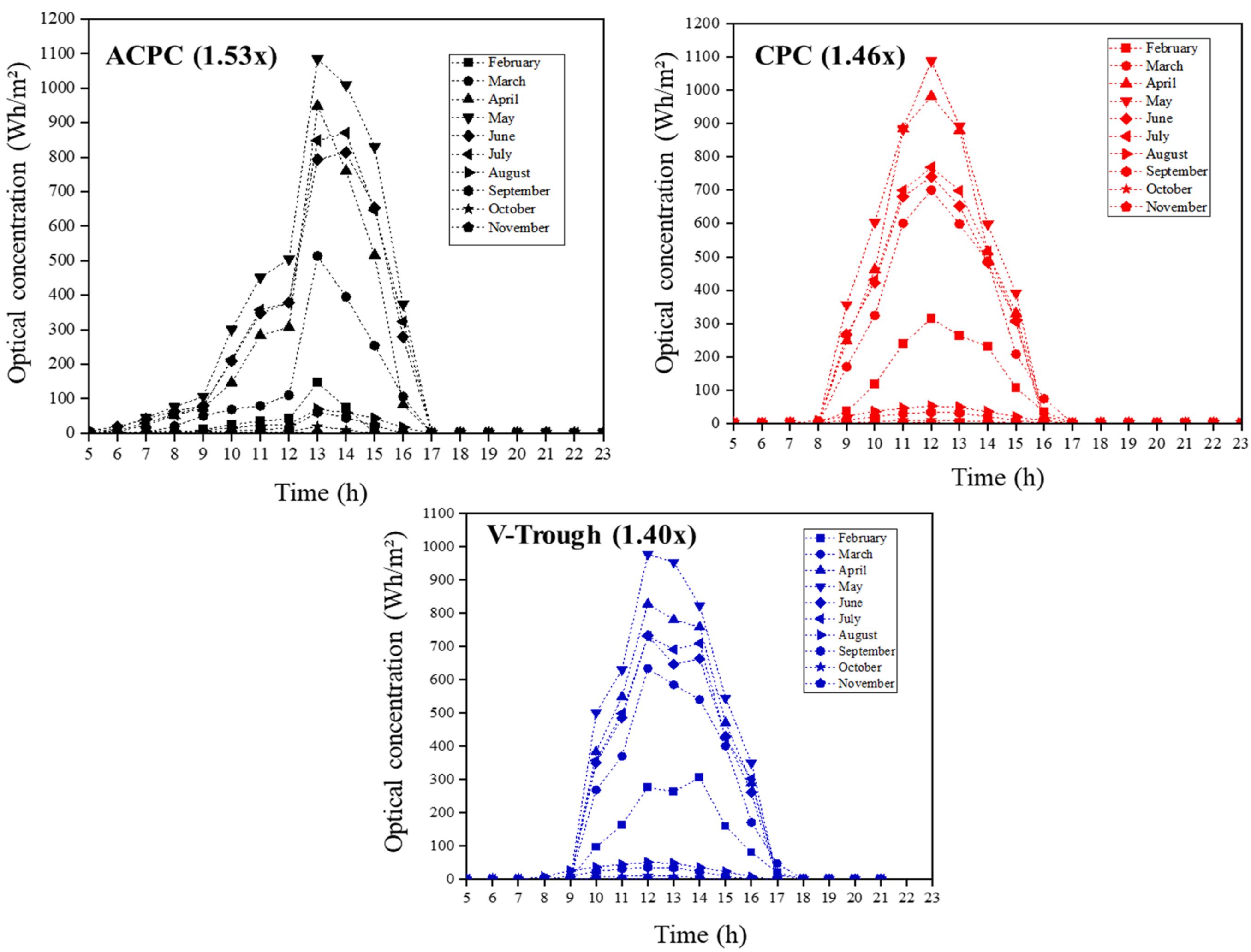

Fig. 9. The predicted optical performance of ACPC, CPC, and V-Trough concentrators.

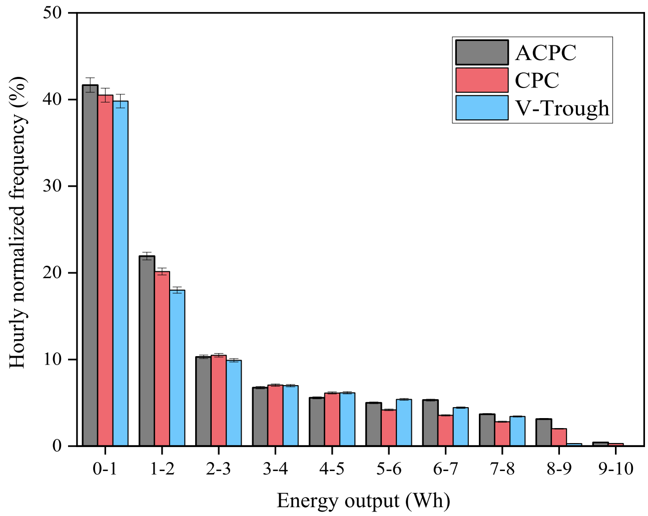

Fig. 11. The hourly normalized distribution of energy generated by the LCPV panels.

$$\eta_e = \frac{(E_{DC})}{I_t \times A} \tag{3}$$

The monthly variation of the electrical conversion efficiency of the developed LCPV concentrators is shown in Fig. 12. The ACPC achieved higher conversion efficiencies as compared to the CPC and V-Trough profiles during spring and autumn. The CPC concentrator achieved higher conversion efficiencies as compared to ACPC and V-Trough concentrators during the months of June and July. During the monitoring period, the ACPC concentrator achieved a higher electrical conversion efficiency of 21.2% compared to CPC and V-Trough which achieved 17.8% and 14.9% respectively. The higher electrical conversion performance of ACPC is attributed to its higher optical efficiency seen in Fig. 9.

8. Array yield

Array yield, ratio of measured energy output (E_{dc}) of a PV array over a specific period (daily, monthly, or yearly) to its rated capacity (PV_{rated}) has been calculated using Eq. (4) [25].

$$Y_{Ar} = \frac{E_{dc}}{PV_{rated}} \tag{4}$$

Reference yield (Y_R) determined by the ratio of the total daily solar irradiation (I_t) to the reference irradiation (I_R) of 1 kW/m^2 was calculated by using Eq. (5). Consequently, Y_R represents the number of sunshine hours per day (h/d) [25].

$$Y_R = \frac{I_t}{I_R} \tag{5}$$

The average daily array yields of the LCPV panels for each month are illustrated in Fig. 13. It can be seen that the array yield of ACPC was higher than the CPC and V-Trough when the monthly average reference yield was less than 4.0 h/d during spring and autumn. The array yield of the CPC concentrator was higher than ACPC and V-Trough in the months of summer when the average reference yield exceeded 4.0 h/d. The average reference yield was <3 h/d in the spring and autumn, demonstrating a lower array yield of the LCPV panels.

9. The energy output and performance ratio (*PR*) of the LCPV panels

The measured energy output per unit cell area of the developed LCPV panels and the flat PV panels are presented in Fig. 14. ACPC panel produced 246.2 kWh/m^2 followed by CPC, V-Trough and flat PV modules generating 224.6 kWh/m^2, 196.1 kWh/m^2 and 185.4 kWh/m^2 respectively. Results have showed that the ACPC generated higher energy by 32.5% than non-concentrating flat PV configuration. The CPC and V-Trough concentrators generated 21.0% and 5.31% higher than the flat PV panel respectively.

The performance ratio (*PR*), a dimensionless number indicating the overall effect of losses on the system output, was determined using Eq. (6) [25].

$$PR = \frac{Y_{Ar}}{Y_R} \tag{6}$$

The measured monthly energy output per unit cell area of the developed LCPV panels and their performance ratios are illustrated in Fig. 15. The ACPC generated higher energy with higher performance ratio as compared to other concentrators from February to May, whereas CPC concentrator generated higher energy achieving a greater performance ratio from June to September. Over the full monitoring period, the average performance ratio of ACPC concentrator was 0.72 followed by the CPC at 0.63, the V-Trough at 0.53 and the flat PV panels at 0.49. This clearly demonstrates the benefit of deploying LCPVs particularly those with ACPC concentrator for locations that receive high diffuse solar radiation.

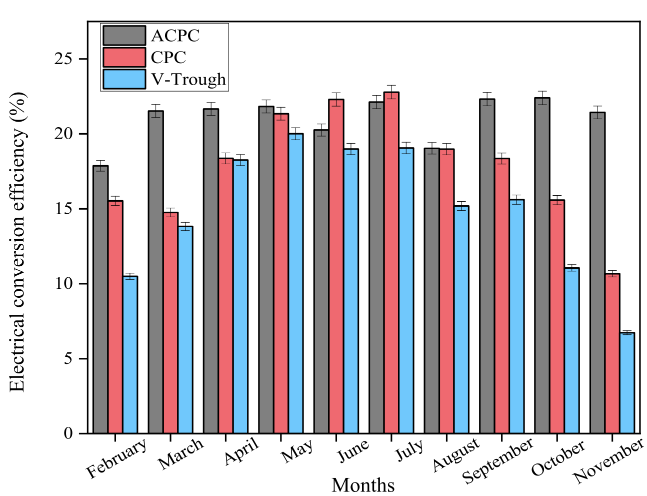

Fig. 12. The electrical conversion efficiencies achieved by the LCPV modules over the monitoring period.

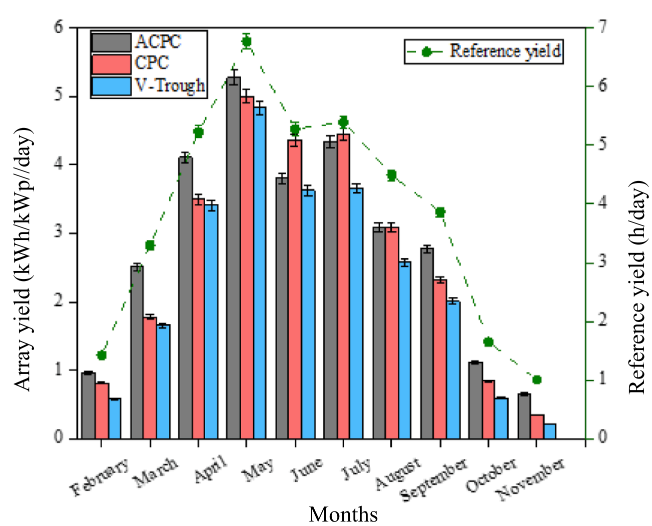

Fig. 13. The array and reference yields of the developed LCPV panels.

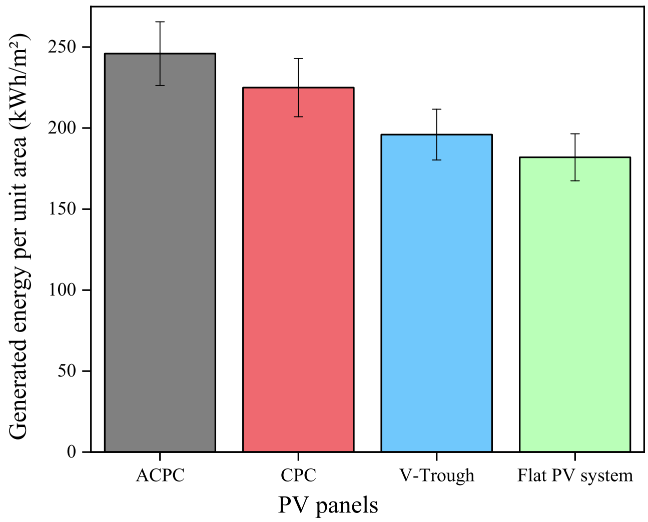

Fig. 14. The generated energy output per unit cell area for the LCPV and flat PV panels.

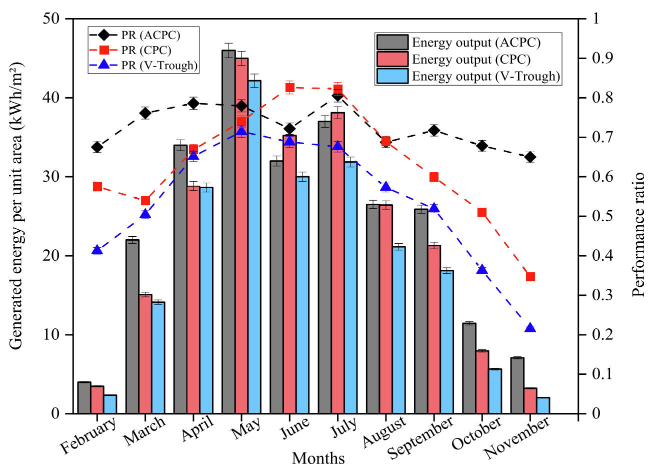

Fig. 15. Performance ratio and the generated energy output per unit cell area of the LCPVs studied.

10. Comparison of the LCPV systems developed with those reported globally

A comparison of the performance of the LCPV panels and the flat PV panels investigated in this study with those reported by other researchers is presented in Table 3. The *PR* and conversion efficiency of LCPV modules investigated in this study are higher than those for PV plants deployed in similar climatic and solar conditions across UK and Germany. The *PR* of the developed LCPV panels is lower than that of other systems falling within the range found in Asian and European countries. It should be noted that a direct comparison cannot be applied to the systems installed due to variation in interfering factors such as geographic location, type of PV modules, weather, angle of tilt and design of the modules.

11. Meeting the energy demand of the building

The annual electrical energy demand of the building was measured as 39,850 kWh. A spreadsheet-based model was developed to predict the installation capacity of the PV plants (LCPV and flat PV systems) needed to fulfil the total energy demand of the building. It was assumed that the generated electrical energy is directly fed into the building, therefore no battery storage was considered. From Fig. 16, it is seen that the flat PV modules require highest PV plant capacity of 49.0 kW_p followed by V-trough, CPC and ACPC with 46.4 kW_p, 40.1 kW_p and 37.0 kW_p

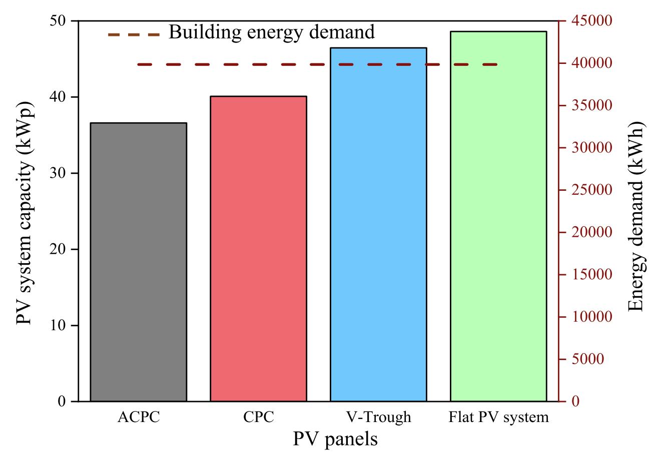

Fig. 16. The comparison of the PV plant installation capacities needed to meet the annual energy demand of the building.

Table 3
The comparison of performance indices of various PV systems installed on the roof/façade of the buildings.

Location	Rated power (kWp)	Non-concentrating/ concentrating	Type of PV technology	Performance ratio	Electrical conversion efficiency (%)	Source
UK, Northern Ireland	13	Non-concentrating	m-C Si	0.60–0.62	7.6	[16]
Turkey, Manisa	30	Non-concentrating	poly-C Si	0.831	13.59	[26]
India, Lucknow	5	Non-concentrating	poly-C Si	0.76	10.02	[27]
Norway	2.07	Non-concentrating	m-C Si	0.83	12.7	[28]
Singapore	142.5	Non-concentrating	poly-C Si	0.81	11.8	[29]
UK, Loughborough	1.8	Non-concentrating	amorphous-Si	0.42	3.2	[30]
UK, Northumberland	39.5	Non-concentrating	m-C Si	0.61	8.4	[31]
Germany	1–5	Non-concentrating	–	0.6–0.79	–	[32]
UK, London	0.01	Concentrating	ACPC/m-C Si	0.72	21.2	Present study
UK, London	0.01	Concentrating	CPC/m- C Si	0.63	17.8	Present study
UK, London	0.01	Concentrating	V-Trough/m-C Si	0.53	14	Present study
UK, London	4	Non-concentrating	m-C Si	0.49	–	Present study

respectively. Owing to the highest electrical conversion efficiency achieved by the ACPC based LCPV system a minimum installation capacity requirement is predicted. Loss of electricity at inverter (2.5%), energy meter (5%), maximum power point tracker (0.5%) and balance of the system (4%) were considered for the flat PV panel analysis. For LCPVs developed in this study a total electric loss of 2% was assumed.

12. Economic and environmental performances

Simple payback period calculations using Eqs. (7) and (8) have been performed for the PV panels studied assuming fixed unit price of electricity of £0.1174/kWh [33] without accounting for feed-in-tariffs over their full-service life.

$$Payback\ \ period = \frac{Installed\ \ Cost(£)}{Income(£/y)} \tag{7}$$

$$Installed\ \ Cost = cost\ \ of\ \ materials + manufacturing\ \ costs + installation\ \ costs \tag{8}$$

Table 4 shows the economic parameters considered for the calculations. Two scenarios have been considered. In Scenario 1, the LCPV panels were assumed to cost 15% higher than conventional PV panels to account for the cost of reflector sides any additional manufacturing costs.

Predictions have showed that ACPC concentrators achieved the shortest payback period of 6.4 years as compared to CPC at 6.8 years, V-Trough at 7.5 years and flat PV modules at 7.1 years respectively, see Fig. 17 (a).

In Scenario 2, LCPV panels were assumed to cost 35% higher than the flat PV panels allowing 15% for the cost of reflector sides and 20% to cover manufacturing cost. Predictions have showed that ACPC concentrator and flat PV modules achieved the shortest payback period of 6.8 years. The CPC and V-Trough concentrators achieved 7.3 years and 8.1 years respectively, see Fig. 17 (b). Despite the fact that the LCPV panel has a higher installed cost than the flat module, ACPC based LCPV systems achieved remarkably lower payback period potentially resulting in higher profits for the building owners over their full-service life. In a bulk production scenario, if the manufacturing costs of ACPC based LCPV panels are comparable to the flat PV panels, ACPC modules will earn 30.2% higher income than flat PV panels over a service life span of 25 years.

Any clean energy generator expectedly has a positive impact on the environment compared to conventional fossil fuel using power plants. An emission factor of 0.23750 kgCO_2e/kWh [37] for the network electricity in the UK was used by this study to determine the amount of greenhouse gas (GHG) emission displaced through the use of solar PV systems. Emission factor considered in this study is a sum of displaced CO_2, CH_4 and N_2O for the electricity generated and supplied to the grid from fossil fuels. The solar PV modules (LCPV or flat PV systems) with a generation capacity of 49.0 kW_p could potentially reduce GHG emission by 9381.2 kgCO_2e/kWh/y for the building.

By 2030, the EU has proposed a set objective of at least a 40% reduction in domestic GHG emissions compared to 1990 levels. In order to achieve the goal of the Paris Agreement on GHG emissions, the EU parliament voted to increase clean energy generation to 35% by 2030. As a consequence, the renewable energy generation capacity would need to be in the range of 1200 to 1250 TWh to achieve this target. Solar power was expected to contribute 380 TWh, needing an increase the solar PV installation capacity particularly rooftop installations to 350 GWp by 2030 [38]. However, LCPV technology would require a total installed capacity of roughly 237 GW_p to generate the required 380 TWh of electricity.

Table 4
Variables used in the payback period calculations.

Investment	Scenario 1 Cost per unit (£)	Scenario 2 Cost per unit (£)	Number of units
Flat PV panel with m-C Si solar cells	225 [34]	225 [34]	143
ACPC panel with m-C Si solar cells	259	303.7	108
CPC panel with m-C Si solar cells	259	303.7	118
V-Trough panel with m-C Si solar cells	259	303.7	136
Inverter, cables and energy meter	4100 [35]	4100 [35]	1
Supporting frame and structure	8000 [35,36]	8000 [35,36]	1
Installation cost	5000	5000	1

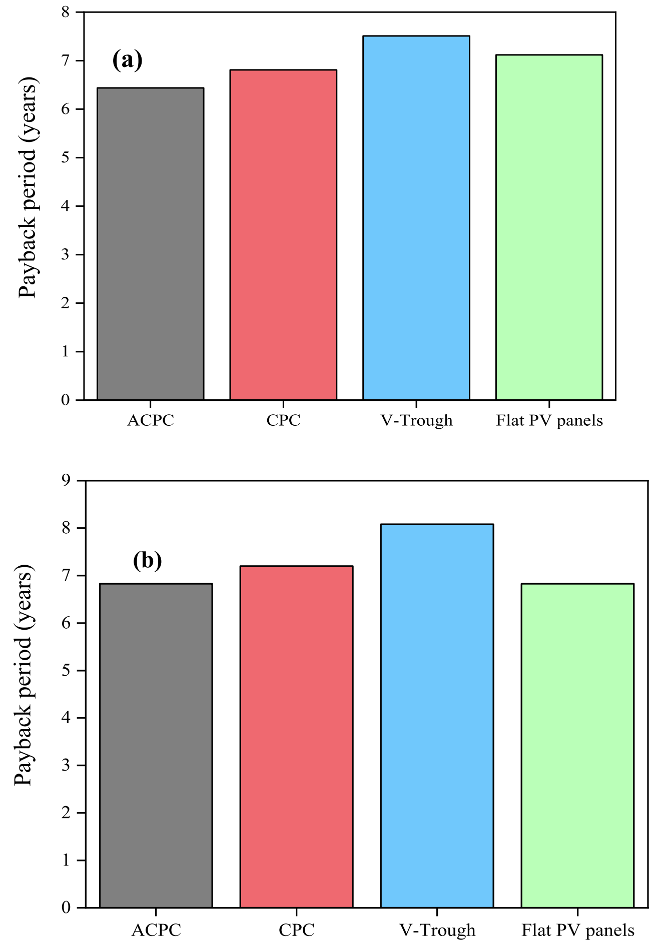

Fig. 17. Payback periods predicted for the LCPV and the flat PV panels (a) scenario 1, (b) scenario 2.

13. Conclusion

In this study, three LCPV panels employing ACPC, CPV and V-trough optical concentrator in conjunction with m-C Si cells were developed and studied with a purpose of establishing their suitability for building deployment. Technical, economic and environmental performances of the LCPV panels under real life settings have been presented.

The measured operating cell temperature of the CPC concentrator was higher than the ACPC and the V-Trough concentrators during the full monitoring period.

During the monitoring period, the average reference yield was found to be 3.82 h/d and the average final yields of the ACPC, CPC, and V-Trough based LCPV systems were 2.82 h/d, 2.65 h/d, 2.31 h/

d respectively.

LCPV panels generated higher energy per unit cell area as compared to non-concentrating PV system. The generated energy per unit area of ACPC was 32.5% higher than that of flat PV panels, followed by CPC and V-Trough with 21.0% and 5.3% respectively. ACPC based LCPV panel requires an installation capacity of 37 kW_p as compared to flat PV panel needs 49.0 kW_p to fulfil the buildings' energy needs. One particular conclusion of the study is that the ACPC based LCPVs perform better in locations where diffuse component of solar radiation is predominant as is in the case of the UK.

The payback period predictions showed ACPC based LCPVs achieved the shortest payback period of 5.4 years than the flat PV panels at 6.14 years. There are still uncertainties concerning the use of low-cost materials (reflectors and solar cells) in manufacturing LCPV concentrators but there is a possibility of achieving additional cost reductions through technological developments. The comparative analysis showed ACPC based LCPV panels have a great potential for reducing the payback period which could lead to their wide scale uptake. Furthermore, these systems can be easily mounted on the same supporting frame as that used for flat PV panels. Absence of any requirement of sun tracking makes their operation as simple as that of flat PV modules. This research has shown that replacing conventional PV systems with advanced LCPV technology would reduce the installation capacity while simultaneously eliminating the GHG emissions more swiftly. Currently commercial designs of LCPV are not available, efforts should be made to commercialize these products to enable mass production such that the environmental, economic and performance benefits described by this research can be attained. For the concentrating PV systems to economically compete or outcompete flat PV panels, the challenge will be to compensate the cost of reflector profiles and manufacturing costs with higher amounts power generated. If one accounts for the carbon savings, justification will be even easier. It is imperative that low cost reflector materials in conjunction with efficient manufacturing methods such as 3-D printing and volume production are employed such that the economic performance of LCPVs will always be higher than flat plate modules.

CRediT authorship contribution statement

Ranga Vihari Parupudi: Conceptualization, Methodology, Writing – original draft, Visualization, Investigation, Formal analysis, Software, Validation. **Harjit Singh:** Conceptualization, Supervision, Reviewing, Editing, Project administration. **Maria Kolokotroni:** Supervision, Project administration. **Jose Tavares:** Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This project has received funding from the European Union's H2020 research and innovation programme under grant agreement no 768576 (ReCO2ST project).

References

[1] Li Y, Kubicki S, Guerriero A, Rezgui Y. Review of building energy performance certification schemes towards future improvement. Renew Sustain Energy Rev 2019;113:109244. https://doi.org/10.1016/j.rser.2019.109244.
[2] Zomer C, Custódio I, Goulart S, Mantelli S, Martins G, Campos R, et al. Energy balance and performance assessment of PV systems installed at a positive energy building (PEB) solar energy research centre. Sol Energy 2020;212:258–74. https://doi.org/10.1016/j.solener.2020.10.080.
[3] Wells L, Rismanchi B, Aye L. A review of Net Zero Buildings with reflections on the Australian context. Energy Build 2018;158:616–28. https://doi.org/10.1016/j.enbuild.2017.10.055.
[4] Energy performance of buildings and Directive 2012/27/EU. DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018. https://eur-lex.europa.eu/eli/dir/2018/844/oj [accessed 28 January 2021].
[5] Smart Export Guarantee (SEG). OFGEM, About the Smart Export Guarantee (SEG) | Ofgem; 2020 [accessed: 05 May 2021].
[6] The carbon Plan. The carbon Plan: Delivering our low carbon future, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf; 2020 [accessed 28 January 2021].
[7] Chemisana D, Zacharopoulos A. Building-Integration of High-Concentration Photovoltaic Systems. High Concentrator Photovoltaics. Springer; 2015; Doi: 10.1007/978-3-319-15039-0_13.
[8] Winston R. Principles of solar concentrators of a novel design. Sol Energy 1974;16(2):89–95.
[9] Current status of concentrator photovoltaic technology. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy16osti/65130.pdf; 2015 [accessed 10 February 2021].
[10] Baig H, Sellami N, Chemisana D, Rosell J, Mallick TK. Performance analysis of a dielectric based 3D building integrated concentrating photovoltaic system. Solar Energy 2014;103:525-540. https://doi.org/10.1016/j.solener.2014.03.002.
[11] SANGANI C, SOLANKI C. Experimental evaluation of V-trough (2 suns) PV concentrator system using commercial PV modules. Sol Energy Mater Sol Cells 2007;91(6):453–9. https://doi.org/10.1016/j.solmat.2006.10.012.
[12] Mallick TK, Eames PC, Hyde TJ, Norton B. The design and experimental characterization of an asymmetric compound parabolic photovoltaic concentrator for building façade integration in the UK. Solar Energy 2004;77:319–327. https://doi.org/10.1016/j.solener.2004.05.015.
[13] Mallick T, Eames P. Design and fabrication of low concentrating second generation PRIDE concentrator. Sol Energy Mater Sol Cells 2007;91(7):597–608. https://doi.org/10.1016/j.solmat.2006.11.016.
[14] Winston R, Minano J C,Benitez P. Nonimaging optics. 3rd ed. Massachusetts; 2005.
[15] Alanod. Alanod MIRO-SILVER®, https://www.alanod.com/products ;2019 [accessed 24 February 2020].
[16] Mondol JD, Yohanis Y, Smyth M, Norton B. Long term performance analysis of a grid connected system in Northern Ireland. Energy Convers Manage 2006;47(18–19):2925–47. https://doi.org/10.1016/j.enconman.2006.03.026.
[17] MONO CELL 5BB PERC. AOXUAN SOLAR, http://www.aoxuanpv.com/MONO-CELL-5BB-PERC-pd42323057.html; 2020 [accessed 10 February 2021].
[18] Thermocouples. TC Direct, https://www.tcdirect.co.uk/;2021[accessed 21 February 2021].
[19] SQ2010. Grant Instruments, https://www.grantinstruments.com/data-acquisition/squirrel-loggers/sq2010 [accessed: 23 February 2021].
[20] Kipp and Zonen pyranometers. Equinox Instruments, https://s3.eu-west-1.amazonaws.com/equinoxinstruments.co.uk/documents/SPLite2-Brochure.pdf.; 2020 [accessed 22 February 2021].
[21] Wireless voltage sensor. Pasco instruments, https://www.pasco.com/products/sensors/pasport/ps-2193#specs-panel;2021 [accessed 24 February 2021].
[22] Single Rate Meter for Utility and Generation Metering. Emlite, http://www.em-lite.co.uk/generation_metering.html; 2020 [accessed 22 February 2021].
[23] SOLIS 4.0KW 5G DUAL MPPT – SINGLE PHASE WITH DC. Segen, https://www.segen.co.uk/product/solis-4-0kw-5g-dual-mppt-single-phase-with-dc/; 2020 [accessed 28 March 2021].
[24] Parupudi RV, Singh H, Kolokotroni M. Low Concentrating Photovoltaics (LCPV) for buildings and their performance analyses. Appl Energy 2020;279:115839. https://doi.org/10.1016/j.apenergy.2020.115839.
[25] Marion B, Adelstein J, Boyle K, Hayden H, Hammond B, Fletcher T, Canada B et al. Performance parameters for grid-connected PV systems. In: Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference; 2005. p. 1601-1606. Doi: 10.1109/PVSC.2005.1488451.
[26] Murat Ates A, Singh H. Rooftop solar Photovoltaic (PV) plant – one-year measured performance and simulations. J. King Saud University-Sci. 2021;33(3):101361. https://doi.org/10.1016/j.jksus.2021.101361.
[27] Yadav SK, Bajpai U. Performance evaluation of a rooftop solar photovoltaic power plant in Northern India. Energy Sustainable Develop 2018;43:130–8. https://doi.org/10.1016/j.esd.2018.01.006.
[28] Adaramola MS, Vagnes ET. Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions. Energy Convers Manage 2015;90:458–65. https://doi.org/10.1016/j.enconman.2014.11.028.
[29] Wittkopf S, Valiappan S, Liu L, Ang KS, Cheng SCJ. Analytical performance monitoring of a 142.5 kWp grid-connected rooftop BIPV system in Singapore. Renew Energy 2012;47:9–20. https://doi.org/10.1016/j.renene.2012.03.034.
[30] Simmons AD, Infield DG. Grid connected amorphous silicon photovoltaic array. Prog Photovoltaics Res Appl 1996;4(5):381–8.
[31] Pearsall N M, Hynes K M, Hill R. Analysis of operation of the Northumberland building photovoltaic façade. In: 14th European photovoltaic solar energy conference; 1997, Barcelona, Spain. p. 1968–71.
[32] Decker B, Jahn U. Performance analysis of 170 grid connected PV plants in Northern Germany- Analysis of Yields and Optimization Potentials. Sol Energy 1997;59(4–6):127–33. https://doi.org/10.1016/S0038-092X(96)00132-6.
[33] British Gas. British Gas, https://www.britishgas.co.uk/GetAQuote/#/new/quote-details; 2019 [accessed 28 January 2019].

[34] LG Solar PV panels. Wind and Sun, http://www.windandsun.co.uk/products/Solar-PV-Panels/LG-Solar-PV-Panels#.XtuLjkVKg2w; 2021 [accessed 10 February 2020].
[35] Batteries and Chargers. Sunshine solar, https://www.sunshinesolar.co.uk/Category/Batteries; 2020 [accessed 26 December 2020].
[36] Mounting frame. Roof runner, https://www.roofrunner.co.uk/; 2021 [accessed 10 February 2020].
[37] Methodology Paper for Conversion factors Final Report. 2020 Government greenhouse gas conversion factors for company reporting, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/901692/conversion-factors-2020-methodology.pdf; 2020 [accessed 10 February 2020].
[38] PV status report 2017. JRC Publications Repository. https://publications.jrc.ec.europa.eu/repository/handle/JRC108105; 2017 [accessed 10 June 2020].