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Potential of Implementing the Low Concentration Photovoltaic Systems in the United Kingdom

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ABSTRACT

This paper discusses the prospect of integrating a novel type of low concentration photovoltaic (LCPV) design known as the rotationally asymmetrical compound parabolic concentrator (RACPC) in a building in the United Kingdom. This is done by proposing a number of building integration designs to create a zero carbon building. A cost reduction analysis of installing the LCPV systems in the country is also presented. It was found that an RACPC design could reduce the LCPV module's manufacturing cost by 31.75% and the LCPV module's cost per unit power output by 33.87% when compared with the conventional PV module.

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1. INTRODUCTION

The building sector is one of the largest energy consumers. The Intergovernmental Panel on Climate Change (IPCC) in its *Climate Change 2014* report states that this sector 'is responsible for 46% of the final natural gas consumption, 76% of combustible renewables and waste, 52% of electricity use, and 51% of heat' [1]. It is therefore crucial to meet the energy demand in the building sector, which is expected to increase every year [2]. The European Commission (EC) stated that the building sector has the largest potential in terms of energy savings and reduction of greenhouse gas (GHG) emissions in the future [3]. This can be achieved by implementing the Zero Carbon Building (ZCB), a concept in which a building is capable of independently generating energy for its own consumption and in which it must also be energy efficient to minimise the energy requirements and energy loss [4],[5]. A solar photovoltaic (PV) system has the potential to be implemented in a ZCB construction. In recent years, the installation of solar PV systems has changed from simply being mounted on a roof or facade (known as the building applied photovoltaic (BAPV) system) to replacing part of or the entire building structure itself (which is widely known as the building integrated photovoltaic (BIPV) system) to create semi transparent windows, PV skylights, exterior cladding panels etc. [4],[6].

Although there has been an oversupply and declining prices of PV modules, the overall installation cost of a PV system in many countries is still considered very expensive. The PV module contributed approximately 45% of the total cost of installation [7]. The PV material contributes to approximately 73% [8] of the cost of the PV module. To reduce the usage of expensive PV material without compromising the module's performance, a number of researchers have suggested to incorporate a solar concentrator, typically a low concentration photovoltaic (LCPV) device in the PV module [9]–[14].

A novel type of an LCPV device known as the rotationally asymmetrical compound parabolic concentrator (RACPC) has been proposed for use in building integration (see Figure 1). The steps to produce the RACPC have been discussed in detail in Ref [15]. One specific design was fabricated and tested indoors and the results indicated that the specific RACPC could increase the maximum power output by 3.33x when compared with a bare cell [16].

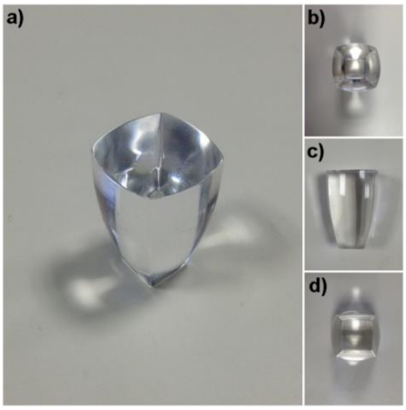

Figure 1. The RACPC prototype fabricated for experimental purposes, (a) the isometric view; (b) the top view; (c) the side view, and (d) the bottom view of the concentrator

2. TOWARDS THE CREATION OF ZERO CARBON BUILDING IN THE UK

In 2002, the EC approved the Energy Performance of Buildings Directive (EPBD), which officially started in January 2003 [17]. This Directive was aimed at improving the energy efficiency of the buildings within the European Union (EU) through various cost-effective measures [17]. This Directive also catalysed the United Kingdom (UK) government to implement a series of legislations and programmes in the subsequent years that are closely aligned with this Directive. It is not the aim of this paper to provide a detailed description about each legislation and programme related to solar PV, since it has been covered in many literature, e.g. in Refs [18]–[21].

The Zero Carbon Building (ZCB) policy was first announced in late 2006 by the UK government, with the target of making all new homes 'zero carbon' from 2016 onwards [22]. In order for a home to be qualified as a ZCB, there are three major conditions that need to be met, which are [22],[23]:

1. The building's fabric must fulfil the Fabric Energy Efficiency Standard (FEES), i.e. it must be very well insulated and air-tight to minimise the energy demand in the building.
2. Any CO_2 emissions after taking into account the heating, cooling, lighting and ventilation, must not exceed the 'Carbon Compliance' limit established for the ZCB, e.g. 10, 11 and 14 kg CO_2/m^2/year for a detached house, an attached house and a low rise apartment respectively. This means that any building must generate enough energy for its own consumption, which can be achieved through the implementation of low carbon technology such as solar PV and solar thermal systems.
3. Any remaining CO_2 emissions (after meeting requirements 1 and 2) must be reduced to zero. There are two ways to achieve this; either by 'over performing' on requirements 1 and 2, or by investing in 'Allowable Solutions'.

In mid 2015 however, the ZCB policy was scrapped by the UK government [24]. Many groups expressed their dissatisfaction about this issue [25]. Nevertheless, the creation of a ZCB policy is still being pursuit by many parties, i.e. developers, energy leaders, environmentalists etc. [25].

3. POTENTIAL OF LCPV INTEGRATION IN THE BUILDING

The ZCB provides an interesting platform for the LCPV design to be implemented in the UK, mainly as an alternative to the conventional solar PV system. It has been indicated in Refs [15],[16] that an LCPV system could generate not only electricity, but it has the capabilities to provide natural illumination into the building, to provide space heating and hot water generation or ventilation (depending on the heat extraction method to utilise the co-generated heat from the photovoltaic effect) which further reduces the energy consumption in a building. The RACPC-PV module can be implemented in a number of ways and could replace the windows, rooftops and building facades.

To maximise its potential, a number of ways of interconnecting the concentrators in the module are proposed. The most typical installation of a traditional solar PV is on the rooftop. The LCPV module can be integrated into a new building, with configurations shown in Figures 2 and 3. In Figure 2, the array of concentrators is placed on top of a glass substrate and the thin layer of material that holds the concentrators together replaces the front glass substrate as the front cover of the module. The LCPV module is inclined at the optimum tilt angle to capture as much sun energy as possible. The distance between the concentrators can be designed either to maximise the electricity generation (by reducing the distance between the concentrators in an array) or can be arranged in such a way that it can allow more natural light to illuminate the building interior. This LCPC design also acts as a skylight. This arrangement is suitable for a typical residential building.

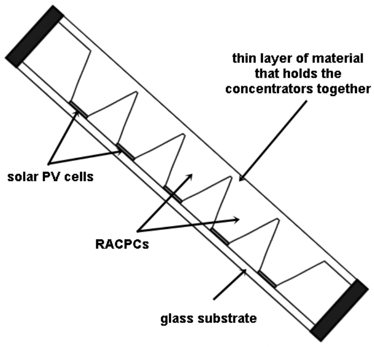

Figure 2. Proposed configuration for installing the LCPV module on an inclined rooftop

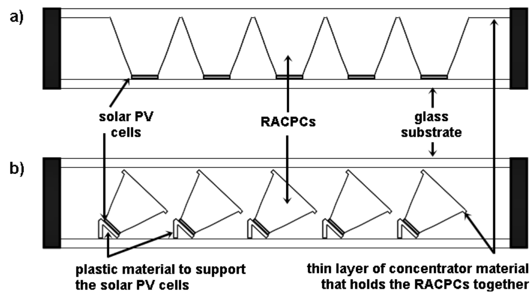

Figure 3. Proposed configuration for installing the LCPV module on horizontal surfaces, e.g. a flat rooftop

For a horizontal rooftop – normally for commercial and industrial buildings, different arrangements are proposed, as illustrated in Figure 3. The first configuration involves arranging the exit aperture of the concentrators in parallel with the horizontal rooftop, as indicated in Figure 3(a). However, specifically in a country at a higher latitude such as the UK, this configuration will not yield optimum electrical output. This is because the sun light will already be outside the half-acceptance angle of the concentrator (due to the seasonal variations of sun path). Because of this, this design is more suitable for countries that lie within the equatorial belt. An alternative arrangement involves tilting the concentrator at the optimum angle in the module design itself, as illustrated in Figure 3(b). The solar cells will be soldered on a layer of plastic material, and an array of concentrators (in rows of *N*) can then be mounted on the solar cells. This enables this LCPV design to maximise the collection of sunlight for electricity generation throughout the year.

For vertical integration (e.g. in a building facade or windows), two LCPV arrangements are proposed, either the concentrators are tilted at optimum angle or lay parallel to the building facade, as presented in Figures 4(a) and (b) respectively. Comparing these two designs, the former arrangement is more desirable than the latter mainly to have an optimum tilt angle with respect to the sun, which will ensure maximum electricity generation from the LCPV module. It is possible to say that these arrangements offer an added advantage to new building structures, when they employ transparent/semi transparent facades to maximise the natural illumination. The LCPV module can be an excellent substitute to conventional PV systems in these situations.

Despite this advantage, the assembly process of producing a tilted concentrator in the module could be challenging. Therefore, more extensive research needs to be carried out with respect to the assembly process and the building integration using the LCPV module.

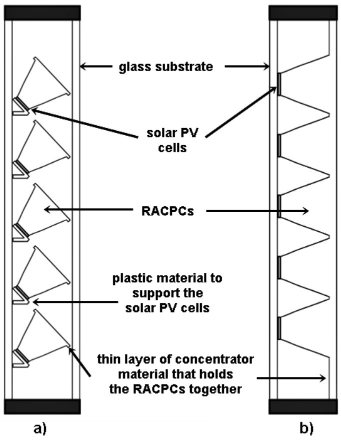

Figure 4. Proposed configuration for installing the LCPV module on a vertical surface, e.g. a building facade and a window

4. COST REDUCTION ADVANTAGE OF USING THE LCPV SYSTEM

It has been indicated earlier that the aim of pursuing the LCPV design is to reduce the installation cost of a solar PV system. It is therefore important to predict theoretically the cost reduction that can be achieved by incorporating the RACPC design to create an LCPV module. According to Sarmah et al. [26], the typical conventional BIPV module is made of silicon solar cells laminated between two thick glasses. Therefore, the cost comparison of the LCPV module should be compared with the commercially available glass-laminated PV module. To simplify the analysis, other costs such as inverter, external wiring from the modules to the inverter and overall PV system installation cost are not considered in this analysis. The concentrating and non-concentrating PV modules used for the calculation here have dimensions of 111 cm x 85 cm x 4 cm. The breakdown cost for a glass-laminated conventional PV module and the LCPV module that incorporates the RACPC design are presented in Table 1. From the table, it can be seen that the RACPC-PV module could reduce the manufacturing cost by 31.75% when compared with a traditional solar PV module.

Table 1. Theoretical cost of fabricating a 0.94 m^2 module (in £)

Item	Conventional solar PV module	RACPC-PV module
PV[28]	30.72	7.59
Concentrator [29–31]	0.00	11.10
Glass [32]	5.28	2.64
Encapsulation [33–36]	3.62	4.82
Frame [37,38]	3.18	3.18
Wiring [6,39]	1.29	0.76
Labour [40]	6.17	4.21
Total	50.26	34.30
Cost reduction (%)		31.75

To determine the price per unit watt of the RACPC-PV module, the cost to produce a 1 kWp panel is estimated and presented in Table 2. Based on the datasheet from Solar Capture Technologies [27] and the experiments carried out in Ref [16], a 0.94 m^2 of conventional PV module and the RACPC-PV module could produce 89.63 W and 92.50 W under standard test conditions respectively. Therefore, in order to produce a 1 kW power output, these modules must cover an area of 10.48 m^2 and 10.16 m^2 correspondingly. By using the information in Table 1, the cost to create the modules per m^2 is estimated to be £53.47 for the traditional PV module and £36.49 for the RACPC-PV module. Therefore, the overall cost to produce a 1 kWp panel is estimated to be £560.81 for the conventional PV panel and £370.84 for the RACPC-PV panel. The analysis shows that the RACPC could reduce the cost per unit power output from £0.56/W to £0.37/W, a reduction of 33.87%.

Table 2. Theoretical cost per unit power of a panel in (£/W)

Item	Conventional PV panel	RACPC-PV panel
Power (kW)	1.00	1.00
Area covered (m^2)	10.48	10.16
Cost (£/m^2)	53.47	36.49
Cost (£/W)	0.56	0.37
Cost reduction (%)		33.87

The cost reduction obtained from implementing the LCPV system could attract other consumers (including architects, manufacturers, builders and end users) in implementing these designs into the building. Taking into account the UK's feed-in tariff and the green deal schemes, the consumer could further benefit from a lower installation cost, which translates into a higher annual return on investment and a shorter payback period [4],[20],[28].

5. CONCLUSION

The potential of implementing the LCPV system in the UK has been discussed in this paper. The ZCB policy aims at making all new homes to be 'zero carbon' from 2016. It has been discussed that one of the ways to meet the ZCB criteria is for the building to generate its own energy to meet its energy requirements e.g. from a solar PV system. The LCPV system could be a potential candidate as an alternative for the conventional solar PV system to be integrated in a building and some ways to integrate the LCPV designs, i.e. the RACPC-PV module, were presented as well. It was found that an RACPC design could reduce the LCPV module's manufacturing cost by 31.75% and the LCPV module's cost per unit power output by 33.87% when compared with the conventional PV module.

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