Solar Energy 169 (2018) 362–373

Contents lists available at ScienceDirect

Solar Energy

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

Integration and architectural issues of a photovoltaic/thermal linear solar concentrator

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ARTICLE INFO

Keywords:
Integration of photovoltaic/thermal (PVT) system
Solar concentrator
Solar panels
PV panels
Thermal concentrator
Building envelope integration

ABSTRACT

Modern photovoltaics and thermal technologies are widely available for the building sector at competitive prices. However, innovative approaches must be explored and implemented to find new architectural solutions at the building scale.

This paper presents an electro-thermal solar concentrator and proposals for its building integration. The proposed device has a small size and is based on a 20x semi-parabolic mirror concentrating the sunlight on a linear focus where a string of mono-crystalline PV cells is placed. A thermal receiver is placed on the back-side of the cells, a fluid circulating in the thermal receiver provides the heat recovery. The linear focus allows a monoaxial sun tracking. The proposed device has been numerically analyzed with the support of experimental data. The small size and the linear focus make feasible the integration of arrays of the proposed innovative device in roofs or façades of both new and existing buildings where they contribute to the auto-generation of a portion of the overall required energy. Several examples of the possibilities of array building integration of the described small-size solar concentrator are proposed. The device can be horizontally and/or vertically mounted to better match the architectural needs. The potential yearly power generation of a single unit three meters long, is evaluated to be as high as 120 $kWh_{elettric}$/year and 500 $kWh_{thermal}$/year. Horizontal mounting results in a power production about 30% higher than the vertical mounting.

The significance of this paper is that small size, single axis solar tracking, suitable for building integration is presented, studies of its possible integration in the building are given, the power generation capabilities of the proposed solutions are analyzed in detail. These capabilities have been derived using data achieved by experimental tests performed on a prototype constituted by four semi-parabolic mirrors. The novel contribution is that a new research direction toward further improvement of the performance, system design and installation of a prefabricated modular façade component, is presented. Moreover, the proposed PVT low concentrated solar device is integrable into buildings, easy to install and manage. Finally, the modern and attractive architectural designs are proposed.

1. Introduction

Building integration of active solar energy technologies represents a great potential for both architectural and cost benefits to achieve high-quality standards for NZEB (Deng et al., 2014; Marique and Reiter, 2014) and represent a possible answer to recent European policies and IEA recommendations, (IEA SHC Task 41) which ask for more efficient buildings.

D'agostino and Parker (2018) show that an over 50% reduction of natural gas and electricity consumption in the building is possible.

Solar energy is a significant source of energy for buildings and many projects investigated how this resource is exploitable; CPVT devices are an interesting example.

One advantage of PVT is that PV cells are cooled (Siecker et al., 2017), and this increases their efficiency. Moreover, the heat recovered from the cells is usefully utilized for hot water generation.

Good (2016) emphasizes how a PVT system can result in an average 4–6 year energy payback time (EPBT) while the expected device life is 20 years. Sharaf and Orhan (2015a, 2015b) presented a review of several CPVT solar collector systems. Elbreki et al. (2016) shows how the thermal and electric efficiencies present an opposite response to the design and operative parameters. Some recent review works (Al-Waeli

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https://doi.org/10.1016/j.solener.2018.05.013
Received 26 June 2017; Received in revised form 2 May 2018; Accepted 4 May 2018

Nomenclature

i	incident angle [Deg]
A	capturing area [m]
R	rotation angle [Deg]
BIPV	building integrated photovoltaics
CPVT	concentrated photovoltaic thermal
CPV	concentrated photovoltaic
DR_w	direct radiation
ORC	Organic Rankine Cycle
NZEB	nearly zero-energy buildings
PV	photovoltaic
PVT	photovoltaic thermal

Greek symbol

β	surface tilt, angle [Deg]
β_a	axis tilt, angle [Deg]
γ	surface azimuth, angle [Deg]
γ_a	axis azimuth, angle [Deg]
γ_s	solar azimuth, angle [Deg]
θ_z	zenith angle, angle [Deg]
η_{inv}	inverter efficiency
η_{pv}	cell efficiency
η_b	thermal efficiency

et al., 2017; Lamnatou and Chemisana, 2017; Sathe and Dhoble, 2017) analyzed over two hundred devices and researchers. The results emphasize that many innovative PVT and CPVT solutions have been developed in the last decades, but only a small number of them are commercially available.

For many years, active solar technologies have been intended as mechanical systems mounted on buildings, just utilized for power generation only. In a few cases, the proposed solutions make interiors more comfortable, however, seldom their design and their architectural integration in the building structures have been considered. The primary installation option for a solar device is the flat panel, but this solution results in a low integration with the building.

There are some studies (Good et al., 2015; Norton et al., 2011; Visa and Duta, 2016) where different solutions are proposed to achieve integration between devices buildings. These solutions are static, so their performances are limited (Bowden et al., 1994; Rabl, 1976; Yoshino et al., 1997, 1994). Very often, PVs systems have been designed aiming to achieve the maximum energy harvesting from sun power simply by installing standard flat panels on the building roofs and façades. Building-integrated photovoltaic (BIPV) are solutions, that can be used as a construction material, the system becomes part of the building envelope, architectural solutions for designers, maximizing the energy building performance, and reducing installation costs. CPVT systems can be applied for the building integration giving not only electric but also the thermal contribution, for this reason it is important to study new technical solutions for designers to give them the opportunity to use hybrid systems in the architectural contest without losing aesthetic attractiveness or reducing solar system power generation capability. This can be achieved by paying attention to the project design, by planning the integration of active solar devices since the very early stage of the architectural process, and by improving the architectural integration quality and flexibility of active solar products and devices. Small size solar concentrators are not largely investigated in literature; therefore, experimental results are seldom available on this kind of devices. Data of experimental tests confirm a high-efficiency operation of the proposed small size solar concentrator. The integration of semi-parabolic concentrator with natural convection cooling has been recently proposed (Piratheepan and Anderson, 2017, 2015). Wu et al. (2016) presents a solution for the management of sunlight with a lightweight static concentrating device, installable on façades or windows. The device uses a thermotropic layer to reduce the flux on sunlight. Parasol device in linear Fresnel configuration (Chemisana, 2011; Chemisana and Rosell, 2011) permits to obtain two benefits, which are shading and electric power generation. The Janus PVT collector (Buonomano et al., 2013a,b, 2016; Calise and Vanoli, 2012) adjoin a PV panel with a roll bond, where the electric efficiency is about 12% and constant. A solar concentrator can result in a large component number, which can be limited by a proper design to reduce its cost (Whitfield et al., 1999). Ji et al. (2012) and Li et al. (2011) investigate the cell efficiency, confirming that monocrystalline cells work better than GaAs cells at a lower concentrating factor. A spectral filter (Jiang et al., 2010; Otanicar et al., 2015) permits to move the heat recovery on a different device. The reflective properties of aluminum foils and sheets showed that aluminum foil results in high specular reflectances (Kostic et al., 2010). A high efficiency in a CPV could be carried out if the concentrating mirror or lens produces a uniform solar flux on the PV cells. Meller and Kribus (2013) propose some solutions based on the kaleidoscope homogenizer concept. However, the varying shading situations reduce the kaleidoscope optical efficiency. Water desalination can take advantage of the CPV (Mittelman et al., 2009, 2007) but the cost is high and the operative temperature over 100° C is an important issue for the durability. Another application of CPVs is as a desiccant Air Handling Units where these devices contribute to a significant energy need reduction (Calise et al., 2014; Calise and Vanoli, 2012). The limit on PV cell working temperature prevents the use of collectors with high concentration factors. Some researchers (Kosmadakis et al., 2011; Tourkov and Schaefer, 2015) proposes the combination of CPV with ORC cycles to increase the performance and the economic advances.

Rosell et al. (2005) utilizes an electro-thermal linear CPV based on Fresnel lenses with a point focus, resulting in 60% total efficiency but the proposed device cannot be integrated into any building structure as any point focus solar concentrators because these devices require two axes solar tracking systems. Linear-focus solar concentrators, as shown in this paper, are suitable for integration in building structure but this has never be considered because most of the proposed linear focus solutions have very-large parabolic mirrors and most of them have a focus far away from the parabolic mirror surface. One example is CHAPS (Combined Heat And Power Solar), one of the most investigated CPVT devices (Coventry, 2005; Quaia et al., 2012), which is based on a linear concentrator with one-axis tracking and in-house manufactured cell. This device results in an excellent overall performance but the parabolic mirror has a two-meter width and nearly ten meters long and has the focus more than one meter outside the parabolic mirror surface. The experimental tests show the maximum efficiency is as high as 69%, where 58% is the contribution of thermal output and 11% is given by the generated electrical power. The sizes of this device allow for its mounting on a building roof, but completely prevent its integration with the building structure.

This paper presents a small-size parabolic mirror solar concentrator where the linear solar focus is close to the parabolic mirror and inside the parabolic mirror cross-section. This solution makes the proposed devices suitable for building integration. The paper also presents several examples of possible building integration of arrays based on the proposed solar concentrator. The described small size solar concentrator is very suitable for building integration and easily mountable in many parts of a building, such as a roof, and facades (Good et al., 2015; Norton et al., 2011; Piratheepan and Anderson, 2017). Studies, presented in this paper, develop the design concept of prefabricated innovative shading devices, incorporating a series of linear semi-parabolic concentrator with a monoaxial sun tracking system as a solar