Universitat de Lleida

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Dielectric solar concentrators for building integration of hybrid photovoltaic-thermal systems

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TESI DOCTORAL

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Dielectric solar concentrators for building integration of hybrid photovoltaic-thermal systems

Alberto Riverola Lacasta

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Daniel Chemisana Villegas

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Summary

The goal of this thesis is to develop, optimize, fabricate and experimentally test a low-concentrating photovoltaic thermal system (CPVT) for building façade integration where the cells are directly immersed in a dielectric liquid. The objective sought is perfectly aligned with the Energy Performance Building Directive established by the European Commission in terms of energy efficiency.

Building-integrated PVT systems present an on-site cogeneration of electricity and heat with global efficiencies around 70% and lower space utilization compared to a separate thermal collector and PV module. On the other hand, low-concentrating systems improve the cost effectiveness by using standard cells, single axis-tracking and reduced cell areas. In addition, direct-immersion of solar cells in dielectric liquids brings associated benefits such as a reduction of Fresnel losses and a better temperature control. From the state-of-the-art performed and the previous facts, the need for further developing and studying these systems for building integration purposes was found.

The proposed design is composed by a cylindrical chassis and an inner cavity filled with the circulating dielectric liquid (deionized water or isopropyl alcohol) in which the cells are immersed. The module tracks the solar height by rotation and it is designed to be placed in rows as an array so that the appearance is akin to ordinary window blinds. A secondary movement has been implemented to control the vertical distance between modules and to avoid shading between them while provide lighting control.

For an appropriate development, the spectral distribution of the incident solar irradiance to which solar cells are exposed under real working conditions has been modeled. An in-depth analysis of suitable dielectric liquid candidates based on the required properties for this application has been performed. The absorptivity/emissivity of standard silicon solar cells has been modeled from the ultraviolet to the mid-infrared and validated by an experimental measurement. Then, a full ray-tracing algorithm was developed to optimize the concentrator optical design and the optimum collector was fabricated and analyzed by a CFD simulation to thermally characterize the system. Finally, an energetic simulation with the concentrators superimposed in front of the windows in a standard house aiming to partially cover the building demands has been performed for three locations.

The system performance has been studied for locations with mild winters and latitudes not achieving very high solar heights with satisfactory solar fractions regarding domestic hot water, electrical and space heating and cooling demands.

Resumen

El objetivo de la presente tesis es desarrollar, optimizar, fabricar y caracterizar experimentalmente un sistema solar de baja concentración, fotovoltaico y térmico, para integración arquitectónica en fachadas donde las células están sumergidas en un líquido dieléctrico. Este objetivo está perfectamente alineado con el cumplimiento de la directiva sobre eficiencia energética en edificios establecida por la Comisión Europea.

Los sistemas solares fotovoltaicos y térmicos para integración en edificios atesoran la cogeneración de electricidad y calor en el mismo edificio con unas eficiencias globales alrededor del 70% y utilizando una menor superficie que si incorporamos un colector térmico y un módulo fotovoltaico separados. Por otra parte, los sistemas de baja concentración permiten reducir costes utilizando células solares estándar, con un área reducida y seguimiento en un solo eje. Además, la inmersión de las células en líquidos dieléctricos conlleva unos beneficios agregados como son la reducción de las pérdidas de Fresnel y un mejor control de la temperatura. Del estado del arte realizado y las cualidades previamente descritas, se desprende la necesidad de estudiar y desarrollar estos sistemas para su integración en edificios.

El diseño propuesto está compuesto de un chasis cilíndrico y una cavidad interna por donde circula el líquido dieléctrico (agua desionizada o alcohol isopropílico) en el cual están las células sumergidas. Cada módulo sigue la altura solar rotando y está diseñado para ser colocado en filas formando una matriz. De este modo, la apariencia del conjunto es similar a la de las lamas que se encuentran comúnmente en ventanas. Además, un movimiento secundario que regula la distancia vertical entre los módulos para evitar sombreo entre ellos mismos y para controlar la iluminación interior, ha sido implementado.

Para llevar a cabo un desarrollo óptimo, se ha modelado la distribución espectral de la luz solar incidente a la cual se ven expuestas las células solares en condiciones reales. Se ha realizado un análisis exhaustivo de los líquidos dieléctricos susceptibles de cumplir con los requerimientos para la presente aplicación. Se ha modelado la absortividad/emisividad de las células de silicio comerciales en un rango espectral que va desde el ultravioleta hasta el infrarrojo medio y se ha validado experimentalmente. A partir de aquí, se ha desarrollado un algoritmo de trazado de rayos para optimizar el diseño óptico del concentrador con el fin de posteriormente fabricarlo y analizarlo mediante una simulación CFD. Hecho que nos permite caracterizarlo ópticamente y térmicamente. Finalmente, se ha realizado una simulación energética con el sistema instalado sobre las ventanas de una casa estándar para evaluar que parte de las demandas energéticas del edificio es capaz de satisfacer. Esta simulación se ha realizado en tres localizaciones distintas.

El rendimiento del sistema ha sido estudiado en lugares caracterizados por inviernos suaves y alturas solares no muy elevadas, cubriéndose una gran parte de las demandas de agua caliente sanitaria, eléctricas y de climatización.

Resum

L'objectiu de la present tesi és desenvolupar, optimitzar, fabricar i caracteritzar experimentalment un sistema solar de baixa concentració, fotovoltaic i tèrmic, per a integració arquitectònica en façanes on les cèl·lules estan submergides en un líquid dielèctric. L'objectiu està alineat cap al compliment de la directiva sobre eficiència energètica en edificis establerta per la Comissió Europea.

Els sistemes solars fotovoltaics i tèrmics per integració en edificis permeten la cogeneració d'electricitat i calor al mateix edifici amb unes eficiències globals al voltant del 70% i utilitzen una menor superfície comparat amb un col·lector tèrmic i un mòdul fotovoltaic independents. D'altra banda, els sistemes de baixa concentració permeten reduir costos utilitzant cèl·lules solars estàndards, amb una àrea reduïda i seguiment en un sol eix. A més, la immersió de les cèl·lules en líquids dielèctrics comporta uns beneficis agregats com ara la reducció de les pèrdues de Fresnel i un millor control de la temperatura. La necessitat d'estudiar i desenvolupar aquests sistemes per a la seva integració en edificis ve donada per les qualitats prèviament descrites i per l'estudi de l'estat de l'art realitzat.

El disseny proposat està compost d'un xassís cilíndric i una cavitat interna per on circula el líquid dielèctric (aigua desionitzada o alcohol isopropílic) en el qual hi ha les cèl·lules submergides. Cada mòdul segueix l'altura solar rotant i està dissenyat per ser col·locat en files formant una matriu. L'aparença del conjunt és similar a la de les lames que es troben normalment en les finestres. S'ha implementat un moviment secundari que controla la distància vertical entre mòduls per evitar l'ombra entre ells mateixos i controla la il·luminació interior.

Per dur a terme un desenvolupament òptim, s'ha modelat la distribució espectral de la llum solar incident a la qual es veuen exposades les cèl·lules solars en condicions reals. S'ha dut a terme un anàlisis exhaustiu dels líquids dielèctrics susceptibles de complir amb els requeriments per a la present aplicació. S'ha modelat la absortivitat / emissivitat de les cèl·lules de silici comercials en un rang espectral que va des del ultraviolat fins a l'infraroig mitjà i s'ha validat experimentalment. A partir d'aquí, s'ha desenvolupat un algoritme de traçat de raigs que computa l'energia per optimitzar el disseny òptic del concentrador per posteriorment fabricar-lo i analitzar-lo mitjançant una simulació CFD. Fet que ens permet caracteritzar el sistema tèrmicament i òpticament. Finalment, s'ha realitzat una simulació energètica amb el sistema instal·lat a les finestres d'una casa estàndard per tal d'avaluar quines parts de les demandes energètiques de l'edifici és capaç de satisfer. Aquesta simulació s'ha dut a terme en tres localitzacions diferents.

El rendiment del sistema ha estat estudiat en llocs caracteritzats per hiverns suaus i altures solars no molt elevades, obtenint resultats satisfactoris cobrint una gran part de la demanda de climatització, d'aigua calenta sanitària i elèctrica.

Table of contents

Chapter 1: Introduction and objectives

1. Framework and motivation

The buildings sector is responsible for 40% of the total energy consumption and 36% of the total CO_2 emissions in the European Union. Hence, there is a vast potential to increase energy independence and reduce greenhouse emissions in the Union by retrofitting or adapting existing buildings. Steps have been taken by the European Commission stablishing the Energy Performance of Buildings Directive towards the "20-20-20" objectives: share of renewable energy (20%), improvements in energy efficiency (20%) and reduction of the greenhouse gas emissions (20%) [1]. New buildings must be nearly-zero energy buildings (NZEB) and in this regard, Building-Integrated Solar (BIS) systems are considered to be a technology which perfectly matches the European requirements, generating energy in an efficient and green way.

During the last decades, photovoltaics (PV), which basically implies direct conversion of sunlight into electricity by the photovoltaic effect, have become one of the most promising renewable energy sources with an additional installed capacity approaching 100 GW in 2018 [2].

Among photovoltaics, concentrating photovoltaics (CPVs) allow to replace expensive solar cell material with lower cost optical elements improving the cost-effectiveness and the environmental impact while enhancing the solar cell conversion efficiency [3,4]. For building integration purposes, low-concentration modules which can use standard crystalline silicon (c-Si) cells and whose tracking requirements are less restrictive than in high CPV (HCPV) (single-axis instead of two-axis) are very promising [3,5–9]. Nowadays, HCPV modules are only profitable for locations with high direct normal irradiance (DNI), above 2000 kWh/m^{2}year, limiting a wider application of this technology and positioning c-Si as an attractive option in terms of cost for building integration [10].

Bearing in mind that c-Si cells are a technology that is reaching its fundamental efficiency limits stemming from sub-bandgap photons and thermalization losses (a world record of 26.3% announced in 2017 [11] to be compared with the Shockley-Queisser maximum efficiency of about 32%), there is a considerable part of the total incident radiation which is heating up the cells and of crucial importance for concentrating systems. The fact that the efficiency of most PV cells decreases linearly with increasing temperatures, often characterized by the temperature coefficient being between 0.28 - 0.52 %/°C for today's commercial available c-Si cells [12], highlights the necessity to incorporate cooling mechanisms. These avoid considerable efficiency losses due to elevated temperatures likely to appear under concentrated irradiances.

Operating temperatures can be reduced by either passive or active cooling strategies. Passive cooling is achieved by transmitting heat by radiation, natural convection and conduction, from the generation zone to the dissipation area [13,14], while active cooling systems transfer heat either to a heat exchanger placed at the cell back side [15] or the cell is directly immersed in a dielectric fluid that extracts the heat [16].

Systems which also harvest the solar energy that is not useful for the photovoltaic conversion and extract heat from the PV cells are known as hybrid photovoltaic-thermal (PVT) solar collectors (within the field of PVT, CPVT are a specific category known as concentrating photovoltaic-thermal). The main advantage of these systems is related to the fact that they offer on-site cogeneration of electricity and heat with global efficiencies around 70% (electrical near 20% and thermal higher than 50%) [17]. Considering that the intrinsic limitation of building-integrated solar systems is the space availability and that a separate solar thermal collector and PV module require an area 60% higher to produce the same yield as a PVT liquid system [18], the appropriateness of PVTs for buildings is verified.

Direct-immersed PVs and CPVs in dielectric liquids offer benefits such as enhanced efficiencies attending to a reduction of the Fresnel losses with respect to a bare PV, a reduction of the surface recombination losses and a better temperature control by the reduction or elimination of the thermal contact resistance at the interface between PVs and dissipater [19,20]. In addition, dielectric liquids can potentially act as optical filters tailoring the incident spectra to the PV cell maximum spectral response bandwidth and absorb photons out of this zone.

The aforementioned reasons stablish the framework which motivates the present research to develop, optimize, construct and experimentally test a low-concentrating photovoltaic thermal system (LCPVT) for building integration over façades where the cells are directly immersed in a dielectric liquid. Albeit the concept of direct-immersed CPVT modules with circulating dielectric liquids was commenced in the late 70's based on static reflective concentrators, a latent period of inactivity on the topic of around 20 years was registered. Even if in the last decade an increased interest in developing new direct immersion CPV and CPVTs is observed, this type of systems should be further studied for building integration applications [21].This thesis is intended to fill this gap and further develop LCPVT systems for buildings.

2. Objectives and methodology

The aim of this thesis is to develop, optimize, construct and experimentally test a low-concentrating photovoltaic thermal system for building integration purposes where the cells are directly immersed in a dielectric liquid. Several objectives were set to achieve the final aim:

- Spectral distribution modeling of the incident solar irradiance to which solar cells are subjected under real working conditions. It has to be calculated for a predefined location and time as a function of the main atmospheric parameters. It may differ significantly from the reference spectra and it is key to properly perform the optical design. In addition, a review of typical values of the main atmospheric parameters and its associated spectra should be performed. This allows to define proper transmittance windows to be fulfilled by the candidate dielectric liquids as a function of the selected PV technology.
- Identification of the optical, electrical and thermal properties which ideally the dielectric liquid in which the cells are immersed should match. Based on this, dielectric liquid candidates have to be evaluated as a function of their adequateness to render the optimum liquid.

- Modeling and experimental characterization of the solar cells emissivity/absorptivity up to the mid-infrared range as a function of wavelength and incidence angle. Despite being a fundamental property of solar cells, very little is known about the emissivity of real devices and its physical origins. Moreover, it can have significant implication for PVT systems.
- Optical design and optimization of the concentrator by ray-tracing algorithm implementation.
- Computational Fluid Dynamics (CFD) simulations to thermally characterize the concentrator by conjugating fluid mechanics and heat transfer in a multiphysics environment have to be conducted.
- Fabrication of the optimum modules and experimental validation of the theoretical performance.
- Energetic modeling and simulation of the system installed in a standard building over a year to evaluate the fraction of thermal and electrical demands which the system can cover.

3. Structure of the thesis

The goals previously stated are addressed in the following 9 chapters. Each of them (except the state-of-the-art and the conclusions) corresponds to a paper already published or accepted in an international peer-reviewed high-ranking journal. These chapters are arranged in a logical order so that the reader will begin with an introduction to photovoltaics, then all the modeling and design stages are explained and finally the experimental and simulation work is exposed. The detailed outline of this thesis is as follows:

Chapter 2: Fundamentals of solar cells. This chapter is essentially an introduction to photovoltaics. The solar resource, the photovoltaic energy conversion, semiconductors, the basis of the p-n junction, the structure of solar cells, its operation principles and the main parameters which characterize them are presented. Understanding these concepts is the basis to address the goal of the present research.

Chapter 3: State-of-the-art. A state-of-the-art of low-concentrating photovoltaics systems for building integration from 2010 on is provided.

Chapter 4: Spectral modeling. In this section, the model developed to obtain the spectral distribution of the incident irradiance to which solar cells are subjected under real working operations is explained. Its inputs are the main atmospheric parameters, the location and the time. The paper describes the spectra modeling together with a study of how the energy yield of several solar cell architectures is altered due to their increased sensitivity to the spectral distribution. This research was performed in collaboration with CNRS-PROMES in Odeillo (France) and it is based on the journal paper "Should energy output be preferred over conversion efficiency to qualify advanced multi-junction solar cells?" published in Progress in Photovoltaics: Research and application in 2017.

Chapter 5: Dielectric liquids analysis. A deep analysis of suitable dielectric liquid candidates based on the properties for this specific application is performed. It allows to state which liquids best suit the optical, thermal and electrical requirements of PVT generators. This section is based on the journal paper “Fluid-based spectrally selective filters for direct immersed PVT solar systems in building applications” published in Renewable Energy in 2018.

Chapter 6: Emissivity modeling. An optical model to obtain the solar cells absorptivity/emissivity in a spectral range which includes absorption from ultraviolet to the near-infrared and emission in the mid-infrared is developed and validated by an experimental measurement. This study fills the gap regarding the mid-infrared emissivity of c-Si cells to potentially engineer cells for PVT collectors where low emissivity in the thermal emission range can lead to a higher thermal output. This chapter is related to the journal paper “Mid-infrared emissivity of crystalline silicon solar cells” published in Solar Energy Materials and Solar Cells in 2018. It was developed in collaboration with the Experimental Solid State Physics Group from the Imperial College London (United Kingdom) where the candidate spent a four-month internship.

Chapter 7: Optical design. Following the previous chapters and based on the outcome and results, the concentrator optical design and optimization are addressed in this chapter. The requirements are set so that the system should be integrated on a building’ façade and use low-accuracy trackers and standard cells. A full ray-tracing algorithm was developed for this purpose and the optimized systems were also fabricated and experimentally tested. This section is related to the manuscript “Performance of a dielectric PVT concentrator for building-façade integration” submitted for publication in Optics Express.

Chapter 8: Energetic dynamic modeling and simulation. Finally, this chapter is related to the journal entitled “Energetic simulation of a dielectric photovoltaic-thermal concentrator” published in Solar Energy in 2018. An energetic simulation with concentrators superimposed in front of the windows in a 2-storey family house is performed. The system aims to partially cover thermal and electrical demands utilizing a radiant floor and a reversible air-air heat pump for space heating and cooling (SH&C) and an electrical circuit which combines direct consumption and battery storage. It has been performed for three locations (Lisbon, Barcelona and Genoa) which indicate an appropriate performance of the system analyzed

Chapter 9: Conclusions and future research. The overall conclusions, discussion and opportunities for further research on PVT systems for building integration purposes are included at the end of this thesis. In addition, the publication status of the papers enclosed is reported.

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Chapter 2: Fundamentals of Solar Cells

Fundamentals of Solar Cells

Abstract

The present chapter aims at introducing the reader to the basic concepts necessary for the comprehension of the subsequent chapters. First, the solar resource and specifically the spectral distribution of the incident irradiance are exposed. In addition, the main atmospheric parameters which alter this spectral distribution and the main reference standard spectra are introduced. Later, the bases of the photovoltaic energy conversion together with suitable materials for this purpose are explained. Among them, semiconductors, which are by far the most utilized, are further developed and the basis of the p-n junction is given. Once the p-n junction is introduced, the structure of solar cells, its operation and the parameters which characterize them are presented.

1. Introduction

During the last decades, photovoltaics (PV) have become one of the most promising renewable energy technologies, with installed capacity of PV panels approaching 100 GW in 2018. High conversion efficiencies at reasonable costs undoubtedly represent a *sine-qua-non* condition to be fulfilled toward promoting an even wider deployment of solar electricity. The development of strategies aiming at an improved PV efficiency has instigated a broad range of research activities in the last decades. In this objective, strategies involving nanomaterials, implementation of nano-objects, or manipulation of light at a nanometer scale, have prompted a considerable amount of research work. In this first chapter, we aim to provide the reader with several fundamental concepts necessary to better grasp the underlying physical mechanisms governing PV cells (A detailed explanation of these concepts can be found in other textbooks [1,2]).

The photovoltaic effect, which was discovered by Edmund Becquerel in 1839, basically implies direct conversion of sunlight into electricity using a PV cell, made of a semiconductor material tailored to ensure both a high absorption of sunlight, and an efficient extraction of the photo-generated carriers.

2. The Solar Resource, Solar Energy

The spectral distribution of sunlight spans a broad range of wavelengths ranging from the ultraviolet to the near infrared. The relation between the photon energy (E) and its wavelength (λ) is given by:

$$E = \frac{hc}{\lambda} \tag{1}$$

Where c is the light speed in vacuum (approximately 3.00×10^{8} m/s) and h is the Planck's constant (6.63×10^{-34} J.s).

The spectral distribution of sunlight may vary noticeably depending on 1) the position of the sun in the sky (which is function of the characteristic latitude of the site where the PV cell is supposed to operate, the time of the day, and the day in the year) 2) typical atmospheric parameters values, which are likely to change noticeably depending on the climatic and atmospheric conditions.

Air Mass (AM) is the atmospheric variable to which the solar spectrum is normally more sensitive. It is defined as the distance, relative to the shortest (vertical) path length, that sunrays traverse through the atmosphere before impacting on the Earth's surface. Air Mass can simply be defined as:

$$AM = \frac{1}{\cos\theta} \tag{2}$$

Where θ is the so called *solar zenith angle*, i.e. the angle between the zenith and the center of the Sun's disc.

Nonetheless, a more accurate expression that considers the Earth's curvature is commonly used to predict or define the solar spectrum [3]

$$AM = \frac{1}{\cos\theta + 0.50572 \cdot (96.07995 - \theta)^{-1.6364}} \tag{3}$$

Figure 1 shows two commonly used solar spectra: AM0 (standard extraterrestrial solar spectrum mainly used by the aerospace community) and AM1.5 Global (where the receiving surface is defined as an inclined plane at 37° tilt toward the equator, facing the sun).

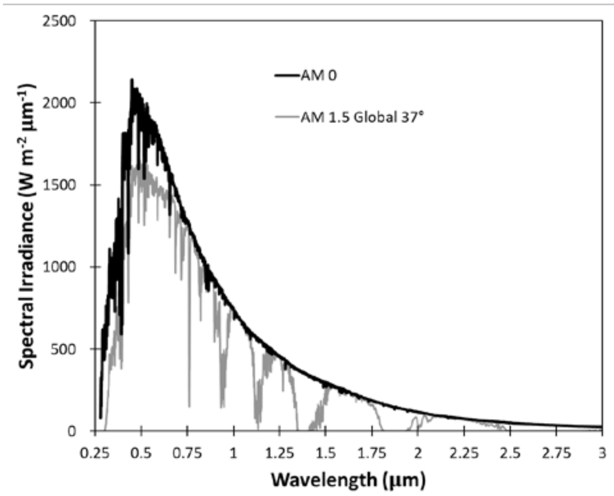

Figure 1. Extraterrestrial solar spectrum (AM0) and the standard terrestrial spectrum (AM 1.5 Global) retrieved from [4].

The spectral distribution corresponding to AM0 solar spectrum can be approximated, with a good accuracy, to the spectrum of a black body at 5758 K (The spectral distribution for Blackbody radiation being only determined by its temperature, as stated by Planck's law).

The AM1.5 Global spectrum often serves as the terrestrial standard (reference), and is measured on a surface which faces the sun, with a tilt angle of 37° over the horizontal plane, under specified atmospheric conditions (aerosol optical depth, AOD, of 0.084, precipitable water, PW, of 1.42 cm and total column ozone equivalent of 0.34 cm). An air mass of 1.5 corresponds to a solar zenith angle of approximately 48°. Passing through the atmosphere, the spectrum is attenuated differently for each wavelength due to absorption or scattering by atmospheric particles. For instance, water vapor absorption bands are mainly located in the near-infrared and infrared regions of the spectrum (around 0.94, 1.10 and 1.40 µm). The amplitude of light scattering in the atmosphere is correlated to the AM value: the higher the AM, the higher the light scattering by atmospheric molecules (such as nitrogen and oxygen). Consequently, the terrestrial irradiance (which is commonly normalized to 1000 W m^{-2}) is lower than the extraterrestrial one (around 1353 W m^{-2}). The peak solar irradiance, which corresponds to wavelengths typically comprised between 0.4 and 0.8 µm, is associated with “visible” light in the sense that human vision evolved to be particularly sensitive to this spectral range. One should distinguish different definitions for solar irradiance: Direct Normal irradiance (DNI) refers to the photons coming directly from the sun. It should be noted that the definition of Direct Normal Irradiance is not univocal. This ambiguity stems from the fact that the angular distance from the center of the sun and the penumbra function (fraction of collimated light rays that reach the pyrheliometer’s sensor) are not well limited. Several definitions of the DNI can be found in the literature, explicitly or implicitly referring to different limit angles and penumbra functions, which inherently leads to varying amounts of integrated radiance in the vicinity of the sun [5]. Global Horizontal Irradiance (GHI) refers to the total irradiance received from above by a horizontal surface, and includes both the contributions of direct normal irradiance, and diffuse radiation, associated to photons scattered in the atmosphere. The amount of diffuse radiation changes depending on the climate (and especially the cloud coverage) and the latitude, and typically represent ~15% of the total radiation. AM1.5D solar spectrum is commonly used as a reference spectrum for the characterization of concentrator solar cells (because of the fundamental inability of these cells to concentrate diffuse light).

The other atmospheric variables that significantly affect the solar spectrum characteristics are AOD and PW. AOD characterizes the radiative strength of aerosols (urban haze, smoke particles, desert dust, sea salt…) in the vertical direction while PW is the amount of condensed water corresponding to the total water vapor contained in a vertical atmospheric column above any location. Water vapor has strong absorption bands in the near infrared, which directly impacts the spectrum.

3. Principles of photovoltaic energy conversion

Solar cells should be designed to ensure a maximum absorption of photons coming from the sun, and to promote electrons to high-energy states where they are able to move. The material should have at least two energetically separated bands to guarantee an efficient extraction of the charge carriers from the PV cell. The band gap (E_g) of PV cell corresponds to the energy gap separating the maximum energy level in the low-energy band (referred as “valence band, VB”), from the minimum energy level in the high-energy band (known as "conduction band, CB"), where the electrons should be promoted. The typical time during which the electron is maintained in a high energy state should be high enough to guarantee an efficient extraction of the excited carriers (a constraint which may be fulfilled if the band gap is higher than the thermal energy k_BT (where k_B is the Boltzmann's constant and T the temperature)).

Only photons whose energy is higher than E_g are able to pump electrons from the valence band to the conduction band. The charge separation mechanism, which is required to extract charge carriers from the PV cells, involves the use of a "membrane" to separate the different charge carriers. This is commonly achieved with an electric field originating from the potential difference between contacts.

Semiconductor materials have historically been seen as a very attractive option toward efficiently converting sunlight into electricity using the photovoltaic effect. Emerging technologies using organic or/and inorganic substances such as Perovskite or polymer solar cells are currently instigating a great amount of research work, but these technologies will not be addressed in this chapter, since the underlying physical mechanisms are sensibly different (the reader should refer to the following chapters for deeper insights into these technologies).

4. Semiconductors

Materials can be classified into 3 main categories, depending on their typical electronic properties: Semiconductors and insulators both show an energy gap between their valence and conduction bands, whereas metals show an overlap between energy levels in the valence band and the conduction band (and, as a consequence, no energy gap). The development of efficient PV cells requires both an efficient absorption of solar photons, and the establishment of 2 distinct charge carrier populations, which can only be achieved with semiconductor materials.

In this section, some basic concepts related to semiconductor physics will be introduced. Electrons, holes and electronic bands will first be explained. The principles of semiconductor doping will then be detailed, before concluding this section by a description of generation and recombination of electron-holes pairs in semiconductors.

4.1 Bands, electrons and holes

In an atom, electrons move in orbitals around the nucleus and can only have certain energy values, called *energy levels*. In a solid material consisting of an immensely high number of atoms, the original orbitals are combined to form orbitals with a large number of energy levels. Because of the huge number of atoms involved, these levels are very close one from another so that they form *energy bands*. The bonds between atoms and their electronic properties determine the bands energy distribution, as well as the crystalline structure. For instance, silicon atoms share four electrons of the outermost shell (valence shell) with the neighboring atoms, creating stable and strong covalent bonds which result in a diamond lattice type crystalline structure.

The atoms chemical properties are determined to a great extent by the number of electrons in the valence shell. In a similar manner, the last occupied bands define the electronic properties of crystals. As previously mentioned, the occupied band with the highest energy, which contains the valence electrons, is called the valence band (VB) whereas the unoccupied band with the lowest energy is called the conduction band (CB). The energy between both bands is the band gap energy (E_g).

In metals, electrons move without difficulty from one energy level to another, since the valence and the conduction bands overlap in energy (E_g=0) giving rise to a high electrical conductivity. In semiconductors, the valence and conduction bands are separated ($0.5 < E_g < 3$ eV), and the valence band is filled with bonded electrons which don't have sufficient energy to overcome the energy gap and freely move in the crystalline network. At a temperature higher than 0K, a certain fraction of these electrons have sufficiently high thermal energy to be expelled to the conduction band (this fraction being function of both the temperature and the energy gap of the semiconductor material). Insulators have very high band gaps, which practically avoid electrons from the valence band to be ejected to the conduction band, because of the high energy required to overcome the band gap. As a consequence, the absence of free electrons in the conduction band precludes efficient electrical transport, and these materials are characterized by low conductivity. Figure 2, shows a scheme of insulators, semiconductors and conductors.

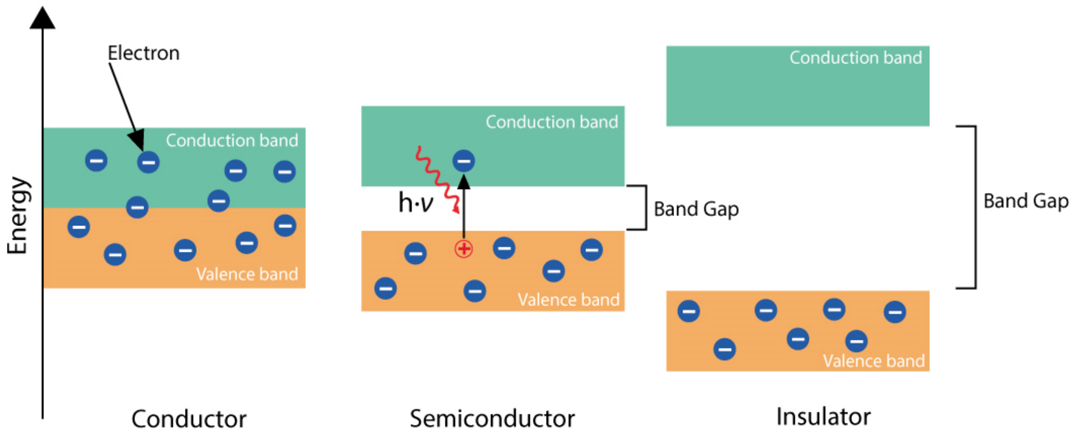

Figure 2. Scheme of conductor, semiconductor and insulator band gaps.

Electrons whose energy is high enough to overcome the electronic gap of the material, because of their thermal energy or after absorption of a solar photon, may break free from the atoms and become a free electron in the conduction band. The remaining broken bond in the valence band, is associated with a vacancy referred as a "hole". Semiconductor theory predicts that holes behave as if they were positive charges. In the presence of holes (or vacancies), other valence electrons in the valence band can move into these vacancies, thus leading to an apparent movement of “holes” in the opposite direction. Because the concentration of electrons in the valence band largely outnumbers the concentration of the remaining vacancies associated with electrons ejected in the conduction band, it is practically more convenient to describe this mechanism as a “holes” movement.

Semiconductor characterized by identical concentrations of free electrons and holes are called “intrinsic”. The concentration of free carriers (often referred as “intrinsic carrier concentration”), is correlated to both the electronic gap of the semiconductor and the temperature, and translates the ability of charge carriers to move from one band to another under the sole effect of temperature. Therefore, the higher the temperature, the higher number of electrons in the CB and the higher the conductivity (unlike conductor materials which show decreasing conductivity with increasing temperature).

4.2 Doping, n and p types

As previously explained, the conductivity of semiconductors increases as the temperature raises and the band gap decreases. For example, the electrical conductivity of Gallium Arsenide (GaAs), which has a band gap of 1.42 eV, is two orders of magnitude lower than the conductivity of Silicon (1.11 eV).

A mean to control the conductivity of semiconductors, known as *doping*, consists in introducing impurity atoms in the crystalline network, characterized by different electronic structure (and in particular, different number of valence electrons). One can distinguish two different kinds of impurity atoms:

- Donor: They possess one extra valence electron which is shared with the lattice, as a free electron. In a silicon structure, consisting of four valence electrons, phosphorous atoms are typical *donor* impurities. These atoms, which comprise five valence electrons, share four of them with their neighboring Si atoms under the form of covalent bonds, the remaining one being free to move in the crystalline network. The phosphorous atoms become ionized (positively charged) and both the electron density and the electrical conductivity are increased, relative to intrinsic silicon.

- Acceptor: Unlike *donors*, *acceptor* atoms comprise less valence electrons than the bulk atoms, and their introduction in the network give rise to the generation of extra *holes*: The impurity atoms become negatively ionized by taking a valence electron from another bond and then releasing a *hole* to the band, thus leading to increased *hole* concentration as well as higher conductivity. Boron atoms are typical acceptor atoms in silicon lattices.

Doping is thus the process by which both the conductivity and the concentration of one kind of charge carriers (either electrons or holes) are increased, through the introduction of impurity atoms showing different electronic properties than the bulk atoms. Doping allows to increase the conductivity without any external energy input (light, heat…), and semiconductors whose electronic properties are controlled using this mean are known as *extrinsic* semiconductors.

The type of doping is governed by the nature of the impurity atoms introduced in the network: if the *donor* impurity concentration exceeds the intrinsic carrier concentration, the doping is *n-type*. Conversely, if the *acceptor* impurity concentration exceeds the intrinsic carrier concentration, the semiconductor becomes *p-type*. Figure 3 schematically illustrates intrinsic and extrinsic semiconductors.

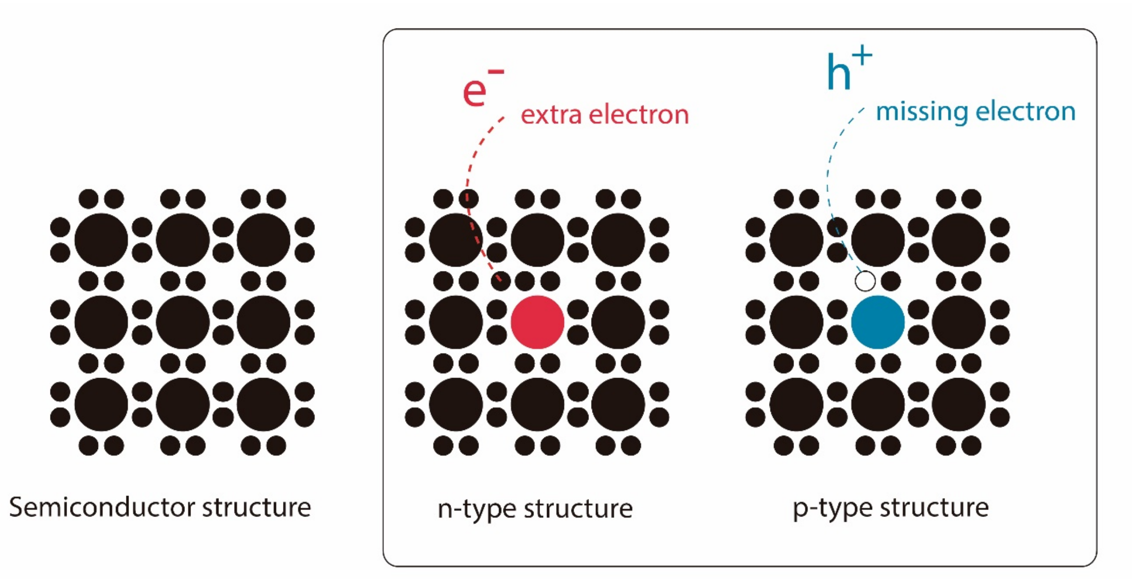

Figure 3. Structures of an intrinsic, *n-type* and *p-type* semiconductors.

4.3 Generation and recombination of electron-holes pairs

The process by which electrons are excited from the valence band to the conduction band, creating an electron-hole pair (*e-h*), is called *generation*. The inverse process is called *recombination* and involves the relaxation of free electrons from the conduction band to a vacancy (hole) in the valence band, thus leading to the annihilation of an electron-hole pair. Under thermal equilibrium, *Generation* and *Recombination* occurs at the same rate within the cell to maintain the populations of electrons and holes.

If *generation* process requires an input energy provided by photons, phonons (vibrational energy of the lattice) or kinetic energy of other particles, *recombination* is a relaxation process in which energy is released through the same mechanisms

Photogeneration, is the process leading to the creation of an *e-h* pair in the cell after photon absorption and the main generation process. Only photons with energies higher than the band gap may give rise to the generation of *e-h* pairs. Photons with energy lower than the band gap cannot participate to the photogeneration process. In addition, photons whose energy exceeds the band gap are only partially used: the difference between the incident photon energy and the electronic gap of the cell is wasted as heat. The process by which excited electrons quickly release their excess energy until they reach the edge of the conduction band is known as *thermalization* (see Figure 4). This cooling process is very fast (typically occurring at a picosecond timescale) and fundamentally explains, together with the transparency of PV cells to low-energy photons, the wide discrepancy between the high efficiency with which it is theoretically possible to convert sunlight into electricity (~90%) and the best PV efficiency experimentally achievable (which does not exceed 29% for single junction solar cells). Photogeneration is characterized by the *absorption coefficient (α)* that quantifies the semiconductor absorption as a function of wavelength, and which translates the ability for a photon of a given wavelength to be efficiently absorbed in the PV cell. The absorption process is easier in direct band gap semiconductors, due to their band structures, leading to very high absorption coefficient and, as a consequence, reduced thicknesses (the material thickness required to ensure complete absorption of the incident light being much smaller than in the case of indirect band gap semiconductors, such as Silicon).

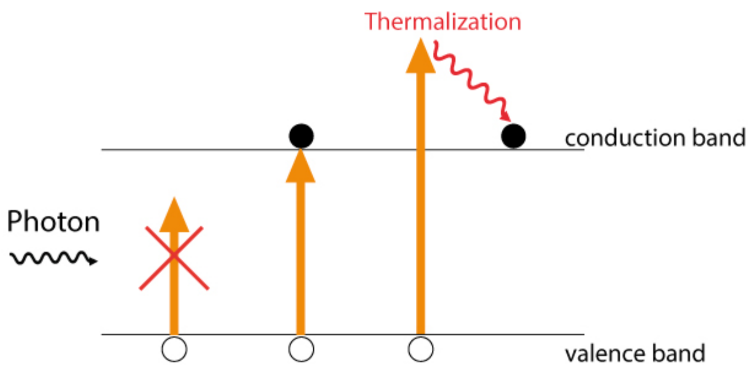

Figure 4. Sketch of the photogeneration process, depicting a) transparency loss mechanism (left) b) photogeneration (center) c) thermalization loss (right)

There are 3 main recombination processes, whose amplitude largely depend on the nature and the quality of the semiconductor materials involved, as well as on the typical density of charge carriers in the cell:

1) *band-to-band* recombination refers to the annihilation of an *e-h* pair followed by the emission of a photon of corresponding energy. These *unavoidable* recombination (in the sense that, unlike other recombination mechanisms, they must occur in any PV cell) are particularly effective in direct band gap materials, such as GaAs.

2) *Shockley-Read-Hall* (SRH) recombination involve impurities or defects in the crystalline structure, giving rise to unwanted energy levels acting like traps in the forbidden gap: annihilation of an *e-h* pair may occur if both a free electron in the conduction band, and a hole in the valence band, simultaneously fall into an impurity trap. SRH recombination is often strong in many semiconductor materials, and a particular care should be brought toward minimizing the defect density in the PV cell, through appropriate fabrication and doping conditions. Trap states are also likely to

appear at the surface of the cell, because of material discontinuities. These recombination mechanisms, known as surface recombination, may be minimized with high quality surface passivation.

3) *Auger* recombination, refers to a 3 particles mechanism where the energy of an electron in the conduction band (or alternatively, the energy of a hole in the valence band) is transferred to another electron (or hole). The excess energy is rapidly dissipated as heat in the crystalline network.

Carrier lifetime (τ) is a measure of the mean lifetime of a free charge carrier before recombination occurs. This parameter, which should be kept long enough to ensure an efficient carrier extraction from the PV cell, is largely dependent on the semiconductor and the doping.

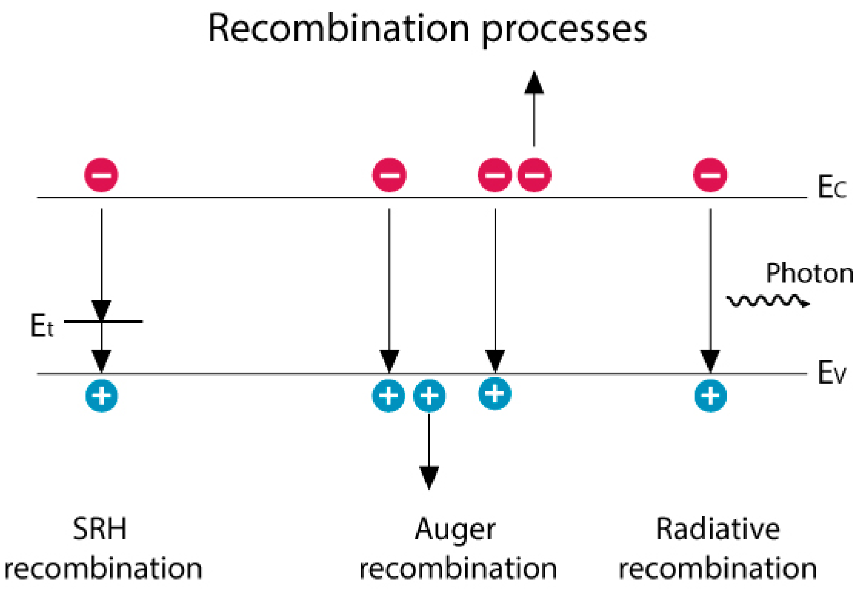

Figure 5. Scheme of the main recombination processes (SRH, Auger and Radiative).

The *diffusion length (L)* expresses the mean distance that a free carrier can travel in the cell before a recombination event occurs. The diffusion length, which should be high enough to guarantee that the carriers travel the distance separating them from the *p-n* junction, is related to the lifetime and the diffusivity (D) by the following equation:

$$L = \sqrt{D\tau} \quad (4)$$

The diffusivity determines how carriers repeal each other, whereas the mobility (μ) allows calculating carriers' velocity under an electric field. These quantities are related by the Einstein equation:

$$D = \frac{k_B T}{e}\mu \quad (5)$$

5. Solar cell structure, operation and main parameters

5.1 P-n junction

Efficient photogeneration of free charge carriers is a fundamental requirement in PV cells. However, separate collection of holes on one electrode, and electrons on the other, requires an additional mechanism to effectively extract these 2 types of carriers. This charge separation is usually achieved using a *p-n* junction (Figure 6): the electric field appearing at the interface between the *p-side* and the *n-side* of the solar cell acts as a membrane, repelling the different charge carriers in different regions of the cell where they can be separately extracted.

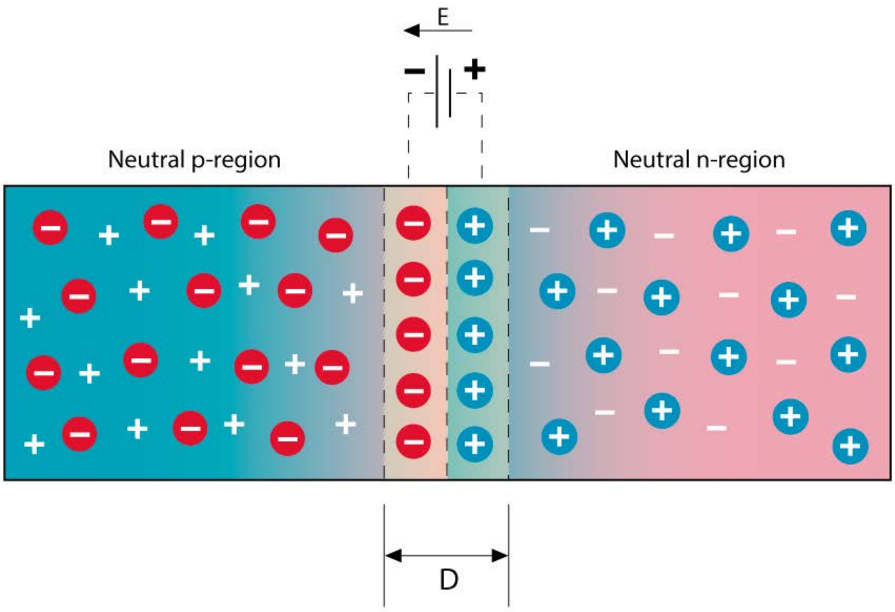

Figure 6. Scheme of the *p-n* junction showing the depletion region (D), the neutral regions and the electric field originated (E).

The *p-n* junction is realized by bringing together an *n*-type and a *p*-type semiconductor layer. On the *n*-side, electrons move by diffusion toward the *p*-side (where their concentration is orders of magnitude lower), leaving positively charged ions behind them. Similarly, holes on the *p*-side tend to diffuse to the *n*-side (where their concentration is significantly lower), thus creating negatively charged ions. The presence of negatively and positively charged ions in close contact gives rise to an electric field at the interface between the 2 regions, repelling electrons in the *n*-side and holes in the *p*-side. The region where the electric field arises is commonly referred as *depletion region* (D) since it is depleted of carriers. Consequently, two competing mechanisms constitute the driving forces for the movement of charge carriers in the cell: *diffusion*, caused by gradient in carrier concentration, represents the main driving force in the *p* and *n* neutral regions, whereas *drift*, caused by the interaction between the electric field and the electrical charges hold by electrons and holes, principally controls the movement of charge carriers in the depletion region.

5.2 Structure, operation and main parameters of solar cells

In practice, solar cells are a two-terminal device that can provide electrons to an external circuit while illuminated with sufficiently high-energy photons. Metal front and back contacts are added to extract carriers. Since the presence of a metal grid on top of the cell may avoid a significant fraction of the incident light to be absorbed, the front contact should be designed to minimize shading on the cell. However, because the metal grid geometry is also constrained by series resistance losses, the optimal grid geometry stems from a compromise between shading and series resistance.

The front surface is commonly textured to both increase the light absorption and lower the reflectivity. In addition, anti-reflection coatings with adequate refractive indexes are deposited atop of the texture to reduce Fresnel losses.

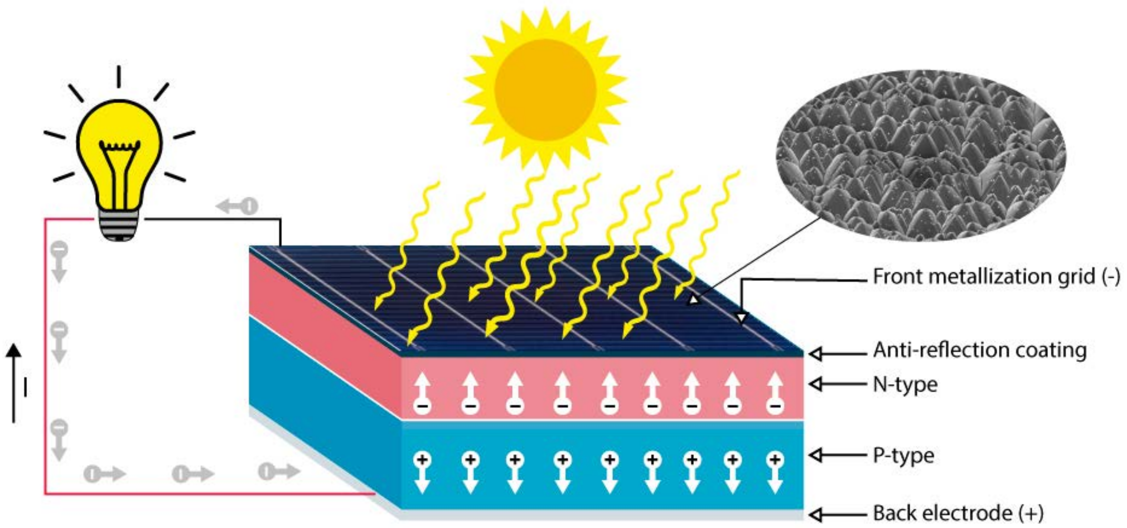

Figure 7. Sketch of a PV cell.

Figure 7 summarizes the operation of a PV cell: 1) light is absorbed in the cell and create e-h pairs 2) charge carriers move under the combined effect of *diffusion* (in the neutral regions) and *drift* (in the depletion region) 3) the *p-n* junction at the interface between the *n* and *p* side behaves as a membrane, repelling electrons in the *n*-side and holes in the *p*-side 4) electrons and holes are separately collected and injected in the external circuit.

Applying a voltage between the electrical contacts of the cell will affect the cell operation: when no voltage is applied (or alternatively, when the cell is short-circuited), the cell is said to operate in *short-circuit*, and the corresponding current, which is called *short-circuit* current (I_{sc}), represents the maximum electrical current one can extract from a PV cell. Applying a voltage bias on the PV cell leads to larger *diffusion* current associated with the flow of electrons from the *n*-side to the *p*-side, and holes from the *p*-side to the *n*-side. This current, which flows in opposite direction to the photogenerated current, grows exponentially with the applied voltage, and lowers the total current one can extract from the PV cell. For a sufficiently high value of the applied voltage, the diffusion current equals the photogenerated current, and the total current extractable from the cell is thus equal to zero. The corresponding voltage value is known as *open-circuit* voltage (V_{oc}) and corresponds to the maximum voltage that can be extracted from a PV cell.

The short circuit current depends on the spectral distribution of the incident sunlight: Achieving high I_{sc} necessarily requires an important fraction of the incoming photons to possess an energy exceeding the electronic gap of the cell. In addition, each photon with sufficiently high energy should ideally be converted into an electron-hole pair. The ability of any particular cell to fulfill this requirement is usually characterized by *quantum efficiency* (QE) measurements, which indicate the probability that a given photon of a certain wavelength (λ) will provide an electron to the external circuit.

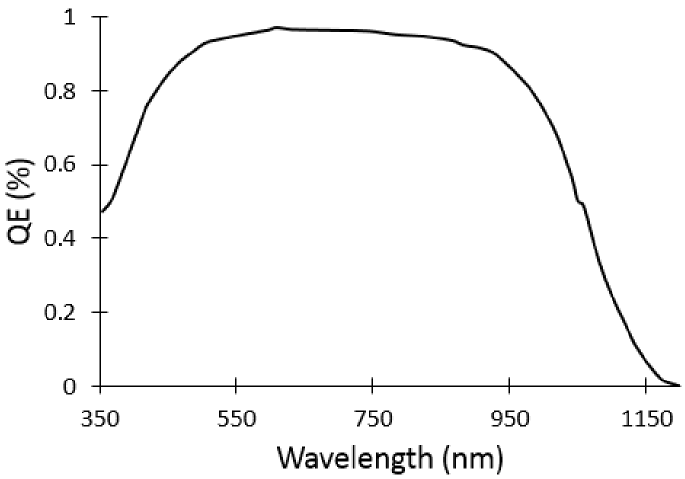

Figure 8. Quantum efficiency of a crystalline silicon solar cell

Figure 8 shows the quantum efficiency of a crystalline silicon solar cell. QE curves provide key information for solar cell manufacturers, such as the ability of the cell to efficiently collect charge carriers, the amplitude of front surface recombination or reflection losses.

Considering that the spectral incident photon flux density *F(λ)* is known, the short circuit current can be obtained using the following equation:

$$I_{SC} = eA \int F(\lambda) QE(\lambda) \frac{\lambda}{hc} d\lambda \quad (6)$$

Where *e* is the electron charge and *A* is the solar cell area.

The spectral response of a solar cell (SR) is analogous to the QE but expressed in Amperes per Watt of incident light. Both are related by the following equation:

$$SR(\lambda) = e \frac{\lambda}{hc} QE(\lambda) \quad (7)$$

Dark current due to voltage.

Applying a potential difference between the electrical contacts gives rise to a reverse current flowing in opposite direction to the photogenerated current, which is called *dark current*. This current, which is associated with the flow of majority carriers (electrons from the *n*-side to the *p*-side, holes from the *p*-side to the *n*-side), grows exponentially with the voltage, thus reducing noticeably the current extractable from the cell at high voltage values. The dark current (I_D) can be expressed as a function of the potential difference (V) by the following equation:

$$I_D(V) = I_o\left(e^{\frac{eV}{mTk_B}} - 1\right) \quad (8)$$

Where I_o is the diode reverse saturation current (associated to the movement of minority charge carriers in reverse bias), m the diode ideality factor and T the temperature in Kelvin. The diode reverse saturation current depends largely on the temperature, as well as on the material quality. The ideality factor typically ranges from 1 to 2.

Superposition and IV Curve

Solar cells follow the superposition principle, which means that the current-voltage curve of a PV cell under illumination simply correspond to the sum of the dark IV curve and the photogenerated current. The equation governing PV cell operation can thus be written:

$$I(V) = I_{SC} - I_D(V) = I_{SC} - I_o\left(e^{\frac{eV}{mTk_B}} - 1\right) \quad (9)$$

Note that, for simplicity, the sign of the photogenerated current is commonly considered as positive in the sign convention. The IV curve of the cell is thus deduced by subtracting the dark current from the photogenerated current.

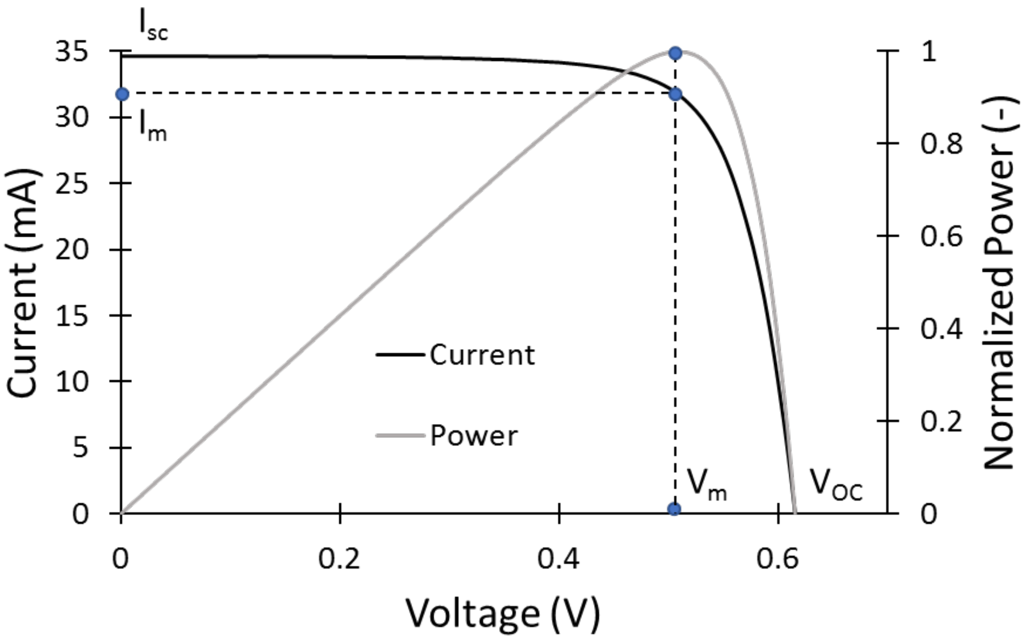

Figure 9. IV curve of a PV cell, showing the main solar cell parameters

Figure 9 shows the IV (current-voltage) curve of a solar cell which follows equation 9. The photogenerated current shifts the IV curve up, enhancing the available power to be extracted. Under low voltage values, the output current remains close to the short-circuit value. However, as the voltage increases, the dark current grows exponentially and the output current decreases.

The open-circuit voltage, which corresponds to the point of the IV curve where the dark current and the photogenerated current compensate each other, leading to an output current equal to zero, can simply be derived from equation 9:

$$V_{OC} = \frac{mk_BT}{e} ln\left(\frac{I_{SC}}{I_0} + 1\right) \quad (10)$$

Achieving high V_{oc} requires the short-circuit current to be as high as possible, and the dark saturation current to be as low as possible. Mechanisms giving rise to increased dark saturation currents (such as high operating temperature or high recombination rates) may thus significantly lower the open-circuit voltage.

Solar cells can be electrically modeled by a current generator in parallel with a diode. The generator produces a photogenerated current whose intensity is function of the illumination level to which the cell is submitted, while the diode accounts for the dark current. In real solar cells, a precise description of the electrical behavior requires power dissipation through series resistance losses to be taken into account. These are electrically modeled by a resistance in series R_s (originating from bulk, emitter, front contact and metal grid) and by a resistance in parallel R_{sh} (associated with the presence of electrical paths allowing current leakage in the cell) as depicted in Figure 10.

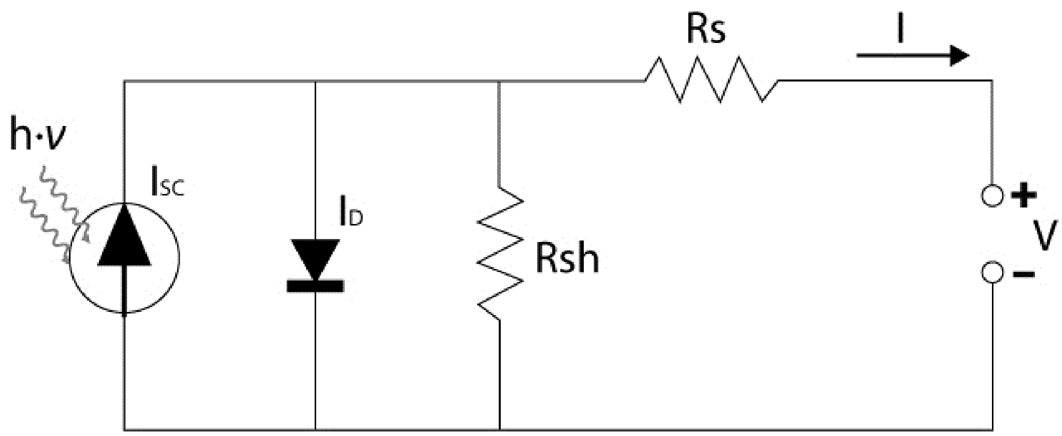

Figure 10. Equivalent circuit of a solar cell.

The IV curve of a more realistic solar cell including both series and shunt resistance can be written:

$$I = I_{SC} - I_o\left(e^{\frac{eV+IR_S}{mTk_B}} - 1\right) - \frac{V+R_S I}{R_{sh}} \quad (11)$$

The temperature dependence of PV cells mainly stems from two different mechanisms (as shown in Fig. 11): 1) the decrease in the semiconductor band gap with increasing temperature, which leads to slightly higher photogenerated current values (the fraction of the incident photons likely to create electron-holes pairs being larger) 2) the increase in the intrinsic carrier concentration with increasing temperature, giving rise to higher dark current and, in turn, lower open-circuit voltage (see eq. 10). The negative effect of temperature on the open-circuit voltage being more significant than the positive effect on short-circuit current, there is an overall detrimental effect of temperature on the cell efficiency (with a temperature coefficient typically comprised between -0.28 - 0.52% / °C for Si) [6].

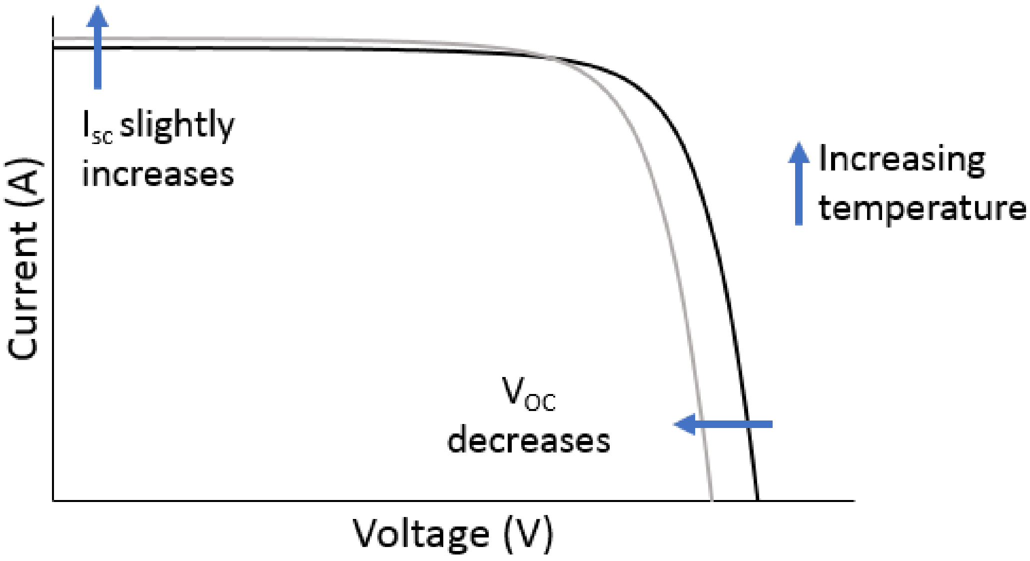

Figure 11. Effects of temperature on the IV curve of a PV cell

The electrical power delivered by a solar cell is simply calculated as the product between the current and the voltage output.

The electrical power output, depicted in Figure 9 together with the corresponding IV curve, shows a peak value denoted P_m, characterized by a voltage value V_m and a current value I_m. Achieving the highest solar to electricity conversion efficiency thus requires to apply a load equal to V_m/I_m.

The fill factor is defined as:

$$FF = \frac{I_m V_m}{I_{SC} V_{OC}} \quad (12)$$

Finally, the most important parameter to characterize the cell ability to efficiently convert sunlight into electricity is the conversion efficiency, which can simply be written:

$$\eta = \frac{I_{SC} V_{OC} FF}{A P_S} \quad (13)$$

Where P_s is the incident power per unit area.

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Chapter 3: State-of-the-art

The present thesis is based on journal papers that are enclosed in the following chapters. Therefore, a specific state-of-the-art in which the level of development reached and the last methodologies employed until the time this thesis was written can be found at each paper. Albeit the state-of-the-art of LCPV and LCPVT systems for building integration purposes is succinctly introduced in several chapters along this document, and given its importance for the present research, in this chapter a comprehensive review is presented.

Concentrating systems are classified into three categories (low, medium and high) according to their geometrical concentration ratio (C_g). Low-concentrating systems are characterized by C_g < 10X, medium by 10X < C_g < 100X and high by C_g > 100X [1]. Low- and medium-concentrating systems (only up to about 50X) are of particular interest for building integration purposes since they can use low-accuracy and, therefore, low-cost trackers (one tracking axis) and standard silicon solar cells. In addition, systems with C_g < 5X can be static due to their high acceptance angles, facilitating the integration and avoiding tracking and maintenance costs [1,2].

If a proper thermal management strategy is not adopted, concentrated irradiances may result in elevated operational temperatures of the cells and a decrease in their electrical production. Therefore, active cooling systems, which cool down the cells and provide electricity and useful heat (hybrid PVT systems), present a very high potential for market penetration, especially in the buildings sector [3].

Building integrated CPV and CPVT systems are meant to replace traditional parts of the building envelope such as roofs, façades or windows, fulfilling a function as an architectural element and as an electricity generator (in certain cases, there is also production of heat). Therefore, these systems bring an on-site production of electricity (and potentially heat) which can have a positive contribution towards NZEB buildings and help to meet the European directive of energy consumption in buildings. Building-integrated systems can change the thermal transmittance of the constructive element where they are installed or alter the amount of light entering inside the building and consequently, they modify the building energy performance. Moreover, the building can affect the performance of the photovoltaic system and therefore their introduction should be meticulously evaluated [4,5].

In the frame of building-integrated photovoltaics, Chemisana performed a review about building integrated concentrating photovoltaic systems [1]. Jelle et al. presented an overview of commercially available building integrated photovoltaic products and reported future research opportunities [4]. Sharaf and Orhan reviewed the implemented CPVT solar collectors in the literature, evaluated its performance and proposed future directions [3]. Yang and Athienitis performed a review about the research and developments in building integrated PVT systems [5]. In this section, an overview about CPV and CPVT systems with C_g < 50X for building integration purposes from 2010 on is addressed. Systems are divided into three groups according to their concentration system: 1) reflective, 2) refractive and total internal reflection and 3) other technologies.

1. Reflective concentrators

Within the field of reflective systems, several categories have been established to better explain each one and its corresponding features.

<u>Compound parabolic concentrators (CPC)</u>

Compound parabolic concentrators (CPC) have been largely used for static concentrators since they can be installed in a wide variety of locations such as façades or roofs where light is not supposed to pass through.

There are different types of CPC systems such as 3D cross-compound parabolic concentrators (3DCCPC) or compound parabolic trough concentrators. Their geometrical concentration ratio ranges from 3X to 4X with an angular acceptance around ±30° and an optical efficiency around 75% [6–9]. Therefore, CPCs are well positioned for static applications due to the high acceptance angles. These could be lens-walled and include an air gap between the parabolic reflector and the lens structure in order to promote total internal reflection (TIR) at the lens-air camera interface (Figure 1, Top). In this way, optical efficiencies and irradiance uniformities over the cell are improved. In addition, some of them have also been attached to heat extraction units leading to enhanced operational electrical efficiencies and achieving global efficiencies of 70% [7,8,10–12].

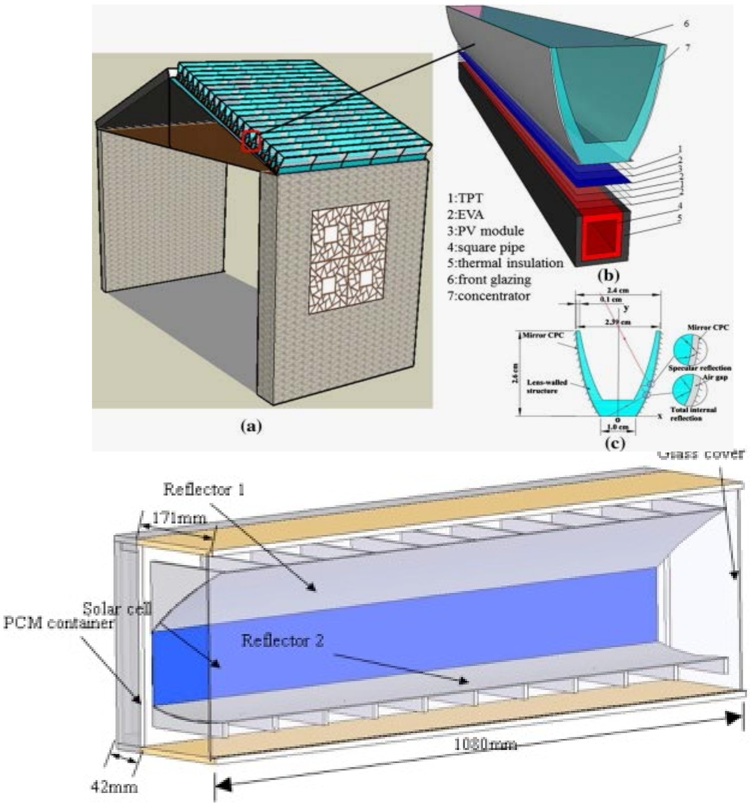


Figure 1: (Top) Trough compound parabolic concentrator with lens-walled structure and air gap with a heat extraction unit for integration in buildings [8]. (Bottom) Air filled asymmetric compound parabolic concentrator attached to a PCM container [13].

Moreover, an asymmetric CPC integrated with a Phase Change Material (PCM) for façade integration was recently reported (Figure 1, Bottom). It has a C_g of 2X and a total acceptance angle of 55°. The PCM system causes an electrical efficiency increase of 5% in comparison to the system without it [13]. Other studies with PCMs and nano-enhanced PCMs cooling systems show great potential stressing the effectiveness increase with growing irradiances [14,15].

Although being systems based on total internal reflection (TIR) and due to the similarities with the aforementioned designs, some conjugate reflective-refractive systems will be mentioned here. A refractive-based CPC similar to the 3DCCPC which achieves higher optical acceptances (±40°) with a Cg =3.6X was presented in [16]. This concentrator was fabricated using polyurethane and focuses light by TIR towards the cell. Another refractive design which focuses radiation by means of TIR is composed by an asymmetric solid CPC trough made of polyurethane with a reflective film along the edges (Figure 2). It is designed to operate under angles of incidence from 0° to 55° with C_g=2.8X. The reflective film along the edge increases the average power output (16%) [17].

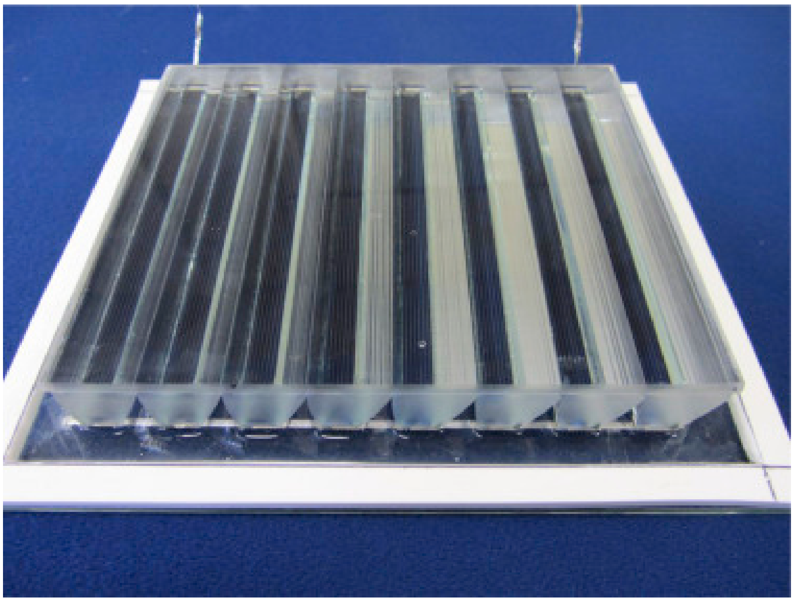


Figure 2: Asymmetric CPC trough made of polyurethane [17].

<u>Fresnel reflectors</u>

Fresnel reflectors offer some possibilities for building integration, especially those which track the sun by rotation and use one single driver. In the next paragraphs some applications are presented.

An interesting and aesthetically-appealing CPVT system developed by the Australian National University (ANU) in collaboration with Chromasun Inc. called the “micro-concentrator” (MCT) was first reported in 2010 and its experimental field performance evaluated in 2013 (Figure 3, Top). Two linear Fresnel reflector (LFR) arrays are incorporated in every generator with its corresponding PVT modules. Each module encloses silicon monocrystalline cells placed on the focal points. The modules are located over a one axis tracker suitable to be added in building roofs with a C_g = 20X and a total conversion efficiency of 75% [18,19]. This system is considered to be building added and not building integrated since it does not replace any building component.

An alternative design proposed by Chemisana et al. is a Fresnel transmission system which consists of a double-side reflective strips and a static PVT receiver. The system has a C_g= 16.7X with respect to the PV cells (10.3X referred to the gross module aperture) and achieves an average optical efficiency of 51% (Figure 3, Bottom). In this case, the reflectors track the sun by one single driver which rotates all of them simultaneously and can be integrated over façades [20–22] .

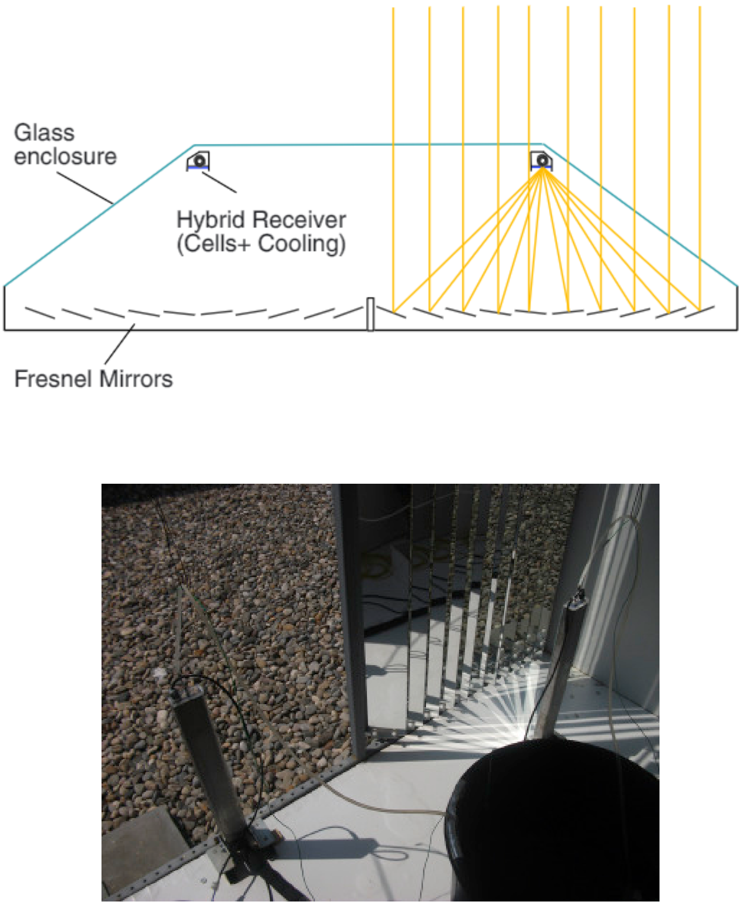


Figure 3: (Top) Micro-concentrator with two LFRs developed by ANU and Chromasun Inc. [18,19]. (Bottom) Fresnel transmission system focusing light towards the PVT receiver [20–22].

Other reflective systems

In this section some reflective systems not included in the previous categories will be described.

Davidsson et al. developed a CPVT system called “Solar Window” to be integrated at the inner part of standard windows so that the frame and glazing are shared (Figure 4, Top Left). Booster reflectors are incorporated in a way that the irradiance is concentrated onto the PV receiver (C_g=2.45X) which is cooled down by tubes embedded within the receiver. Reflectors tilt angle can be adjusted to control the amount of light entering the building [23].

Piratheepan and Anderson studied static flat and parabolic reflectors combined with PVT absorbers and a vertical glazed aperture to be integrated over façades. They also characterized the natural convection heat transfer arising from the asymmetric enclosed air gap (Figure 4, Top Right) [24]. Then, the authors studied the performance of this system for a geometrical concentration ratio of 3.6X to conclude that the number of cooling tubes plays and important role to enhance the electrical efficiency. In addition, they point out that this system is well suited only for moderate and low elevation angles [25].

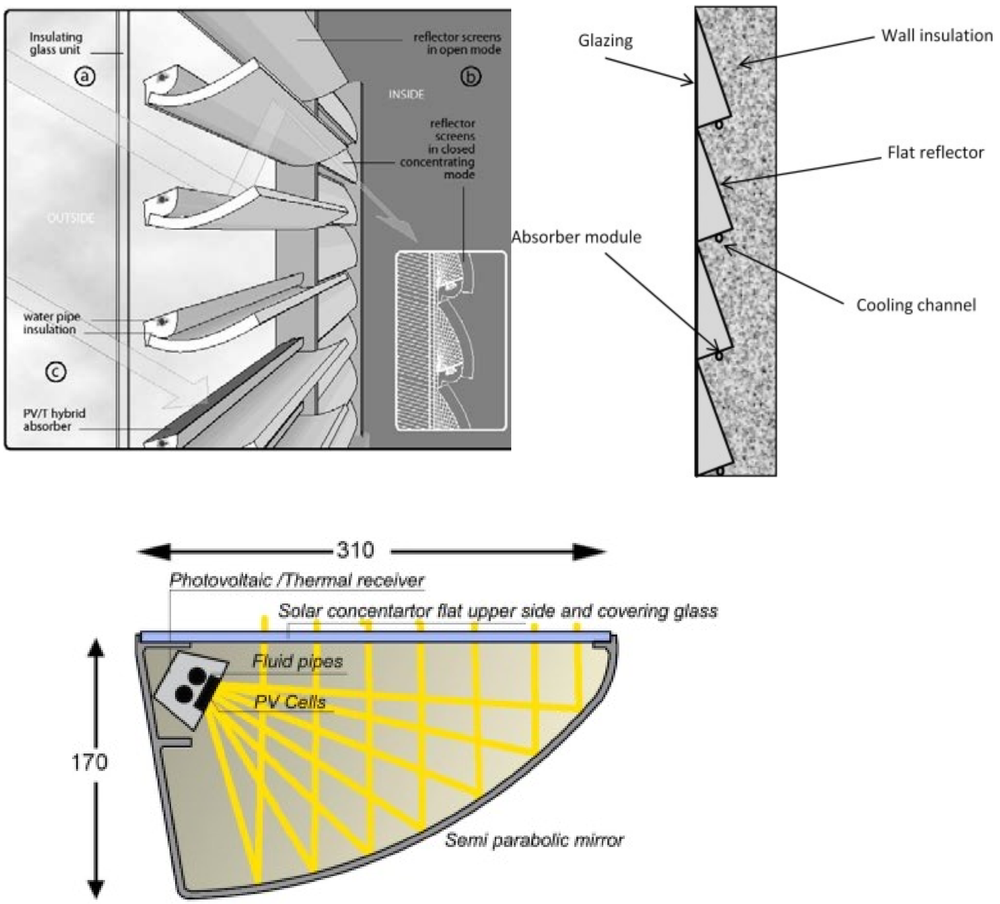


Figure 4: (Top Left) “Solar Window” CPVT system for integration on windows [23]. (Top Right) Static concentrating reflectors for façade-integrated configurations [25]. (Bottom) Semi-parabolic mirror for monoaxial sun tracking [26].

An alternative CPVT reflective system characterized by a higher geometrical concentration ratio (C_g = 20X) and composed by a trough semi-parabolic mirror and single axis tracking was recently proposed (Figure 4, Bottom). The PV cells are cooled down on the back side with a fluid circulating and it is well suited for several integration possibilities. The authors concluded that the production horizontally mounted is 30% higher than vertically mounted [26].

Furthermore, several reflective planar systems have been proposed in recent times for building integration. A planar static CPV module with Lambertian reflectors achieving a geometrical concentration ratio of 2X and an optical efficiency of 62.5% shows less angular dependence than systems equipped with V-groove rear reflectors (Figure 5, Left) [27].

Another CPV system intended for roofs which only requires lateral displacements for an effective sun tracking was introduced (Figure 5, Right). The system is composed by a mirror-coated lenslet array whose focal point experiments a lateral displacement as the incidence angle varies, allowing the use of a lateral displacement tracking mechanism. Optical efficiencies approaching 90% for a C_g=50X were reported. High tracking tolerances position this system as a low-cost candidate for a wide deployment [28].

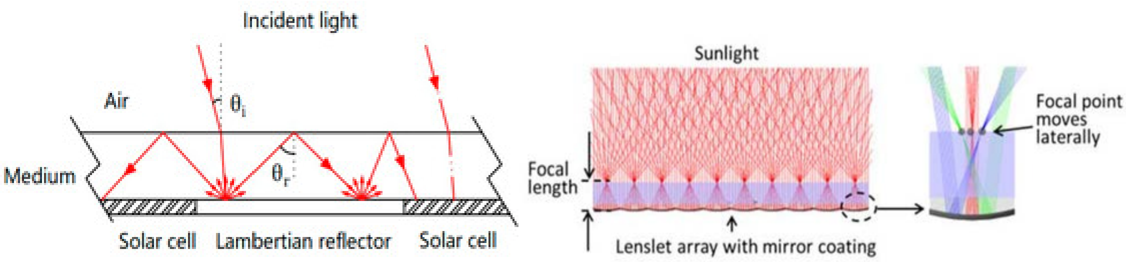


Figure 5: (Left) Planar Static PV Concentrator with Lambertian Rear Reflectors [27]. (Right) Mirror-coated lenslet array for lateral displacement tracking [28].

In addition, some building added systems, which can be installed over building roofs but do not substitute any architectural component, can be consulted in the literature such as parabolic trough PVT systems [29,30]. These systems are included here since these are technologies with potential to be integrated with similar designs. The experimental electrical efficiency was found to be very low (6.4%) [29] and Li et al. highlighted that GaAs cells possess good performance characteristics at high concentration ratios whereas polysilicon cells exhibited poorer performance characteristics [30].

2. Total internal reflection (TIR) and refractive systems

A refractive, static and concentrating (C_g=2X) see-through prism which focuses radiation by TIR for window integration was proposed (Figure 6). The system allows diffuse light to be transmitted inside the building while achieving an experimental optical efficiency of 70%. This system produces 15% more electricity than a standard module while operating 63% less PV cell area [31].

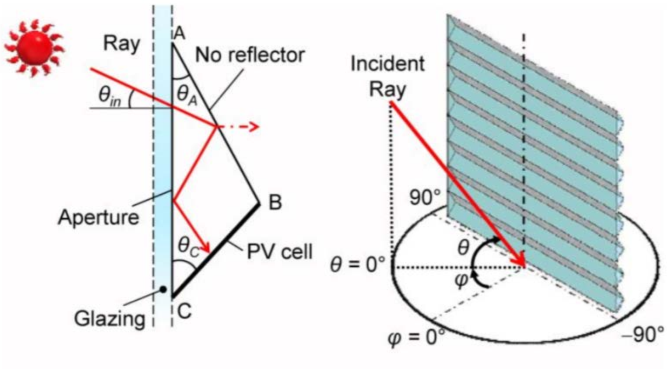
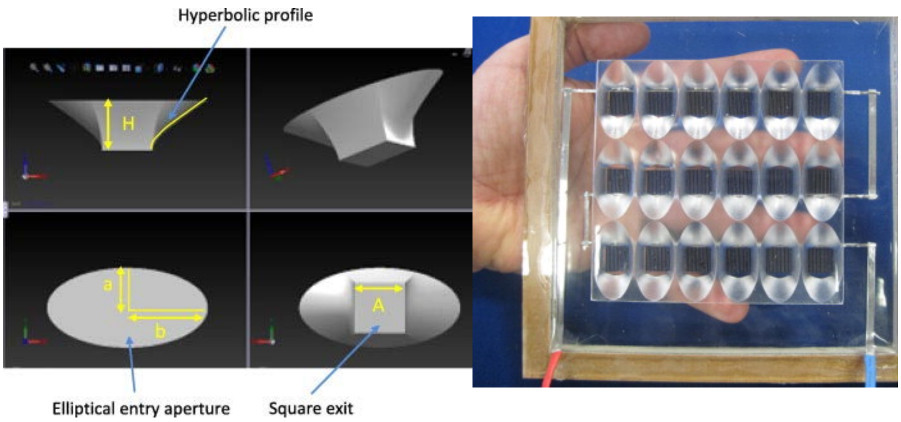


Figure 6: See-through prism which focuses radiation by TIR for window integration [31].

The "CoPeG" concept developed at University of Ulster follows the same philosophy than the previous system with C_g = 2.7X but an evacuated glazing technology has been included providing significant thermal insulation [32].



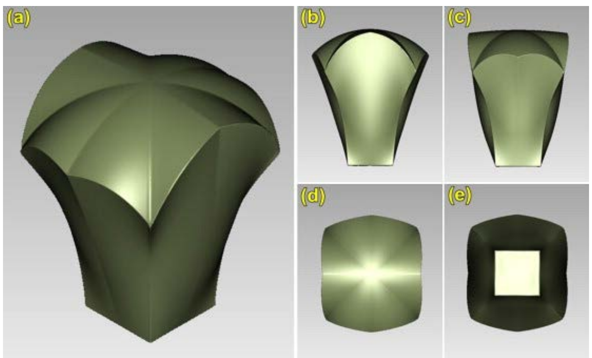


Figure 7: (Top) Square Elliptical Hyperboloid (SEH) refractive system designed for transparent façades [33]. (Bottom) Symmetrical dielectric totally internally reflecting concentrator (MSDTIRC) [34].

Another type of refractive system working on TIR is a Square Elliptical Hyperboloid (SEH) system designed for transparent façades or roofs in buildings. The proposed system does not need trackers and does not prevent natural lighting to pass through (Figure 7, Top). The system is solid, made of a dielectric material and constructed by an elliptical aperture, a hyperbolic profile section and a square exit. Several concentrations were tested observing that the one with 6X is the optimum achieving an optical efficiency of 55%. The SEH has a large acceptance angle of 120° and therefore allows for an effective sun collection [33].

Similar to the previous system, another dielectric concentrator by TIR is presented. This configuration was named as “mirror symmetrical dielectric totally internally reflecting concentrator (MSDTIRC)” (Figure 7, Bottom). This design achieves a C_g = 13.54X with optimum gains over two different planes and reduces the PV cell size [34].

Another system based on a refractive 5X dome-shaped linear Fresnel lens optically coupled with a CPC (C_g=2X) suitable for façade integration was presented by Chemisana et al. An optical efficiency of 85% and the fact that the receiver and not the Fresnel lenses tracks the sun and allows a better lighting control were the most notable aspects [35–37].

3. Other technologies

Thermotropic layer

A novel static concentrator for windows or for a glazed façade called the “smart window” which incorporates a thermotropic layer has been designed (Figure 8). The thermotropic layer is responsible for varying the fraction of light transmitted or scattered as a function of the heat that it is subjected to. Then, an important share of the scattered light is driven by TIR to the solar cells placed on the edges, achieving a geometrical concentration ratio up to 1.2X and an optical efficiency ranging from 10% to 25% depending on the thermotropic reflectivity [38,39].

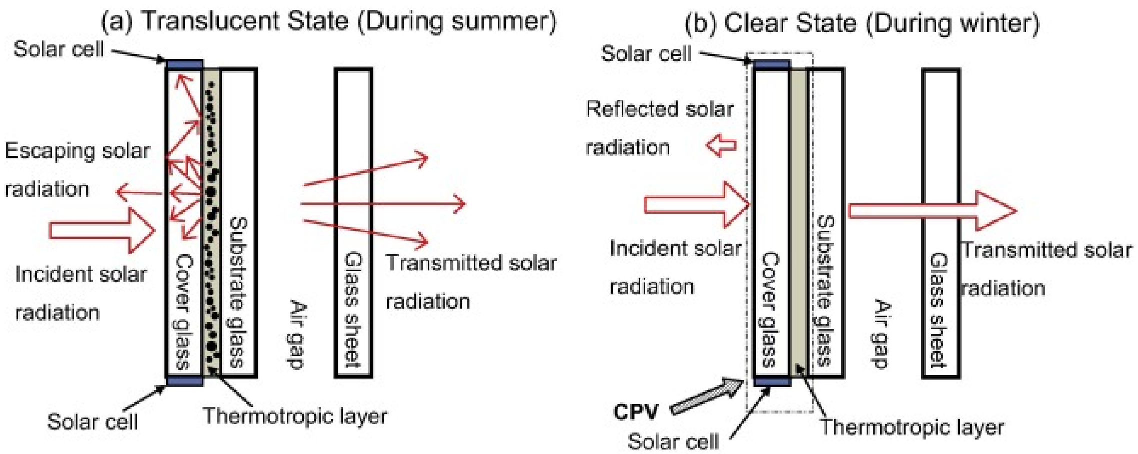


Figure 8: Thermotropic layer for integration in windows [38,39]

Holographic systems

Holographic systems for solar energy applications were first proposed more than thirty years ago due to their light weight, their ability to perform different functions, reproducibility and transparency [1]. Among holograms, volume holograms are the most widely utilized due to their high efficiency and their angular and chromatic selectivity. These last properties are key to design systems for lighting, solar shading or solar concentration. Collados et al. presented an analysis of the main existing holographic solar energy systems reported until 2016 studying in detail the optical element characteristics [40]. From 2016 several systems have also been reported and can be consulted in the literature [41–43].

This technology offers many advantages for building integrated systems and some examples are given below.

A holographic lens with single-axis tracking which diffracts light in the spectral bandwidth to which the cell presents the highest sensitivity with a concentration ratio of 3.6X was presented. This design avoids infrared photons not contributing to photogeneration to reach the cell [44]. The holographic element increases the efficiency of the PV cell by 3% and the fill factor by 8%.

Another PVT system has been designed to be superimposed into a solar shading louvre (Figure 9). Solar altitude tracking is obtained by rotation already available on the blinds. The geometric concentration ratio is around 10X and the annual mean optical efficiencies are ranging between 30% and 43% depending on the location [45].

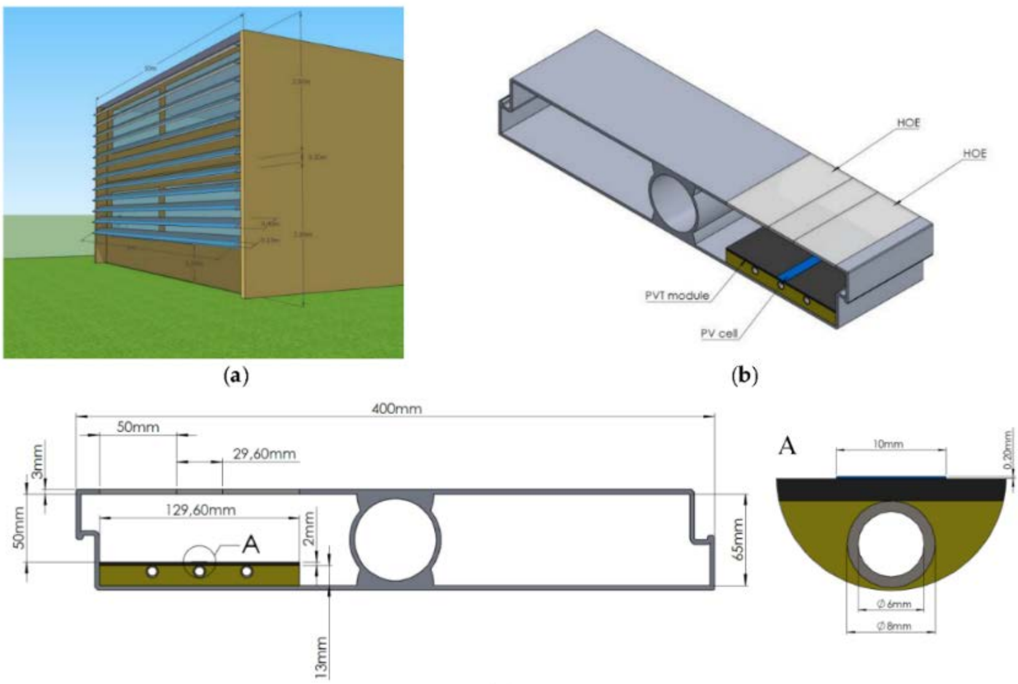


Figure 9: Holographic concentrator for solar shading louvres [45].

Luminescent solar concentrators (LSC)

Luminescent solar concentrators (LSC) have been subject of interest in the last 30 years due to their reduced cost and flexibility [46]. LSCs use luminescent particles and a polymeric or glass waveguide, in which light gets transmitted. These particles are enclosed into the waveguide and absorb the transmitted sunlight to re-emit it at longer wavelengths. Then, the light is concentrated by means of TIR towards the edges where PV cells are attached. These concentrators are generally static and able to concentrate both direct and diffuse light while having high transmittances for the visible light. Being this last fact, key for integration in buildings. Many groups keep working on this topic and some improved versions based on quantum dots are reported on the literature aiming to achieve higher efficiencies and, consequently, a wider range of applications [47].

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Chapter 4: Spectral modeling

A. Vossier, A. Riverola, D. Chemisana, A. Dollet and C. A. Gueymard, Is conversion efficiency still relevant to qualify advanced multi-junction solar cells?, Progress in Photovoltaics: Research and application, 25, 242–254, 2017

1. Introduction

In this paper, the model developed to obtain the spectral distribution of the incident irradiance to which solar cells are submitted under real working operations is explained. The model inputs are the main atmospheric parameters retrieved from the AERONET database, the location and the time. In addition, a study of how the spectral variability affects the annual energy yield of Multi-Junction (MJ) solar cell architectures has been performed to stress its importance.

MJ solar cells allow a more efficient absorption of the solar spectrum and achieve higher conversion efficiencies than these with a single junction. In fact, the higher the number of pn junctions involved in the MJ stack, the higher the theoretical efficiency is. However, the process to grow multiple subcells on top of each other is very challenging due to several constraints such as lattice and current matching and suitable optical and electrical properties. Until now, MJ cells comprising 5 different subcells have been already fabricated by manufacturers showing significant progress.

It is worth to note that indefinitely increasing the number of subcells is not necessarily the best option towards achieving higher energy outputs for two fundamental reasons. First, the efficiency gain of adding an extra pn junction decreases as the number of junctions gets higher. Therefore, the extra cost associated with its fabrication might not be balanced with the efficiency enhancement. Second, the sensitivity to variations in the irradiance's spectral distribution has been shown to be enhanced for MJ involving a large number of subcells.

The question of whether or not CPV systems involving MJ solar cells are likely to outperform standard PV devices considering the spectral variations over a long period of time is raised. In order to answer this question, the annual energy yields of CPV systems based on MJ cells involving up to 10 subcells are calculated for different locations using the inputs from the spectral model.

2. Results and contribution to the state-of-the-art

This paper shows that increasing the number of subcells in MJ cells does not necessarily lead to a higher annual energy output under real spectral conditions. Even if it leads to a higher conversion efficiency subjected to a specific spectral distribution, the annual energy output can have detrimental impacts due to the weak ability of these MJ architectures to accommodate changes in the spectral content.

The results indicate that architectures involving tandem or triple-junction solar cells bring increased energy outputs compared to single-junction solar cells. However, this gain becomes highly location-dependent for systems comprising MJ cells with 4 subcells or more.

Therefore, MJ cells involving more than 3 subcells do not guarantee a higher annual energy output. The optimum number of subcells ranges from 4 to 7 depending on the location. Also, the gap between the simulated annual energy output and the expected (based on the efficiency under standard conditions) energy output appears to grow steadily when the number of subcells increases.

The capacity to optimally generate energy throughout an extended period of time, representative of actual operating conditions, should be carefully evaluated rather than rating MJ cells against a unique set of standard conditions.

3. Contribution of the candidate

The candidate participated analyzing the main atmospheric variables impact on the solar spectrum and performing the spectral simulation with its validation. In addition, the candidate contributed in the paper writing and in all the other research tasks in a collaborative framework.

4. Journal paper

The complete study can be found in the following research paper:

Authors: A. Vossier, A. Riverola, D. Chemisana, A. Dollet and C. A. Gueymard

Title: Is conversion efficiency still relevant to qualify advanced multi-junction solar cells?

Journal: Progress in Photovoltaics: Research and application

Volume: 25 **Pages:** 242-254

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RESEARCH ARTICLE

Is conversion efficiency still relevant to qualify advanced multi-junction solar cells?

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ABSTRACT

For better conversion of sunlight into electricity, advanced architectures of multi-junction (MJ) solar cells include increasing numbers of subcells. The Achilles' heel of these cells lies in their increased sensitivity to the spectral distribution of sunlight, which is likely to significantly alter their performance during real working operation. This study investigates the capacity of MJ solar cells comprising up to 10 subcells to accommodate a wide range of spectral characteristics of the incident radiation. A systematic study is performed, aimed at a realistic estimation of the energy output of MJ-based concentrating photovoltaic systems at characteristic locations selected to represent a large range of climatic conditions. We show that optimal MJ architectures could have between 4 and 7 subcells. Beyond seven subcells, the slight gains in peak efficiency are likely outweighed by detrimental increases in dependence on local conditions and in annual yield variability. The relevance of considering either conversion efficiency or modeled energy output as the most appropriate indicator of the cell performance, when considering advanced architectures of MJ solar cells, is also discussed.

KEYWORDS
multi-junction; solar cell; CPV; energy yield; solar spectrum

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Chapter 5: Dielectric liquids analysis

D. Chemisana, E.F. Fernandez, A. Riverola and A. Moreno, Fluid-based spectrally selective filters for direct immersed PVT solar systems in building applications, Renewable Energy, 123, 263-272, 2018

1. Introduction

Direct immersion of PV cells in dielectric liquids has proved to enhance conversion efficiencies due to a reduction of the Fresnel losses with respect to a bare PV, a reduction of the surface recombination and a better temperature control. However, despite these great benefits, direct-immersed PVTs have not been completely investigated to leverage their potential yet.

In order to fill the gap regarding direct-immersed PVT collectors characteristics and to address the goal of designing high-efficient PVT systems for buildings, this paper evaluates several fluid-based optical filters suitable for direct immersion of solar cells. The candidates should ideally fulfill a double function: (1) transmit photons at the photovoltaic cell maximum spectral response bandwidth (and absorb photons out of this zone); (2) remove the infrared photons emitted by the solar cell to prevent from problems associated with overheating such as efficiency reduction, thermal stress or dilatation of materials.

Based on this, the optical, electrical and thermal properties that a liquid filter for PVT generation should have are first identified in order to finally conduct a series of experiments and calculations. In this way, the adequacy of the candidates for the present application is evaluated.

2. Results and contribution to the state-of-the-art

The key issues which have been identified from the optical, thermal and electrical characteristics of dielectric liquids are: (1) the liquids have to be highly transparent at the region where the solar cells are more efficient, (2) the liquids refractive index should be higher than the air refractive index to reduce Fresnel losses, (3) the adsorption of the liquid dipoles at the cell front and rear surfaces may improve the cell performance and (4) the direct thermal contact between the cell and the liquid enhances heat dissipation.

In order to calculate the bandwidth at which the filter should transmit the maximum, an ideal filter window (IFW) indicator has been defined. This indicator is obtained as a function of the spectral response of the selected photovoltaic technology and the incident spectrum. Several technologies and spectra have been considered due to its variability.

A series of dielectric liquid candidates have been selected based on their adequateness for the present application. These candidates have been evaluated optically, thermally and electrically to state their advantages and disadvantages for a PVT direct-immersed solar module. Moreover, operational features have been considered as freezing temperatures, stability, degradation of components, etc.

Two liquids have been identified as optimal from the obtained results: a mixture of deionized water (DIW) with isopropyl alcohol (IPA) and a mixture of deionized water (DIW) with dimethyl sulfoxide (DMSO). Both achieve high transmittance for the bandwidth obtained with the IFW criteria, high absorbance for photons above the upper interval of the IFW and good thermal characteristics to remove heat with the highest efficiency and lowest pumping power necessary. However, a mixture of DIW and DMSO may not properly work in cold climates as the freezing temperature is above 0ºC.

3. Contribution of the candidate

The candidate actively participated in the literature review to find suitable dielectric liquids for this application. Also, the candidate collaborated in the spectra calculation, in the definition of the ideal filter window parameter and in the experimental work carried out.

4. Journal paper

The complete study can be found in the following research paper:

Authors: D. Chemisana, E.F. Fernandez, A. Riverola and A. Moreno

Title: Fluid-based spectrally selective filters for direct immersed PVT solar systems in building applications

Journal: Renewable Energy

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Fluid-based spectrally selective filters for direct immersed PVT solar systems in building applications

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A B S T R A C T

Liquid filters applied in hybrid photovoltaic-thermal (PVT) solar systems report potential benefits as they allow for selecting the wavelengths at which the solar cell operates with higher efficiency. Among the rest, low frequency photons are absorbed by the liquid, therefore not warming the cell up. In addition, direct immersion of photovoltaic cells in liquids enhances temperature control by cooling the cells under almost negligible contact resistance between the liquid and the cell. The characteristics of the liquids for direct immersed PVT application are described, defining an indicator (ideal filter window) to select the best liquid depending on the PV technology and the incident irradiance. Several liquids are assessed based on the required properties for the present application. As a conclusion, regarding optical, thermal, electrical and operational aspects, a mixture of deionized water and isopropyl alcohol results as proper candidate satisfying well all of them.

Chapter 6: Emissivity modeling

A. Riverola, A. Mellor, D. Alonso Alvarez, L. Ferre Llin, I. Guarracino, C.N. Markides, D.J. Paul, D. Chemisana and N. Ekins-Daukes, Mid-infrared emissivity of crystalline silicon solar cells, Solar Energy Materials and Solar Cells, 174, 607-615, 2018

1. Introduction

The radiative emissivity of PV cells is gaining increasing interest in the community since engineering cells for PVT collectors with low emissivity in the thermal emission range can lead to a higher thermal output. In another applications, enhancing the emissivity in this range can promote radiative cooling to reduce operating temperatures. However, despite being a fundamental property of a solar cell, very little is known about the emissivity of real devices and its physical origins.

In this paper, the emissivity of presently-manufactured silicon solar cells has been measured in the 0.35 – 16 μm range, and the first full radiative model of a solar cell considering both absorption in the spectral range of sunlight and thermal emission in the mid-infrared (MIR) has been developed. The model considers the complete cell structure with realistic layer properties and front and back textures. Also, a discussion of how light trapping/outcoupling contributes to emissivity and in which spectral regions is provided. Then an investigation about how changes to device parameters such as doping levels and texture angle may affect the emissivity was performed. This is important since parameter changes in future PV cell designs may have unintended effects on the emissivity, or the cell design may be intentionally changed in order to control emissivity. The model is then used to predict the emissivity of an encapsulated PV cell under soda-lime-silica low-iron glass.

2. Results and contribution to the state-of-the-art

Both unencapsulated and encapsulated c-Si solar cells are found to be good radiative thermal emitters. The mid-infrared emissivity of the unencapsulated case is around 80%, dominated by highly doped regions and enhanced by the presence of the surface texture. The MIR emissivity of the encapsulated cell is around 90% due to the high emissivity of the cover glass. Furthermore, a sensitivity analysis on the main cell parameters shows that the texture steepness is a major factor which can vary the NIR and MIR emissivity from around 25% to 85% and from 60% to 90%, respectively. Assuming that modern silicon solar cells are mainly textured with elevation angles around 55º, it can be concluded that the mid-infrared emissivity of commercial silicon solar cells will be high (>= 75%) if there is at least one highly doped layer.

The results were obtained using the first full radiative model including UV/VIS/NIR absorption and MIR emission and validated against experimental data. The results show the scope that exists for emissivity control. While there is some scope for increasing solar cell efficiency by enhancing radiative emission, these results show that most PV modules in the field are already good radiative thermal emitters. Conversely, it is likely that the thermal efficiency of PVT collectors is significantly limited by radiative losses. Suppressing these by employing measures to reduce MIR emissivity is expected to lead to improved thermal performance of PVT collectors. The above results confirm that the emissivity of commercial silicon solar cells has been understated in recent works.

The presented study serves to underpin ongoing research into emissivity control, and to better understand a basic property of the c-Si solar cell, which is becoming one of the world's most ubiquitous optoelectronic devices.

3. Contribution of the candidate

The candidate performed the literature review so that previous studies and optical constants related with this work were retrieved. Then, the candidate programmed the optical model and conducted the simulations. Also, the candidate had a major contribution in the paper writing.

4. Journal paper

The complete study can be found in the following research paper:

Authors: A. Riverola, A. Mellor, D. Alonso Alvarez, L. Ferre Llin, I. Guarracino, C.N. Markides, D.J. Paul, D. Chemisana and N. Ekins-Daukes

Title: Mid-infrared emissivity of crystalline silicon solar cells

Journal: Solar Energy Materials and Solar Cells

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Mid-infrared emissivity of crystalline silicon solar cells

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ARTICLE INFO

Keywords:
Emissivity
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Hybrid photovoltaic-thermal
Silicon
Optical modelling
Photon management

ABSTRACT

The thermal emissivity of crystalline silicon photovoltaic (PV) solar cells plays a role in determining the operating temperature of a solar cell. To elucidate the physical origin of thermal emissivity, we have made an experimental measurement of the full radiative spectrum of the crystalline silicon (c-Si) solar cell, which includes both absorption in the ultraviolet to near-infrared range and emission in the mid-infrared. Using optical modelling, we have identified the origin of radiative emissivity in both encapsulated and unencapsulated solar cells. We find that both encapsulated and unencapsulated c-Si solar cells are good radiative emitters but achieve this through different effects. The emissivity of an unencapsulated c-Si solar cell is determined to be 75% in the MIR range, and is dominated by free-carrier emission in the highly doped emitter and back surface field layers; both effects are greatly augmented through the enhanced optical outcoupling arising from the front surface texture. An encapsulated glass-covered cell has an average emissivity around 90% on the MIR, and dips to 70% at 10 μm and is dominated by the emissivity of the cover glass. These findings serve to illustrate the opportunity for optimising the emissivity of c-Si based collectors, either in conventional c-Si PV modules where high emissivity and low-temperature operation is desirable, or in hybrid PV-thermal collectors where low emissivity enables a higher thermal output to be achieved.

Chapter 7: Optical design

A. Riverola, A. Moreno and D. Chemisana, Performance of a dielectric PVT concentrator for building-façade integration, Optics Express, Accepted Manuscript

1. Introduction

Following the previous chapters and based on the outcome and results, the concentrator optical design and optimization are addressed in this paper. The present research aims at developing an innovative direct-immersed PVT concentrator for building integration.

The requirements are set so that the system should be integrated on a building' façade and use low-accuracy trackers and standard cells. This allows having a more cost-effective system. Low-concentration modules ease building integration applications, in particular, cylindrical optical systems whose solar tracking is less restrictive than in high CPV (HCPV) (single-axis instead of two-axis). In addition, the environmental impact and the efficiency are enhanced under concentrated illumination.

For that purpose, the system design is first introduced. Later, the concentrator is optimized and analyzed by a full ray-tracing algorithm which was developed for this purpose. The optimal options derived from the theoretical results are fabricated and experimentally assessed.

2. Results and contribution to the state-of-the-art

The system is based on a cylindrical BK7 chassis which confines the dielectric liquids (deionized water, DIW, and isopropyl alcohol, IPA) where the PV cells are immersed. The interfaces between the BK7 and the dielectrics have been optimized for three different geometrical concentrations (10, 15, and 20), obtaining better results from 10X to 15X for DIW and for 10X with IPA. The system with DIW achieves an optical efficiency of 76%, with a misalignment acceptance angle from 1.11° (10X) to 0.71° (15X) and a non-uniformity coefficient from 0.14 (10X) to 0.19 (15X). On the other hand, in the case of IPA the system optical efficiency is enhanced (81%), the acceptance angle to misalignment is 1.07° and the non-uniformity 0.13. The designs' performances for angular variations in the direction along the cylinder axis (non-tracked direction) have been analyzed obtaining adequate performances in both systems but slightly better for the module with IPA. The optical simulations were validated by fabricating and experimentally testing system prototypes.

The refractive system proposed shows potential to be cost effective and able to cover a considerable share of the electricity and heat energy demands of buildings.

3. Contribution of the candidate

The candidate performed the literature review to find related works. He participated in developing and refining the optical model jointly with the fabrication and the experimental performance evaluation of the prototypes. Finally, the candidate had a major contribution in the scientific article writing.

4. Journal paper

The complete study can be found in the following research paper:

Authors: A. Riverola, A. Moreno and D. Chemisana

Title: Performance of a dielectric PVT concentrator for building-façade integration

Journal: Optics Express (Accepted)

Volume: - **Pages:** -

Year: 2018

Impact Factor: 3.356

Category, Rank and Quartile: OPTICS 19/94, Q1

DOI:-

Chapter 8: Energetic dynamic modeling and simulation

A. Moreno, A. Riverola and D. Chemisana, Energetic simulation of a dielectric photovoltaic-thermal concentrator, Solar Energy, 169, 374-385, 2018

1. Introduction

A dynamic energy simulation of the concentrator previously designed and optimized has been conducted to determine its feasibility. The system aims to partially cover thermal and electrical demands utilizing a radiant floor and a reversible air-air heat pump for space heating and cooling (SH&C) and an electrical circuit which combines direct consumption and battery storage. The simulation has been performed on a typical 2-story single-family house for three different locations: Lisbon (Portugal), Barcelona (Spain) and Genoa (Italy).

It is also worth to note that very few studies of direct immersed CPVTs can be found in the literature and specifically, to the best of the authors' knowledge, no research regarding building integrated direct immersed CPVTs has been conducted yet.

The present research is structured in three main sections. First of all, the CPVT module developed and the building where it is superimposed are described. Then, simulations to thermally characterize the concentrator by conjugating computational fluid mechanics (CFD) and heat transfer in a Multiphysics environment have been conducted and experimentally validated. Afterwards, the methodology followed up in the TRNSYS modeling is explained. Finally, the results obtained are presented and the main conclusions are stated.

2. Results and contribution to the state-of-the-art

A building-integrated concentrating photovoltaic-thermal (CPVT) system with direct immersion of solar cells has been modeled and simulated with TRNSYS 16 in three different cities representative of mild winter and hot summer climate: Lisbon, Barcelona and Genoa. A new TRNSYS type has been programmed based on the CPVT module performance assessment. Specifically, the thermal performance of the collector has been analyzed numerically and experimentally in the frame of the present research.

The thermal energy generated by the CPVT system aims to cover the domestic hot water demand, which is the priority, and partially the space heating energy requirements by means of a radiant floor. In addition, the electrical energy generated by the PV cells is designed to cover the electrical demands of lighting and appliances and to power an air-air reversible heat pump for space heating and cooling.

Regarding the domestic hot water energy demands, the annual average solar fractions (SFs) found are higher than 74.0% in Lisbon and Barcelona and 52.6% in Genoa. In addition, the potential of the CPVT system could provide SFs for space heating and cooling of 68.7% in Lisbon, 62.4% in Barcelona and 38.3% in Genoa. Finally, in the case of electrical loads, SFs take a value of 44.09% in the case of Lisbon, 38.9% for Barcelona and 23.51% for Genoa.

The performance of the CPVT collector analyzed is satisfactory for all the cases but in the case of Genoa the thermal performance is in the limit of achieving satisfactory solar fraction values. The limitations of the CPVT collector (high heat loss coefficient and shading for low latitudes achieving high solar altitudes) indicate system suitability for locations with mild winters and latitudes with not so high solar heights (i.e. not above 75º). The results obtained demonstrate the appropriateness of the system for three selected cities with mild winters and hot summers representative of Csa climate and latitudes in the interval 38.7 º (Lisbon) - 44.4 º (Genoa), which means maximum solar altitudes for the case of Lisbon of around 74º.

3. Contribution of the candidate

The candidate provided the module optical data inputs for the model and collaborated in the thermal characterization which includes the CFD simulation and the experimental validation. Regarding the TRNSYS simulation, the candidate collaborated in all the methodology stages to set-up the final simulation. Finally, the candidate also collaborated with the other authors writing the scientific paper.

4. Journal paper

The complete study can be found in the following research paper:

Authors: A. Moreno, A. Riverola and D. Chemisana

Title: Energetic simulation of a dielectric photovoltaic-thermal concentrator

Journal: Solar Energy

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Energetic simulation of a dielectric photovoltaic-thermal concentrator

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ARTICLE INFO

Keywords:
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Hybrid Photovoltaic-Thermal (PVT)
Direct immersion in dielectric liquids
Energy dynamic simulation

ABSTRACT

A solar concentrating photovoltaic-thermal (CPVT) module with cell immersion in dielectric liquid has been modelled and energetically simulated. The concentrator focuses radiation linearly by using a cylindrical shape optics made of polymethyl methacrylate. The geometric concentration is 12 suns with an optical efficiency of 76.14%. The dielectric fluid, deionized water, flows through the concentrator case fulfilling a double function: to concentrate and to cool the PV cells. The concentrator is designed to be superimposed in front of the windows in a 2-storey family house with 4-person occupancy. The system is modelled to partially cover thermal and electrical demands utilizing a radiant floor and a reversible air-air heat pump for space heating and cooling (SH&C) and an electrical circuit which combines direct consumption and battery storage. The system topology has been simulated for three locations (Lisbon, Barcelona and Genoa). Results indicate an appropriate performance of the system analyzed with DHW solar fractions in a range from around 61% to above 75%. The lowest corresponds to Genoa and the highest to Lisbon and Barcelona. Regarding SH&C solar fractions are also quite adequate with values ranging from 38.3% (Genoa) to above 60% (68.8% in Lisbon and 62.4% in Barcelona). Finally, SFs for electrical loads take a value of 44.09% in the case of Lisbon, 38.9% for Barcelona and 23.51% for Genoa.

Chapter 9: Conclusions and future work

1. General discussion and conclusions

In this thesis, two innovative cylindrical low-concentration photovoltaic systems with the cells directly immersed in dielectric liquids (deionized water, DIW and isopropyl alcohol, IPA) for building integration over façades or windows have been developed. These systems cogenerate electricity and heat leading to meet the European Union directive on energy performance of buildings. In the following paragraphs, the main conclusions according to the logical order linked to the design stages and objectives are reported.

From the spectral simulation, it is concluded that assessing solar cells by its capacity to generate energy under real spectral conditions should be meticulously evaluated rather than evaluating cells against a unique set of standard conditions. The case-study considering multi-junction cells showed that these involving more than 3 subcells do not guarantee higher annual energy outputs due to higher spectral sensitivity with increasing number of junctions.

Dielectric liquids candidates have been evaluated based on their optical, thermal, electrical and operational properties to state their adequateness for a PVT direct immersed system. The results showed that IPA, DIW or mixture of them were the optimal candidates for European climates with a suitable melting point, high absorption of infrared photons, good thermal properties, adequate viscosity and high transmittance in the bandwidth window required for photogeneration.

Regarding the emissivity study of commercial silicon solar (c-Si) cells, both unencapsulated and encapsulated, were found to have high emissivity over the thermal range, being around 80% for unencapsulated cells due to the highly doped regions and enhanced by the texture and 90% for the encapsulated case due to the highly emissive cover glass. These results have also been validated against experimental data obtained by means of an integrating sphere. As a consequence, radiative losses significantly limit the thermal efficiencies of PVT collectors and there exists the opportunity to take measures towards reducing the mid-infrared emissivity and leading to improved thermal collectors.

From the optical ray-tracing optimization of the interfaces between the chassis (BK7/PMMA) and the corresponding dielectric liquid, the system with DIW achieves better results from 10X to 15X and for 10X with IPA. The DIW system has an optical efficiency of 76%, with a misalignment acceptance half angle on the tracking axis from ±1.11° (10X) to ±0.71° (15X) and a non-uniformity coefficient from 0.14 (10X) to 0.19 (15X). In the case of IPA, the system optical efficiency is enhanced (81%), the acceptance angle is ±1.07° and the non-uniformity coefficient is 0.13. The performances for angular variations in the non-tracked direction have been analyzed which indicate an adequate performance for both systems with an angular zone of 50° where optical efficiencies are kept around its maximum value. For wider angular variations, the device containing IPA preserves slightly higher values, reaching mean efficiencies over 50% for an angular range of 90°. Based on these results, the design configuration with the optimized cavity filled with IPA is positioned as slightly better option from an optical point of view. However, from a thermal point of view, DIW presents higher capabilities.

The concentrators track the solar height by rotation around the cylinder axis which can be driven by a single motor and, therefore, building integration is facilitated. Modules are designed to be placed in rows as an array so that the appearance is similar to ordinary blinds and can produce useful energy to cope with building demands. A secondary movement has been implemented to control the vertical distance between modules to ensure no shading between them. This movement also allows controlling the interior illumination depending on the user's requirements to prioritize lighting or energy production.

PMMA was selected to demonstrate performance prior to the final manufacturing with BK7 since from a mechanical processing point of view it is friendlier than the optical glasses, albeit its resistance to alcohols is notably reduced. As a consequence, all the fabrication and associated improvements were conducted in the laboratory of the research group. The lens inner profile was obtained by CNC machining and polishing processes. Nonetheless, the optical properties of PMMA are different from these of BK7 and optimizations for both dielectric liquids and PMMA were conducted to obtain its corresponding interface profiles which vary slightly with respect to BK7. However, since the transmittance of both materials for the Si PV sensitivity bandwidth is analogous and the Fresnel losses do not change to a great extent, the optical efficiency in the frame of the PV generator of both systems remains almost equal (DIW+PMMA = 76% & IPA+PMMA = 80%).

The thermal performance of the system with DIW was numerically analyzed by a computational fluid dynamics (CFD) simulation coupled with a thermal analysis and it has been experimentally validated to fully characterize the system. DIW was chosen prior to IPA for this study since the difference in optical efficiency is outweighed by the enhanced thermal output. The collector thermal characteristic curve was obtained rendering a theoretical thermal efficiency when the ambient temperature is equal to the average fluid temperature of 65% and experimental of 60%. Moreover, theoretical and experimental heat losses coefficients obtained are around 13-14 W/ºCm^2. Good agreement is obtained between experimental and numerical values, attributing minor discrepancies to fluctuating wind speeds during the steady-state experiments.

An energetic simulation with the system integrated in front of the windows of the south facing façade on a two-story four-person single-family house for three different cities representative of mild winter and hot summer climate (Lisbon, Barcelona and Genoa) has been performed. A new TRNSYS type has been programmed to properly describe the CPVT module performance. The results showed that for domestic hot water energy demands, the annual average solar fractions (SFs) found are higher than 74.0% in Lisbon and Barcelona and 52.6% in Genoa. In addition, the system achieves SFs for space heating and cooling of 68.7% in Lisbon, 62.4% in Barcelona and 38.3% in Genoa. Finally, SFs for electrical loads show a value of 44.1% in the case of Lisbon, 38.9% for Barcelona and 23.5% for Genoa. The performance is satisfactory in all the cases but for Genoa the thermal performance is in the limit. The main limitations of this collector are the high heat loss coefficient and the shading between cylinders for locations with low latitudes and, consequently, high solar altitudes that require elevated interspaces between cylinders. These results indicate and prove system suitability for locations with mild winters and latitudes in the interval of 38.7 ° (Lisbon) - 44.4 ° (Genoa) with not very high solar heights (maximum solar altitudes in the case of Lisbon of around 74°).

Analyzing the system global efficiency, the performance is similar to other systems reported in the literature. However, the lighting control and transparency position the system proposed here in an advantageous position for building integration over windows. In addition, this refractive system shows potential to be cost-effective due to the use of standard silicon solar cells, cheap optical elements and low-accuracy trackers to partially cover electricity and heat energy demands of buildings.

2. Future work

The first actions towards improving the system aim to improve the thermal efficiency of the system. Albeit the system has been optically optimized, the thermal heat loss coefficient has been only modeled and experimentally assessed varying the flow rate, the inlet temperature and irradiance. Parametric studies to find the flow rate which better suits the system requirements have also been performed around the reference values stablished in several standards. However, the high heat loss coefficient limits a wider application especially for cold locations. Therefore, new approaches such as vacuum layers embedded into the system to provide a better insulation of the system with respect to the atmospheric conditions could lead to a considerably higher thermal production and needs to be further studied.

The system fabrication has been found to be challenging, starting from the CNC machining and polishing and following with the assembling process. Improved fabrication procedures based on the experience gained with the initial prototypes need to be developed. Tools to achieve a perfect positioning between the concentrator and the PV cells would help in order to standardize the process. In addition, the tracking system adjustment was hard to be implemented in practice and several improvements were performed to finally obtain a working mechanism, even though the tracking requirements were bearable. Based on these improvements and the lessons learned during the process, an improved tracking system will be needed facilitating the whole process.

The solar cells were adapted to the required geometry by Nd:YAG laser cutting but detrimental impacts on the open circuit voltage and the fill factor were noted. These are attributed to edge shunts leading to a decrease on the shunt resistance and higher recombination. Therefore, an improvement in the cutting process should be evaluated.

An evaluation for a long time period and over a real building or a full-scale testing unit would be the next step towards fully addressing the suitability of the system. In addition, the thermal impact of including the system on the building performance and demands can be better evaluated.

While for windows this system is well suited, new designs of concentrating photovoltaic thermal systems based on static or semi static systems where small linear movements of the PV cells allow an effective tracking would be better positioned for integration over façades due to the inexistent or almost negligible tracking requirements and wide acceptance angles. Since these systems do no need to allow light to enter inside the building, other techniques can be proposed.

Other research line which needs to be further investigated is to develop specially designed solar cells for photovoltaic thermal systems. The thermal output could be enhanced by solar cells with low temperature coefficients and whose radiative losses are minimized to a great extent. Several measures such as low emissivity coatings have been tested during my research stay at Imperial College but this should be deeper studied.

3. Publication status of the papers

As it was previously mentioned, this thesis encloses a series of accepted articles to international peer-reviewed journals. The status of every of them can be seen in the following table (Table 1).

Table 1. Publication status of the papers.

Chapter	Journal, Impact factor (IF)	Status	Author position
4. Spectral modeling	Progress in Photovoltaics: Research and application IF: 6.46	Published	2
5. Dielectric liquids analysis	Renewable energy IF: 4.90	Published	3
6. Emissivity modeling	Solar Energy Materials and Solar Cells IF: 5.02	Published	1
7. Optical design	Optics Express IF: 3.36	Accepted	1
8. Energetic dynamic modeling and simulation	Solar Energy IF: 4.37	Published	2

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