UNIVERSIDAD POLITÉCNICA DE MADRID

**ESCUELA TÉCNICA SUPERIOR
DE INGENIEROS DE TELECOMUNICACIÓN**

TESIS DOCTORAL

**CONTRIBUTIONS TO CHARACTERIZATION, MODELING
AND DESIGN OF CONCENTRATOR PHOTOVOLTAIC
SYSTEMS**

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A Gloria y Nino

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ABSTRACT

The constant progress of the efficiency values of the multijunction (MJ) solar cells based on III-V semiconductors, used together with photovoltaic concentration (CPV) technologies, means that competitive costs can be achieved generating solar photovoltaic energy, since with concentration a cell's area is reduced, being substituted by optical elements of a lower cost.

The present thesis collects a series of contributions at different levels that affect CPV systems. The largest part is dedicated to the impact of solar spectrum on these systems based on MJ cells, specifically to the understanding of that effect on MJ cells and CPV systems.

Firstly the spectral matching ratio (SMR) concept is reviewed, an index based on the currents of a set of component cells (isotypes) that is used to estimate which subcell of a MJ cell limits, and its use is extended to MJ cell calibration with the role of spectral index. In particular, through instant filtering using SMR baseline values, prevailing spectral conditions are established with regard to reference spectrum (ASTM AM1.5D G173-03). Based on those component cell currents the so-called equivalent irradiances are defined, with which is possible to estimate the losses due to spectrum (spectral efficiency) when they are compared to the corresponding direct irradiance (DNI). Finally a study about the spectral bias when calibrating is presented, in particular the effect due to the tolerance associated with the SMR filters and the contribution due to spectral mismatch when using component cells of different technology to the MJ cell.

The second contribution about spectrum is a study of the spectral classification based on SMR indexes from several locations around the world for several MJ cell technologies: lattice matched based on germanium and dilute nitrides and metamorphic, both upright and inverted. In this way relations can be established among types of locations defined by their geography and climate and spectral clusters useful for MJ cell ad hoc design. An estimation of losses due to spectral variation for each MJ technology for each location is also given.

In the last contribution related to spectrum a possibility for SMRs as spectral indexes is looked at closely, previously establishing the minimum number of parameters needed to estimate the uniqueness of solar spectra. It is concluded that a single spectral index is

clearly insufficient to establish spectral uniqueness and that three independent indexes are close to the biunivocal spectral identification. Based on this idea the use of SMR to establish correlations among different MJ cell technologies and other devices is suggested.

Following on, a review of the factors that affect the energetic production of a CPV plant is given, and how these factors are modeled in the software photovoltaic (PV) tools that add simulation modules for CPV. Particular emphasis is placed on those factors that, influenced by the way PV systems are modeled, cause errors or present a lack of precision when the same approaches are used in CPV and recommendations and used limitations are proposed. All this is applied to an experimental 50 kW CPV plant in the NGCPV European-Japan project and its energy production for two years is compared with the models of integrated power and annual energy forecast.

Finally, a hybrid CPV design with lighting is proposed as part of the Spanish project LUZ-CPV, where concentration, in addition to generating photovoltaic electricity, is used to transport sunlight directly for indoor illumination. In principle the hybrid concept allows an efficiency improvement of a CPV system used to illuminate by means of electrical luminary, since the transmission of sunlight is direct without energy transformation. A study about the design limitations has been performed, a full prototype has been developed and both CPV and lighting parts have been characterized. To conclude, several light guide materials have been studied to estimate the viability of the concept.

RESUMEN

El avance constante de los valores de eficiencia de las células solares multiunión (MJ) basadas en semiconductores III-V permite que utilizadas junto con tecnologías de concentración fotovoltaica (CPV) puedan alcanzarse costes competitivos en la generación de energía solar fotovoltaica, ya que al concentrar se reduce el área de célula necesaria siendo sustituida por elementos ópticos de mucho menor coste.

La presente tesis recoge una serie de contribuciones a distintos niveles que afectan a los sistemas CPV. La mayor parte está dedicada al impacto del espectro solar sobre dichos sistemas basados en células MJ, en concreto al entendimiento de dicho efecto sobre células MJ y sistemas CPV.

Primero se revisa el concepto de spectral matching ratio (SMR), un índice basado en las corrientes de un set de células componentes (isotypes) que es utilizado para estimar qué subcélula de una célula MJ limita, y se extiende su uso a calibración de células MJ utilizándolo como índice espectral. En concreto, mediante el filtrado de instantes utilizando valores SMR de referencia, se establecen las condiciones espectrales prevalentes con respecto al espectro de referencia (ASTM AM1.5D G173-03). Basándose en las mismas corrientes de las células componentes se definen las correspondientes irradiancias equivalentes, con las que se puede estimar la pérdida debida al espectro (eficiencia espectral) al comparar con el valor de irradiación directa (DNI) correspondiente. Finalmente se ha estudiado la aparición de sesgos en la calibración espectral, en concreto el efecto de la tolerancia asociada a los filtros SMR y la contribución por desajuste espectral al utilizar células componente de distinta tecnología que la célula MJ.

La segunda contribución sobre el espectro trata de un estudio sobre la clasificación espectral basadas en índices SMRs de diversas localidades alrededor del mundo para diversas tecnologías de célula MJ: ajustadas en red basadas en germanio y nitruros y metamórficas tanto rectas como invertidas. De esta forma se establecen relaciones entre tipos de localidades definidas por su geografía y clima y se pueden identificar clústeres espectrales útiles para el diseño ad hoc de células MJ. También se estiman las pérdidas por variación espectral asociadas a cada tecnología MJ para cada localidad.

Como última contribución relacionada con el espectro se profundizan las posibilidades de los SMRs como índices espectrales, estableciendo previamente el número mínimo de parámetros necesarios para estimar unicidad de los espectros solares. Se concluye que un sólo índice espectral es claramente insuficiente para establecer unicidad espectral y que tres índices independientes se acercan bastante a una identificación espectral biunívoca. Basado en ello se sugiere utilizar los SMR para establecer correlaciones entre diferentes tecnologías de célula MJ y otros dispositivos.

A continuación se da una revisión de los factores que afectan a la producción energética de una planta CPV y cómo se modelan en las herramientas software de fotovoltaica (PV) que incorporan componentes para simulación CPV. Se hace especial hincapié en aquellos factores que, influenciados por la forma de modelar sistemas PV, ocasionan errores o falta precisión cuando se utilizan las mismas aproximaciones sobre sistemas CPV y se proponen recomendaciones y limitaciones de uso. Todo ello es aplicado a una planta CPV experimental de 50 kW dentro del proyecto europeo con Japón NGCPV y se compara el modelado con la producción durante dos años, a nivel de potencia y de energía anual estimada.

Por último, se propone un diseño CPV híbrido con iluminación bajo el proyecto nacional español LUZ-CPV en el que se hace uso de la concentración además de para la generación fotovoltaica de electricidad, para el transporte directo de luz solar con el fin de iluminar interiores. El concepto híbrido permite en principio mejorar la eficiencia de un sistema CPV que se utilice para iluminar mediante una luminaria eléctrica, ya que la transmisión de luz es directa sin necesidad de transformación energética. Se ha hecho un estudio para ver las limitaciones de diseño, se ha desarrollado un prototipo completo y se ha caracterizado tanto la parte CPV como la de iluminación. Para finalizar se han estudiado diversos materiales utilizados como guía óptica para estimar la viabilidad del concepto.

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LIST OF SYMBOLS AND ACRONYMS

3J	triple junction
α	variation of thermal resistance with respect wind speed
A	area
AEMET	Agencia Estatal de Meteorología
AERONET	aerosol robotic network
AM	air mass
AM 1.5D G173	reference spectrum for direct radiation (according to ASTM)
AOD	aerosol optical depth
APE	average photon energy
ASTM	American Society for Testing and Materials
B_{dm}	monthly mean of daily direct irradiation
B_i	" equivalent " DNI measured by the i component cell
B_{MJ}	MJ "equivalent" direct irradiance
B_{NIP}	normal incidence pyrheliometer direct irradiance
B_0	extra-atmospheric irradiance
BICPV	building-integrated concentrator photovoltaics
BIPV	building-integrated photovoltaics
CCT	correlated color temperature
CEA-INES	Commissariat à l'énergie atomique et aux énergies alternatives - Institut National de l'Energie Solaire
CNOCT	concentrator nominal operating cell temperature
CNOMT	concentrator nominal operating module temperature

CPV	concentrator photovoltaics
CRI	color rendering index
CSOC	concentrator standard operation conditions
CSTC	concentrator standard testing conditions
CV_RMSE	coefficient of variation of the root-mean-square error
D(0)	horizontal diffuse irradiance
DNI	direct normal irradiance
EIA	Energy Information Administration
ENEA	Agenzia Nazionale per le Nuove Tecnologie, L'energia e lo Sviluppo Economico Sostenibile
$\widehat{\text{energy}}$	predicted energy
EROI	energy return on investment
$F_{\text{convection}}$	convection factor
F_{IV}	current-voltage factor
F_0	optics factor
F_{shading}	shading factor
F_{soiling}	soiling factor
$F_{\text{soiling(initial)}}$	soiling factor (initial characterization)
$F_{\text{soiling(seasonal)}}$	soiling factor (seasonal)
F_{spectrum}	spectrum factor
F_{tracking}	tracking factor
F_v	voltage factor
FF	fill factor

Fraunhofer ISE Fraunhofer-Institut für Solare Energiesysteme

G(0)	horizontal global irradiance
GNI	global normal irradiance
IEC	International Electrotechnical Commission
IES-UPM	Instituto de Energía Solar- Universidad Politécnica de Madrid
IMM	inverted metamorphic
I	current; irradiance
I _{CSOC}	current at CSOC
I _{CSOC(clean)}	current at CSOC (out-of-the-box clean characterization)
I _{CSOC(initial)}	current at CSOC (initial characterization)
I _{DC}	current at maximum power point (DC)
I _{DC_norm}	normalized current at maximum power point (DC)
I _{MP}	current at maximum power point
I _{SC}	short-circuit current
ISFOC	Instituto de Sistemas Fotovoltaicos de Concentración
IR	infrared
IRENA	International Renewable Energy Agency
IV	current-voltage
JRC	Joint Research Centre
k _{cladding}	cladding extinction coefficient
k _D	diffuse fraction
k _T	clearness index
LCOE	levelized cost of energy (or electricity)
LED	light-emitting diode
LM	lattice-matched

MJ	multijunction
MODIS	moderate-resolution imaging spectroradiometer
MODTRAN	MODerate resolution atmospheric TRANsmission
MPP	maximum power point
n	ideality factor; refractive index
$\tilde{n}_{\text{cladding}}$	complex refractive index of the cladding
N_{ref}	number of reflections
N_s	number of cells in series
NA	numerical aperture
NASA	National Aeronautics and Space Administration
NGCPV	A new generation of concentrator photovoltaic cells, modules and systems (European-Japanese project)
NIP	normal incidence pyrhelimeter
NREL	National Renewable Energy Laboratory
nRMSE	normalized root-mean-square error
OECD	Organization for Economic Co-operation and Development
P_{elec}	electrical power
P_{hea}	heating power
P_{CSOC}	power at CSOC
$P_{\text{CSOC(clean)}}$	power at CSOC (out-of-the-box clean characterization)
$P_{\text{CSOC(initial)}}$	power at CSOC (initial characterization)
P_{DC}	power at maximum power point (DC)
$P_{\text{DC_norm}}$	normalized power at maximum power point (DC)
P_{MP}	power at maximum power point

P_{tot}	total power
PC	polycarbonate
PCA	principal component analysis
PC_val	principal component eigenvalues
PC_vec	principal component eigenvectors
PHOTONS	PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire
PMMA	poly methyl methacrylate
POF	plastic optical fiber
PW	precipitable water
QE	quantum efficiency
R	resistance; reflectivity
$R_{\text{th } c_m}$	thermal resistance between cell and module
$R_{\text{th } m_a}$	thermal resistance between module and ambient
REN21	Renewable Energy Policy Network for the 21st century
RMSE	root-mean-square error
SAM	system advisor model
SF	spectral factor
SMARTS	Simple Model of the Atmospheric Radiative Transfer of Sunshine
SMR	spectral matching ratio
SOE	secondary optical element
SoG	silicone on glass
SOLIS	solar irradiance scheme
SOPHIA	Solar Photovoltaic European Research Infrastructure (European project)
SPCTRAL2	Bird simple spectral model

SPD	spectral power distribution
SPICE	Simulation Program with Integrated Circuit Emphasis
t	time
T	transmittance; temperature
T_{amb}	ambient temperature
T_{cell}	cell temperature
T_{filter}	transmission of the mesh filter
T_{Linke}	Linke turbidity factor
T_{module}	module temperature
TIR	total internal reflection
TMY	typical meteorological year
U	uncertainty
UF	useful fraction
UMM	upright metamorphic
UV	ultraviolet
V_{CSOC}	voltage at CSOC
V_{DC}	voltage at maximum power point (DC)
V_{MP}	voltage at maximum power point
V_t	thermal voltage
V_{wind}	Wind speed
Z	spectral parameter Z
α	Ångström exponent; temperature variation coefficient of the short-circuit current
α_{core}	core absorption

β	Ångström turbidity coefficient; open-circuit voltage variation with temperature
$\beta_{\text{plant_DC}}$	maximum power point (DC) voltage variation with temperature of a CPV plant
ΔT	thermal drop
ε	residual (modeling); tolerance (around SMR=1)
η_{cell}	cell efficiency
η_{DC}	DC module efficiency
η_{elec}	electrical efficiency
η_{opt}	optical efficiency
η_{spectral}	spectral efficiency
η_{TIR}	TIR efficiency
θ_{inc}	angle of incidence
λ	wavelength
τ	optical thickness

CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND - THE CHALLENGE OF ENERGY TRANSFORMATION

Energy is essential for any physical/chemical change in Nature, as it is for any human activity. Moreover, human beings seem to have an insatiable appetite for energy, as reflected by the Jevons paradox (Alcott 2005). Already in the industrial revolution of the XIX century William Jevons saw that increases of efficiency in energetic systems paradoxically increase the consumption of energy, more specifically related to coal.

To deal with the need for energy by humanity there are only two actual options: the first option would be to find an infinite source, and the second option should be to limit the need of energy to at least a restricted amount.

1.1.1 ENERGY RETURN ON INVESTMENT

From a realistic perspective where thermodynamics rules and all the energy sources are non-infinite, only renewable energies that are naturally replenished on a human timescale can present a real option, and only when the energetic investment to collect it is lesser than the profitable energy. Some authors quantify this ratio as energy return on investment (EROI) (Cleveland et al. 1984), and ranges from 100:1 of first oil explorations to <1:1 of corn ethanol (Cleveland 2005). EROI's estimation for renewable energies is 84:1 for hydroelectric (the availability of which is very limited to the environment), 18:1 for wind power and between 2.4-12:1 for photovoltaics (PV) (Hall, Lambert, and Balogh 2014; Prieto and Hall 2013; Raugei, Fullana-i-Palmer, and Fthenakis 2012; Brandt, Dale, and Barnhart 2013). Nevertheless renewable energies suffer from low density, as in the case of PV, which establishes a limit per area (de Castro et al. 2013) and are usually intermittent, which is reflected in expected lower values of EROI if storage is considered.

The best example of how a source of energy can transform human society is petroleum. Cheap oil has exponentially changed modern society, however it is not a sustainable energy and peak-oil is certainly reached, or close to happening (Hirsch, Bezdek, and Wendling 2007). Increasing prices are expected in the next decades due to the exploitation of currently less-profitable wells before the definite depletion, translated to reducing EROI (100:1 in 1930, 20:1 in 2000) (Cleveland 2005).

The obvious non-infinite EROI of the available sources of energy emphasizes the need to limit the energetic expenditure. Furthermore, the concrete value of EROI conditions the expense of energy that can be actually expected. While the EROI level to sustain a civilization that has transport as service is reported to be 3:1 (Hall, Balogh, and Murphy 2009), other services of civilization that require energy but don't contribute to generating it will increase this ratio; in developed countries societies is expected to be about 7:1 (Weißbach et al. 2013). Under this scenario, renewable energies are a valid option to sustain developed societies but only under the condition of not increasing the energetic expenditure and without taking into consideration the non-energetic but very relevant aspects linked to the energy transformation.

All these issues prove why energy-related research is so relevant nowadays. Electricity storage, CO₂ capture, energy (conversion and consumption) efficiency and renewable energies are especially trying to increase the EROI of energy sources, to reduce the EROI level of society and to minimize the impact of energy use on the environment.

1.1.2 LEVELIZED COST OF ENERGY

While EROI is a useful theoretical index to compare the net energy obtained from an energy source, another index that considers the monetary cost of the unit of generated energy is commonly used. Levelized Cost of Energy (or Electricity) (LCOE) is the ratio of lifetime costs to lifetime energy (electricity) generation considering the cost of capital. It is a useful metric of the cost of the energy produced by a generator and a practical way of comparing different generating technologies.

1.2 SOLAR ENERGY - PHOTOVOLTAICS

Numerous energy-related institutions oriented to renewables, such as IRENA, Fraunhofer Institute, NREL, REN21 or generic like OECD-IEA, EU-JRC and US-EIA, are indicating that PV LCOE has been notably reduced in the last years, reaching in some situations similar numbers to traditional carbon-based fuels (Arnulf 2014; IRENA 2015; OECD/IEA 2014; Sawin and Sverrisson 2014; Philipps et al. 2016; EIA 2015).

The rapid deployment of renewable power generation technologies, plus a high learning rate, is notably reducing their LCOE (IRENA 2015), which is translated in that in recent years the price per watt of solar panels has been reduced dramatically. Economy of scale and the increase of efficiency are the main factors in particular for PV, and especially in concentrator PV (CPV), since this technology can benefit from solar cells with the highest efficiency even if they are notably expensive.

Among other renewable sources, solar is notable because of its scalability. There is no notable loss in efficiency when systems scale from a few watts to gigawatts systems, while most renewable (and non-renewable) sources are only profitable at megawatt scale. In addition its fuel is abundant, free and dispersed around the whole globe with practically zero residual. All this makes solar energy indeed one of the most democratic and promising sources of energy available.

Current PV panels are around 15-20% efficient while world record solar cell is reaching 46% following a growing learning curve (Green et al. 2016), so there is plenty of room for improvement. The main constraint is that record cells are prohibitively expensive.

1.2.1 CONCENTRATING SOLAR RADIATION

Concentrator photovoltaics (CPV) is expected to make the highest efficiencies in solar cells, seen and coming, economically viable. The main idea under this technology is to substitute expensive solar area by cost-effective optics allowing for the use of these more efficient solar cells. It is here where it is possible to reach a competitive LCOE in certain areas with high direct normal irradiance (DNI). At the moment the highest efficiencies are seen in MJ solar cells based in III-V, but also could be applied to emergent technologies that are nowadays in a less mature phase of development, such as quantum dot solar cells (Nozik 2002) or intermediate band solar cells (Luque, Martí, and Stanley 2012). As example, the current record of PV efficiency is seen in a CPV MJ-based system that is reaching more than 43% (Steiner et al. 2016).

However some issues need to be solved when solar radiation is concentrated at a high ratio. The one with the highest impact is the need for a tracking infrastructure inherent to concentrating due to thermodynamic constraints (Smestad et al. 1990). A second matter is the high operation temperature of the solar cell under concentrated irradiation that reduces its performance and can affect its reliability, so in some cases a heatsink can also be necessary. A third question, but which is only related to MJ solar cells, is the spectral mismatch that appears due to the series connection of subcells that are sensitive to different parts of solar spectrum. This makes CPV systems based on MJ solar cells

especially sensitive to spectral variations, and their performance is going to be affected by spectrum.

The constant improvement of CPV technology currently (boosted mainly by a solid increase of MJ solar cell efficiencies (Green et al. 2016)) presents a learning rate that almost doubles flat panel PV (Haysom et al. 2015). However, CPV global cumulative deployment is very low. For comparison, in 2015, the total installed capacity for CPV is 360 MW (Philipps et al. 2016), while for PV is three orders of magnitude higher, 227 GW (REN21 2016).

Therefore, the key to accomplish competitive cost is going to be a question of time for achieving the critical volume of production, a stage that for PV is moderately mature and for CPV is immersed into it, well supported by cell efficiency increases. Nevertheless, the improvement on efficiency that CPV makes possible is also constrained by the fine tune of the components of CPV systems and the correct solution to the inherent CPV issues that have been presented above.

1.3 AIMS OF THE RESEARCH

Certainly there are other variables in the equation of LCOE reduction than cell efficiency that are worth studying. In that sense the present thesis is focused on contributions on concentration systems, specifically on CPV summarizing the work carried out at the *Instruments and Systems Integration* (ISI) group at the *Instituto de Energía Solar* of the *Universidad Politécnica de Madrid* (IES-UPM).

The main one is to improve the understanding of one important intrinsic MJ-CPV issue: the spectrum sensitivity. This part is related to solar spectrum, specifically trying to characterize one of the main issues of CPV described above, the spectral mismatch and how it affects MJ solar cells and CPV systems. The spectral resource is also well characterize and the corresponding loss due to spectral mismatch from the point of view of CPV.

Another contribution is the identification of CPV modeling peculiarities necessary for CPV bankability with the aim of uncertainty reduction. This section tries to help the modeling of the CPV system, highlighting the differences between PV and CPV models and providing solutions to those parts where classical PV approaches are not accurate enough or can give biased results.

A final section focuses on how to use concentration of solar energy for illumination and how to make it compatible with CPV. Here it is shown how CPV efficiency could be

improved by using concentration directly without electrical conversion in the lighting niche.

1.3.1 THESIS OUTLINE

The book is divided into seven chapters, of which the first is the present introduction.

Chapter 2 deals with the spectral matching ratio (SMR) concept, an index based on the currents of a set of component cells that is used to estimate which subcell of a MJ cell limits, and its use is extended to MJ cell calibration with the role of spectral index. In particular, through instants filtering using SMR baseline values, prevailing spectral conditions are established with regard to reference spectrum.

Chapter 3 is a study about the spectral classification based on SMR indexes of several locations around the world considering several MJ cell technologies: lattice matched based on germanium and dilute nitrides and metamorphic both upright and inverted.

Chapter 4 describes a possibility for SMRs as spectral indexes, previously establishing the minimum number of parameters needed to estimate the uniqueness of solar spectra. Based on this idea the use of SMR to establish correlations among different MJ cell technologies and other devices is suggested.

Chapter 5 is concerned with the factors that affect the energetic production of a CPV plant and how these factors are modeled in the software PV tools that add simulation modules for CPV. All this is applied to an experimental 50kW CPV plant in the NGCPV European-Japan project and its energy production for two years is compared with the models of integrated power and annual energy forecast.

Chapter 6 describes a hybrid CPV design with lighting where concentration in addition to generating photovoltaic electricity and is used to transport sunlight directly for indoor illumination. A study about the design limitations has been performed, a full prototype has been developed and both CPV and lighting parts have been characterized.

Chapter 7 summarizes the main sections of this thesis, including some possible lines of future research. A list of the contributions to journal articles and national and international congresses is also given at the end.

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CHAPTER 2 – USE OF SMR FOR SPECTRAL CALIBRATION OF MJ SOLAR CELLS AND CPV SYSTEMS

2.1 INTRODUCTION

Modern concentrator PV (CPV) modules mostly use multijunction (MJ) solar cells, that is, monolithic stacks of several subcells that are spectrally tuned to collect the maximum power from the sunlight. These subcells are connected in series, hence the changes in the incident spectrum vary the photocurrent of every subcell and influence the current of the device which is limited by the least generating subcell. Consequently, the influence that the spectral variations have on the power generated by a CPV system is of great concern. Several approaches have been proposed to account for the spectral influence on the power generation such as the direct measurement of the spectrally resolved direct normal irradiance (DNI) by means of spectroradiometers (Emery et al. 2000), the atmosphere characterization based on sun photometers which provides significant parameters like aerosols content and precipitable water (Muller et al. 2010; Muller et al. 2011), the atmosphere simulation by radiative transfer models such as MODTRAN (Armijo et al. 2014), SMARTS (Gueymard 2001; Jaus and Gueymard 2012) or SPCTRAL2 (Faine et al. 1991), the analysis of fill factor variations (McMahon et al. 2008) as a mean to determine the influence of spectrum under operating conditions, or the use of component (or isotype) cells and the associated parameters (Z parameter (Meusel et al. 2002; Peharz, Siefer, and Bett 2009), or Spectral Matching Ratio (C. Domínguez et al. 2009a; César Domínguez et al. 2013)). Additional parameters proposed to evaluate spectral distribution of the DNI are Average Energy per Photon (Cornaro and Andreotti 2013), Useful Fraction (Gottschalg et al. 2005), Spectral Factor (Ishii et al. 2013) and absolute Air Mass (AM) corrected with altitude (Kasten and Young 1989; Emery, Delcueto, and Zaiman 2002).

A simple and affordable way to spectrally characterize the solar resource in terms of cost and ease of collecting data is to use a set of component cells (Antón et al. 2012). A component cell is equivalent to a MJ solar cell in which only one of the subcells is electrically connected. Hence, it behaves optically as a MJ solar cell but the photogenerated current corresponds to the connected subcell regardless of the spectral distribution of the incident light. A set of component cells whose architecture is equivalent to a given MJ solar cell provides an exact or very similar spectral response to the original MJ solar cell. This means that by simply sensing a few photocurrent signals we may fully describe the spectral condition of the DNI as it affects the MJ solar cell.

For the case of the widely used lattice matched (LM) GaInP/GaInAs/Ge triple-junction (3J) solar cells, a set of three component cells is needed which must be installed in collimating tubes and track the sun (see Figure 2.1). The complete instrument may be referred to as spectroheliometer and the one used in this thesis was developed at *Instituto de Energía Solar - Universidad Politécnica de Madrid* (IES-UPM) in 2009. The instrument provides three photocurrent values, each one corresponding to one of the subcells, $I_{L,top}$, $I_{L,middle}$ and $I_{L,bottom}$, which are the base of the study presented here (an estimation of the expected uncertainty can be seen in Appendix I).

Figure 2.1. Schema and photography of a spectroheliometer, the instrument based on component cells.

The use of component cells offers significant advantages over other characterization instruments. On the one hand, spectroradiometers allow for a full radiometric characterization, but these instruments have significant drawbacks: their price, drifts in calibration, and the need for continuous maintenance and regular calibration to reduce uncertainty. On the other hand, radiometric simulators such as SMARTS or any other software based on atmospheric parameters require these parameters as inputs, and they are not easily measured. Moreover,

they usually require expensive sun photometers, such as the ones used in the AERONET network (Holben et al. 1998), or must rely on high uncertain satellite data (Mueller et al. 2004; Hubanks et al. 2008).

2.2 SPECTRAL MATCHING RATIO DEFINITION

The Spectral Matching Ratio (SMR) quantifies a particular irradiance spectrum by comparing it to a reference spectrum, i.e. AM1.5D-G173-03. SMR is defined as the ratio between the currents photogenerated by two subcells under the spectrum in study, divided by the same ratio under the reference spectrum (C. Domínguez et al. 2009a; César Domínguez et al. 2013; Núñez et al. 2016), and can be calculated as:

$$SMR_{subcell_j}^{subcell_i}(ref = AM1.5D) = \frac{I_{L, ratio_{subcell_j}}^{subcell_i}}{I_{L, ratio_{subcell_j_{ref}}}^{subcell_i}} = \frac{\frac{I_{L, subcell_i}}{I_{L, subcell_j}}}{\frac{I_{L, subcell_{i_{ref}}}}{I_{L, subcell_{j_{ref}}}}} \quad (2.1)$$

where $I_{L, subcell_i}$ represents the photocurrent of subcell i when illuminated with a particular spectral irradiance distribution and $I_{L, subcell_{i_{ref}}}$ stands for the photocurrent of subcell i under the reference spectrum. From now on we will assume that the aforementioned MJ solar cell and the component cells used to determine the set of photocurrents and consequently SMRs are of the same technology, i.e., they have the same relative spectral responses. The results presented in this chapter are based on LM GaInP/GaInAs/Ge solar cells but similar results can be obtained with different 3J solar cell architectures.

Although the definition of SMR is similar to that of the Spectral Mismatch Factor (MM) ("IEC 60904-7 Computation of the Spectral Mismatch Correction for Measurements of Photovoltaic Devices" 2008) used in the calibration of solar cells, SMR indexes are intended to be used for the evaluation of the spectrum while MM gives an idea about how well a solar cell and a reference cell are matched. MM compares a solar cell under test and a reference cell and, if MM equals one, it means that they are perfectly matched, i.e., both have the same relative spectral response or the relative shape of reference and simulated spectra are the same. However, SMR indexes compares a spectrum to the reference one by means of the photocurrents generated by the subcells of a MJ solar cell and, if SMR equals one, it means that a particular spectrum is equivalent to the reference one in the sense that both spectra produce the same balance between the subcells photocurrents.

Considering, for example, a 3J solar cell and its corresponding component cells, three spectral indexes can be defined: SMR_{mid}^{top} , SMR_{bot}^{top} , SMR_{bot}^{mid} where the scripts *top*, *mid* and *bot* stand for the

top GaInP subcell, the middle GaInAs subcell and the bottom Ge subcell respectively. Two of these SMRs (one is redundant) form a set of indexes that fully characterize the spectral irradiance for that particular MJ solar cell technology. As stated before, two spectra can be considered equivalent for that particular MJ solar cell when they attain the same SMRs or, in other words, the subcells within a MJ solar cell produce the same current ratios under both spectra. It must be pointed out that this spectral equivalence definition does not consider the absolute value of their corresponding photocurrents. Instruments based on component cells should be used together with an absolute irradiance sensor such as a Normal Incidence Pyrheliometer for outdoor characterization or a calibrated irradiance module or similar with CPV solar simulators (C. Domínguez et al. 2009a).

Consequently, from the point of view of a MJ solar cell composed of n subcells, the spectral variation can be described by $n-1$ *SMR* values. In the case of a 3J solar cell, SMR_{mid}^{top} and SMR_{bot}^{mid} are preferred over SMR_{bot}^{top} because they decouple fairly well the effects of AM and aerosol optical depth (*AOD*), both of which mainly affect the top and middle spectral regions, with the precipitable water (*PW*), which mainly affects the middle and primarily bottom spectral regions (Núñez et al. 2014).

2.2.1 EXAMPLE OF SPECTRA AND SMR

As previously stated, SMR indexes can be used to describe the spectrum of the irradiance incident on a MJ solar cell. As an example, two different spectra (corresponding to midday and sunset of the same day in Madrid) are shown in Figure 2.2 together with the reference spectrum AM1.5D-G173-03 and the quantum efficiency of three component cells corresponding to a LM GaInP/GaInAs/Ge solar cell.

Figure 2.2. Quantum efficiency of the component cells used in this study. The reference spectrum AM1.5D G173-03 is also plotted together with two other spectra representative of midday and sunset moments.

The photocurrent generated by every subcell and the corresponding SMR_{mid}^{top} and SMR_{bot}^{mid} parameters are calculated for every spectra showed in Figure 2.2 (Table 2.1). The spectral content of the DNI depends strongly on the solar elevation and aerosol content in the atmosphere, which also affects the SMR values (Núñez et al. 2014). High SMR_{mid}^{top} values indicate blue-shifted spectrum probably caused by low AM values or low aerosol content in the atmosphere (i.e. low AOD). Generally speaking, the lower the SMR_{bot}^{mid} is, the drier the atmosphere (lower PW) is, as it is mainly influenced by the water absorption bands.

Table 2.1. SMR values calculated for the three spectra plotted in Figure 2.2.

spectrum	SMR_{mid}^{top}	SMR_{bot}^{mid}
Midday	1.08	0.89
Sunset	0.69	0.84
AM1.5D G-173-03	1	1

According to the definition in Eq. (2.1), the reference spectrum has SMR values equal to 1. Therefore, the closer the SMRs are to unity, the more similar the photocurrent ratios of the MJ solar cell under the particular spectrum are to their ratios under the reference spectrum.

2.2.2 SPECTRAL FILTERING BY MEANS OF SMRS

In order to graphically describe the spectral changes in the DNI in a particular location (Madrid, in this analysis) throughout a year, a 8000 representative spectra have been generated using SMARTS (Gueymard 2001) using the following inputs: altitude 695 m, mean air pressure 933

hPa, and an urban model for aerosol. The atmospheric parameters have been swept within the ranges that include 90% of the accumulated irradiation in Madrid, i.e., AOD at 500 nm (other ways to express aerosols contents can be valid as is presented in Appendix II) is between 0.02 and 0.6, PW ranges from 0.3 to 3 cm and AM is between 1 and 2.25 (Núñez et al. 2014). Other SMARTS parameters with less influence on this analysis, such as ozone or CO_2 , have been set to reference spectrum conditions.

Figure 2.3. Representative collection of spectra for Madrid throughout a year generated using SMARTS. Spectra are filtered incrementally by imposing direct normal irradiance $DNI=900\pm3\%$ $W\cdot m^{-2}$, spectral matching ratio $SMR_{mid}^{top}=1\pm1\%$ and $SMR_{bot}^{mid}=1\pm1\%$. Adding the filter $SMR_{mid}^{top}=1\pm1\%$ clearly reduces the dispersion of spectra in the top subcell region mainly influenced by AM and aerosols content. Imposing additionally $SMR_{mid}^{top}=1\pm1\%$ and $SMR_{bot}^{mid}=1\pm1\%$ reduces the dispersion in the bottom subcell region, where there are several water absorption peaks.

A first application of component cells and SMRs is the filtering of operating conditions to ensure certain prevailing spectral conditions for both outdoor and indoor measurements and power rating of CPV cells, modules or systems based on MJ solar cells (C. Domínguez et al. 2009b; Meusel et al. 2002; Muller et al. 2015; César Domínguez et al. 2013; Antón et al. 2012). This use is widely accepted by the CPV community (Siefer et al. 2014) and it is included in the current draft of the power rating standard (IEC committee 2015). In order to show how SMR filtering reduces spectral dispersion, several subsets of the aforementioned 8000 spectra are represented in Figure 2.3 after applying consecutive filters, more restrictive at every step, approaching the reference spectrum AM1.5D-G173-03 which is represented in black. First, spectra whose total irradiance value is within $\pm 3\%$ of the reference spectrum irradiance ($900 W\cdot m^{-2}$) are shown in red. This is the only condition that can be limited by means of a pyrheliometer. Second, the condition $SMR_{mid}^{top}=1\pm1\%$ is added in light blue. Latter spectra in green are those which besides previous requirements also meet $SMR_{bot}^{mid}=1\pm1\%$. It can be noted how well the filtered spectra

resemble the reference AM1.5D-G173-03 when the triple condition is applied ($DNI=900\pm3\%$ $W\cdot m^{-2}$; $SMR_{mid}^{top}=1\pm1\%$; $SMR_{bot}^{mid}=1\pm1\%$).

There is currently an open discussion in the CPV community about the limits of SMR filters to establish prevailing spectral conditions for rating purposes (IEC committee 2015). The suitability of the limits will be discussed later. In this section we will focus on the probability of occurrence in Madrid of such prevailing conditions for several filter conditions both for DNI and spectra. The study is based on experimental data of minute-resolved SMR measurements using the spectroheliometer throughout 2013. Spurious data caused by tracking misalignment or unstable irradiances (filter conditions: $100<DNI<1100$ $W\cdot m^{-2}$, $|dDNI/dt|<10$ ($W\cdot m^{-2}$)/min) have been removed. In addition, the spectroheliometer calibration has been continuously verified by comparison of the irradiances provided by the component cells to the pyrliometer under reference spectral conditions given by $SMR_{mid}^{top}=1\pm1\%$ and $SMR_{bot}^{mid}=1\pm1\%$ (to assure low long term drift in the component cells calibration). Table 2.2 summarizes the number of days per year that each condition is met for two DNI filters ($DNI=900\pm3\%$ and $DNI > 700$ $W\cdot m^{-2}$) and two SMR ranges around 1 ($\pm1\%$ and $\pm2.5\%$). The condition of $DNI > 700$ $W\cdot m^{-2}$ has been defined as ‘clear sky conditions’.

Table 2.2. Number of days per year that several filtering conditions are met in Madrid during 2013. SMR stands for Spectral Matching Ratio as defined in Eq. (2.1) and measured using a spectroheliometer. Additional filters for unstable irradiances were applied in all cases ($100<DNI<1100$ $W\cdot m^{-2}$, $|dDNI/dt|<10$ ($W\cdot m^{-2}$)/min). The average and the standard deviation ($W\cdot m^{-2}$) of the population of DNI values are included in brackets for the cases of wide DNI filters ($DNI > 700$ $W\cdot m^{-2}$).

($100<DNI<1100$ $W\cdot m^{-2}$, $ dB/dt <10$ $W\cdot m^{-2}/min$) [Filtering conditions]	$DNI =$ $900\pm3\%$ No SMR filt.	$DNI=900\pm3\%$ $SMR_{mid}^{top}=1\pm\epsilon\%$	$DNI=900\pm3\%$ $SMR_{mid}^{top}=1\pm\epsilon\%$ $SMR_{bot}^{mid}=1\pm\epsilon\%$	$DNI > 700$ No SMR filt.	$DNI > 700$ $SMR_{mid}^{top}=1\pm\epsilon\%$	$DNI > 700$ $SMR_{mid}^{top}=1\pm\epsilon\%$ $SMR_{bot}^{mid}=1\pm\epsilon\%$
$\epsilon=1\%$ for SMRs when applicable	249	90	34	316 [Avg = 856] [Std = 76]	217 [Avg = 860] [Std = 53]	74 [Avg = 848] [Std = 41]
$\epsilon=2.5\%$ for SMRs when applicable		140	94		249 [Avg = 864] [Std = 55]	155 [Avg = 860] [Std = 45]

It must be pointed out that, for the case of Madrid, very narrow filtering ($\pm1\%$ for $SMRs$) would lead to few days where those outdoor operating conditions are met so, from the point of view of probability of occurrence, wider filters such as $\pm2.5\%$ may be more recommended for rating procedures. In addition, there is a strong limitation between the filters over the DNI and the

SMRs. Due to the climate of Madrid, almost 50% of the days where the double condition $SMR_{mid}^{top}=1$ & $SMR_{bot}^{mid}=1$ happens, the irradiance is in the range of $900\pm3\%$ $\text{W}\cdot\text{m}^{-2}$ (34 days of 74 to be exact). Under this triple condition the solar spectra resembles the reference AM1.5D-G173-03 as shown in Figure 2.3. In fact, the average values of the DNI for the $SMRs=1\pm\epsilon\%$ filters are between 848 and 864 $\text{W}\cdot\text{m}^{-2}$ which shows again that, for the climate of Madrid, a high correlation is found between SMRs close to one and DNI values close to 900 $\text{W}\cdot\text{m}^{-2}$ for “clear sky” conditions ($DNI > 700 \text{ W}\cdot\text{m}^{-2}$).

Summarizing this section, the threefold condition ($SMR_{mid}^{top}=1\pm1\%$; $SMR_{bot}^{mid}=1\pm1\%$; $DNI=900\pm3\%$ $\text{W}\cdot\text{m}^{-2}$) leads to a solar spectrum in Madrid very similar to the reference AM1.5D-G173-03, but this conditions only happens about 30 days per year. If the DNI condition is relaxed, i.e., to a simple clear sky condition such as $DNI > 700 \text{ W}\cdot\text{m}^{-2}$, prevailing conditions for CPV based on MJ solar cells can be defined, based on $SMRs=1\pm\epsilon\%$. Accordingly to SMR definition, a bare MJ solar cell would generate the same current under any spectra of the same SMRs, but this is not necessary true for a CPV module or systems including optics or temperature issues. From the point of view of occurrence, SMR ranges of $\pm2.5\%$ seem to be adequate for limiting prevailing conditions but their suitability must be proved.

2.3 USING SMR TO ANALYZE THE DNI SPECTRAL VARIATION

2.3.1 SPECTRALLY CORRECTED DNI FOR A MJ SOLAR CELL

For a particular MJ solar cell technology, equivalent direct normal irradiances, $B_{subcell_i}$, are defined as the ratios of the photocurrents generated by each subcell under a particular DNI to the photocurrents of the same subcell under the reference spectrum AM1.5D-G173-03 (Antón et al. 2012). In the case of 3J solar cells, a set of equivalent DNIs, B_{top} , B_{middle} and B_{bottom} , can be defined as

$$B_{subcell_i} = \frac{I_{L,subcell_i}}{I_{L,subcell_{i_{ref}}}} B_{ref} \quad (2.2)$$

where is B_{ref} is the reference DNI at which the calibrated value $I_{L,subcell_{i_{ref}}}$ is obtained. Using this definition, two spectra that produce the same photocurrent in a particular subcell can be considered “equivalent” for that particular subcell. Hence, SMR can also be defined using $B_{subcell_i}$:

$$SMR_{subcell_j}^{subcell_i} = \frac{B_{subcell_i}}{B_{subcell_j}} \quad (2.3)$$

For a 3J solar cell, a spectrum equivalent to reference meets the condition $B_{top} = B_{middle} = B_{bottom}$, which is equivalent to $SMR_{mid}^{top} = SMR_{bot}^{mid} = 1$.

A spectrally corrected *DNI*, for a particular MJ solar cell technology, can be defined to determine the current generated by the device. This MJ equivalent *DNI* (B_{MJ}) is defined using the photocurrent generated by the MJ solar cell under a certain spectrum I_L , and the photo response under the reference spectrum $I_{L_{ref}}$

$$B_{MJ} = \frac{I_L}{I_{L_{ref}}} B_{ref} \quad (2.4)$$

where I_L is calculated as the minimum among the photocurrents generated by the subcells within the MJ device, i.e., $I_L = \min(I_{L,top}, I_{L,mid}, I_{L,bot})$ for 3J cells. Likewise, at reference spectrum, $I_{L_{ref}} = \min(I_{L,top_{ref}}, I_{L,mid_{ref}}, I_{L,bot_{ref}})$. For instance, for the case in which the top subcell is limiting the current of the 3J device under the reference spectrum ($I_{L_{ref}} = I_{L,top_{ref}}$; $I_{ratio_{mid_{ref}}}^{top} < 1$; $I_{ratio_{bot_{ref}}}^{top} < 1$), as commonly happens in LM GaInP/GaInAs/Ge under concentrators, Eq. (2.4) can be expressed as:

$$B_{MJ} = \min \left(B_{top}, \frac{B_{mid}}{I_{ratio_{mid_{ref}}}^{top}}, \frac{B_{bot}}{I_{ratio_{bot_{ref}}}^{top}} \right) \quad (2.5)$$

Similar expressions can be obtained in case of a different subcell current limitation at the reference spectrum.

For LM GaInP/GaInAs/Ge solar cells, it can be assumed that the bottom subcell does not ever limit the current of the device under operating conditions [$I_{ratio_{bot_{ref}}}^{top} \ll 1$]. Then Eq. (2.5) can be further simplified as:

$$B_{MJ \text{ GaInP/GaInAs/Ge}} = \min \left(B_{top}, \frac{B_{mid}}{I_{ratio_{mid_{ref}}}^{top}} \right) \quad (2.6)$$

2.3.2 SPECTRAL EFFICIENCY OF A MJ CELL

Taking into account that B_{MJ} is directly proportional to the photocurrent generated by a MJ device, a spectral efficiency factor $\eta_{spectral}$ can be defined as the ratio between that irradiance and the *DNI* measured with a normal incident pyrheliometer (NIP), B_{NIP} :

$$\eta_{spectral} = \frac{B_{MJ}}{B_{NIP}} \quad (2.7)$$

For a specific location, $\eta_{spectral}$ varies throughout the day influenced by the sun elevation and variations in the atmosphere. When the photocurrent balance among the subcells of the MJ device is the same as in the reference spectrum, i.e. $B_{top} = B_{mid} = B_{bot}$ or $SMR_{mid}^{top} = 1$ and $SMR_{bot}^{mid} = 1$, $\eta_{spectral}$ is equal to one. Note that $\eta_{spectral}$ could be slightly greater than unity for a

particular MJ solar cell technology if such cell performs better under a certain spectrum than under the reference one.

2.3.3 DAILY EVOLUTION OF EQUIVALENT DNIs

The plot on the left of Figure 2.4 shows the daily evolution on a summer day in Madrid of equivalent DNIs (B_{top} , B_{middle} and B_{bottom}) measured by means of LM GaInP/GaInAs/Ge component cells. In this case, under the reference spectrum, $I_{ratio_{mid}^{top}}^{ref} \cong 1$ and the bottom subcell generates an extra 60% photocurrent.

At the beginning of the day, AM is higher than at midday, hence, the spectrum is more attenuated at the top subcell region due to scattering of the sunlight in the atmosphere which produces a red-shifted spectrum. The same can be said at the end of the day. At midday, when the sun is at its highest elevation the path travelled by the light through the atmosphere is shorter. The equivalent irradiance for the top subcell is higher than for the middle, producing a blue-shifted spectrum. Both periods can be seen in plot on the right of Figure 2.4. The two moments of the day at which the spectrum is equivalent to the reference (they produce the same current ratio) are also marked. In them, the three equivalent DNIs are equal ($B_{top} = B_{middle} = B_{bottom}$) and both SMRs are equal to one ($SMR_{mid}^{top} = 1$ and $SMR_{bot}^{mid} = 1$).

The graph on the right side of Figure 2.4 displays the daily evolution of the MJ equivalent DNI (B_{MJ}) along with the DNI measured with a standard pyrheliometer (B_{NIP}). If the MJ device has been optimized in terms of subcell photocurrent balances for the reference spectrum, its performance under any other spectrum in principle will be lower. This is reflected in a lower value of B_{MJ} compared to B_{NIP} as can be clearly observed in Figure 2.4. Only under a spectral irradiance equivalent to the reference ($SMR_{mid}^{top} = 1$ and $SMR_{bot}^{mid} = 1$) both B_{MJ} and B_{NIP} match and consequently $\eta_{spectral} = 1$. This condition is met at about 8h and 16h for the day shown in Figure 2.4. For the rest of the time the spectrum mismatch causes a limitation of either the top or the middle subcell current and a corresponding decrease in the spectral efficiency that expresses the photocurrent loss of a MJ device, associated with the current mismatch among the subcells, under a particular spectral distribution of the DNI compared with respect to the reference spectrum.

Figure 2.4. Equivalent direct normal irradiance (DNI) for every subcell within a triple-junction solar cell, B_{top} , B_{mid} , and B_{bot} , compared to DNI measured with a pyrliometer B_{NIP} (left). Equivalent DNI for a MJ solar cell B_{MJ} and DNI measured with a pyrliometer B_{NIP} (right). At the particular moments when the three equivalent DNI match, spectral matching ratios (SMRs) are equal to one indicating that the spectrum is equivalent to reference AM1.5D-G173-03. When B_{MJ} is identical to B_{NIP} , $\eta_{spectral}$ is equal to one. Photocurrent losses caused by the differences between the spectral distribution of the DNI at any given moment and the reference spectrum are shown as the grey area between B_{NIP} and B_{MJ} .

As shown in Table 2.2, the triple match situation ($B_{top} = B_{middle} = B_{bottom}$ and $SMR_{mid}^{top} = 1$ and $SMR_{bot}^{mid} = 1$) in the case of Madrid only takes place in a limited numbers of days per year. However since the bottom subcell does not limit the current of LM GaInP/GaInAs/Ge solar cells for most of the operating conditions, for this technology we can consider a spectrum equivalent to the reference when only $B_{top} = B_{middle}$ ($SMR_{mid}^{top} = 1$). Nevertheless, while SMR_{bot}^{mid} influences neither the photocurrent of the MJ solar cell nor B_{MJ} for this cell technology, it does affect the DNI value measured with the pyrliometer (B_{NIP}) and consequently the $\eta_{spectral}$ because it accounts for the spectral region influenced by precipitable water. Therefore SMR_{bot}^{mid} limits cannot be completely relaxed when a NIP is used as reference for the DNI, for example for outdoor rating of CPV. This issue is analyzed in detail in the next section. In summary, estimating SMR_{mid}^{top} in conjunction with the DNI from a pyrliometer is enough to determine the solar cell photocurrent for the LM GaInP/GaInAs/Ge technology but not to evaluate $\eta_{spectral}$ and the performance of a CPV system. Consequently, SMR_{bot}^{mid} must be also monitored and filter limits must be studied.

2.3.4 SPECTRAL EFFICIENCY AND SMRS

The spectral efficiency $\eta_{spectral}$, as defined in Eq. (2.7), quantifies the lack of proportionality between DNI and the current generated by a MJ solar cell due to spectral mismatch. Figure 2.5 displays $\eta_{spectral}$ calculated using equivalent irradiances from component cells of LM

GaInP/GaInAs/Ge technology and DNI measured in Madrid in 2013 without any DNI filtering. $\eta_{spectral}$ ranges from 0.2 to values slightly higher than one where one means the same subcell current balance as at the reference spectrum AM1.5D-G173-03. The lowest values of $\eta_{spectral}$ take place when AM is very high, i.e., at sunset and sunrise. As previously mentioned, it should be noticed that $\eta_{spectral}$ values higher than one indicate that the MJ solar cell produces more current than it was expected by the DNI measured with the pyrliometer. For the case of LM GaInP/GaInAs/Ge technology, this happens when SMR_{mid}^{top} is close to one and both, top and middle subcell regions, have higher irradiances than the reference while the bottom region irradiance is lower. This usually happens when the atmosphere has high water content (PW higher than the reference value 1.42 cm), causing a DNI decrease than mainly affects the bottom subcell region.

Figure 2.5. Distribution of spectral efficiency $\eta_{spectral}$ for different values of spectral matching ratios SMR_{mid}^{top} and SMR_{bot}^{mid} in Madrid in 2013 (sample period of one minute). If filter $SMR_{mid}^{top}=1 \pm 1\%$ is applied (grey dots), it limits $\eta_{spectral}$ to $1 \pm 1.9\%$. If the condition $SMR_{bot}^{mid}=1 \pm 1\%$ is added (black dots), the dispersion of $\eta_{spectral}$ is reduced to $\pm 0.6\%$. No DNI filters are applied, but all the filtered samples meet $DNI > 700 \text{ W}\cdot\text{m}^{-2}$.

When the condition $SMR_{mid}^{top}=1 \pm 1\%$ is used to filter data, the collection of spectra is substantially reduced (only 7.6% of the spectra passes the filter) and $\eta_{spectral}$ is limited to $1 \pm 1.9\%$. Those spectra are represented by gray points in Figure 2.5. If SMR_{mid}^{top} fully defined a solar spectrum for the MJ solar cell, every selected spectrum would have $\eta_{spectral}=1$. However, this is not the case because SMR_{mid}^{top} only takes into account the wavelength regions that top and middle subcells can detect. In order to take into consideration also the spectral region related to the bottom subcell, SMR_{bot}^{mid} range is also limited to $1 \pm 1\%$ and represented in black dots. This leads to a significant reduction in the dispersion of $\eta_{spectral}$ ($1 \pm 0.6\%$).

Figure 2.5 also unveils a remarkable linear correlation ($R^2=0.86$) between $\eta_{spectral}$ and SMR_{bot}^{mid} for SMR_{mid}^{top} values limited to $1 \pm 1\%$, as shown in gray dataset. This is caused by the nature of the solar spectrum and how it is modified by water absorption. The plot shows clearly that, for this particular MJ solar cell technology, SMR_{bot}^{mid} should be limited to establish prevailing spectral conditions in CPV rating procedures, but not as much as SMR_{mid}^{top} . Once SMR_{mid}^{top} is limited around one, SMR_{bot}^{mid} variations as high as $1 \pm 12\%$ (grey dots) leads to spectral efficiency dispersions of only $\pm 1.9\%$ (std. deviation), which means values are within $\pm 6.0\%$ with probability higher than 99%. In other words, the sensibility of the spectral efficiency to SMR_{bot}^{mid} in Madrid for LM architecture is roughly one half the sensibility to SMR_{mid}^{top} so filter limits for SMR_{bot}^{mid} could be twice SMR_{mid}^{top} ones.

2.4 SPECTRAL CALIBRATION

We have seen that we can ensure certain prevailing spectral conditions filtering with component cells at a given tolerance. The resultant set of spectra of the filtering by SMR produces the same MJ subcells photocurrents with different (but similar) spectral power distribution, a family of spectra that are equivalent to AM1.5D G173-03 under the prevailing spectral conditions delimited by that tolerance around the reference spectrum. These are therefore *metameric*¹ spectra for the considered MJ solar cell and consequently they produce the same spectral effects onto that MJ solar cell. It is interesting to notice that even considering filter tolerance zero ($\epsilon=0$), there are a few metameric spectra under the vision of a MJ solar cell because two SMR indexes are not perfect spectral indexes (although the reduced number of spectra proves that they are good approaches; more details can be seen in Chapter 4).

Figure 2.6 shows a representation of sets of representative spectra in the spectral space of Madrid for a year in terms of the main atmospheric parameters (AM , PW and PW) considering different values of tolerance around $SMRs=1\pm\epsilon$ filters. The color map symbolizes the $\eta_{spectral}$ that as it has seen above, quantifies the lack of proportionality between DNI and the current generated by that MJ solar cell because of spectral mismatch.

We plot the same set of spectra representative of Madrid presented in Section 2.2.2 versus atmospheric parameters axis plus the reference spectrum, AM1.5D G173-03, marked in red dots in Figure 2.6 (left). By definition if we filter using $SMR_{mid}^{top}=1$ and $SMR_{bot}^{mid}=1$ with a very low tolerance we obtain only the reference spectrum, but when the tolerance grows ($\pm 1\%$ in the

¹ This term has been borrowed from colorimetry, where colors that match having different spectral power distribution are called metamers. It is interesting to notice that a color is the combination of three independent cones (trichromacy) at a given spectrum. Consequently different combinations of light sources can produce the same color impression.

case of Figure 2.6 (left)), we start to observe a group of metameric spectra for the considered MJ technology, LM based in germanium (LM-Ge). Under this narrow filter the mean value of the spectral efficiency is equal to one, which means that the filtered set of spectra is representative of the reference spectrum for this technology, i.e. there is no bias and a low dispersion around the averaged spectral efficiency: $\langle \eta_{\text{spectral}} \rangle = 1$, $\sigma = 0.4\%$.

If the filter opens even wider ($\pm 10\%$, right side of Figure 2.6), we start to appreciate that more different spectra are passing the filter and the condition of linearity for spectral effects is broken both in bias and variance, $\langle \eta_{\text{spectral}} \rangle = 0.987 \pm 2.7\%$. In this situation we cannot consider the set of spectra to be neither representative of AM1.5D G173-03 nor metameric for LM-Ge.

Figure 2.6 Spectral distribution in spectral parameters dimensions (air mass (AM), aerosols (AOD) and precipitable water (PW)) of a representative collection of spectra for Madrid throughout a year where the color map represents the spectral efficiency (η_{spectral}) generated with AERONET data using SMARTS considering a SMR ($SMR_{\text{mid}}^{\text{top}}$ and $SMR_{\text{bot}}^{\text{mid}}$) filtering with a 1% of tolerance (left) and 10% (right). Red dots on left graph represent the coordinates of the AM1.5D G173-03 reference spectrum.

A caveat here is important. The SMR filters are applied to an annual representative synthetic data set of spectra (composed varying lineally AM , AOD and PW), which means that the spectral space is homogenous in these dimensions (a real annual set also fills all the dimensions but is less descriptive). The main consequence is that most of the low tolerance SMR filters will allow a symmetrical number of spectra around $SMRs=1$ so the bias in $SMRs$ and therefore in spectral efficiency are practically negligible ($\langle SMR_{\text{mid}}^{\text{top}} \rangle = 1$, $\langle SMR_{\text{bot}}^{\text{mid}} \rangle = 1$ and $\langle \eta_{\text{spectral}} \rangle = 1$).

2.4.1 SPECTRAL BIAS DUE TO TOLERANCE AROUND $SMRs=1$

The main motivation to increase the limits of SMR filters is to increase the probability of occurrence of a certain prevailing spectral conditions (i.e. to increase the number of metameric spectra), allowing filtered data under a wider range of other operating variables such as ambient temperature. However, it must be taken into account that, given a set of spectra data

which corresponds to a period of operating conditions, the bias in $\eta_{spectral}$ may depend less on the limit range for $SMRs$ than in the average value of the $SMRs$ for the data collection, which could be the dominant source of error with wider SMR filters. For instance, if $SMR_{bot}^{mid} = 1 \pm 5\%$ is considered as filter condition, the impact on the rated value would be quite different if the average value of SMR_{bot}^{mid} for the data collection is 1.0 (no bias error) or 1.03 (bias error of +3%). As a consequence, wider SMR filters should also include some consideration about the average value of the data collections. The Table 2.3 shows the dispersion of the spectral efficiency for different SMR filters for one year, showing that the average value of $\eta_{spectral}$ is close to one regardless the width of the filters, under the condition of SMR averages close to one for the data population.

Table 2.3. Average values and dispersions of the spectral efficiency $\eta_{spectral}$ for different SMR filters around one. Filters have been applied to one year of minute-resolved SMR measurements in Madrid. Average SMR values are also indicated in brackets for the population of data, showing they are very close to one to avoid causing bias errors in $\eta_{spectral}$.

Filtering condition	$SMR_{mid}^{top} = 1 \pm \epsilon\%$	$SMR_{mid}^{top} = 1 \pm \epsilon\%$ & $SMR_{bot}^{mid} = 1 \pm \epsilon\%$
$\epsilon = 1\%$ for $SMRs$	Avg = 1.006 Std = 1.9% [Average $SMR_{mid}^{top} = 1.000$]	Avg = 1.002 Std = 0.6% [Average $SMR_{mid}^{top} = 1.000$] [Average $SMR_{bot}^{mid} = 1.001$]
$\epsilon = 2.5\%$ for $SMRs$	Avg = 1.005 Std = 2.1% [Average $SMR_{mid}^{top} = 1.001$]	Avg = 1.002 Std = 1.06% [Average $SMR_{mid}^{top} = 1.002$] [Average $SMR_{bot}^{mid} = 1.003$]
$\epsilon = 1\%$ for SMR_{mid}^{top} $\epsilon = 2.5\%$ for SMR_{bot}^{mid}	Avg = 1.006 Std = 1.9% [Average $SMR_{mid}^{top} = 1.000$]	Avg = 1.002 Std = 0.9% [Average $SMR_{mid}^{top} = 1.000$] [Average $SMR_{bot}^{mid} = 1.003$]

2.4.2 SPECTRAL BIAS DUE TO ASYMMETRY OF DATASET

In real rating scenarios considering just a few days, there will be a non-symmetrical distribution of spectra among the limits of the SMR filters around $\langle SMRs \rangle = 1$ and therefore we can expect additional biases. This situation can be seen in the $\eta_{spectral}$ distribution versus SMR dimensions in Figure 2.7, with measured data of Madrid from two different days in spring 2014.

Figure 2.7 Spectral distribution in SMR dimensions (SMR_{mid}^{top} and SMR_{bot}^{mid}) with their corresponding spectral efficiency of two different measured days of spring 2014 in Madrid considering several SMR (SMR_{mid}^{top} and SMR_{bot}^{mid}) filtering with a 2.5%, 5% and 10% of tolerance. A day is spectrally-non-biased (left) and the other is spectrally biased (right).

Since SMR_{mid}^{top} is mainly influenced by AM (so by the solar zenith angle), the crossing with unity occurs twice per day provided that the atmosphere turbidity and solar elevation allow it. SMR_{bot}^{mid} is dependent only on specific atmospheric parameters (usually stable during the same day), so in this case the crossing is not so easily assured. The case of Figure 2.7 (left) is therefore representative of an ideal day in terms of spectral changes. In this case there are no clear biases and for tolerances of 2.5% and 5% the amount of samples is symmetric around $SMR_{mid}^{top} = 1$, compensating the bias from both sides. As example, in the case of 2.5%, $\langle SMR_{mid}^{top} \rangle = 1.004$ and $\langle SMR_{bot}^{mid} \rangle = 1.006$, that is reflected in $\langle \eta_{spectral} \rangle = 1.002 \pm 0.8\%$. In contrast, the day represented in Figure 2.7 (right) is an example of double bias. On the one hand, the atmospheric parameters have shifted the SMR_{bot}^{mid} to values below one and on the other hand, the set of values is not symmetric with respect $SMR_{mid}^{top} = 1$. In this case, considering the same tolerance of 2.5%, $\langle SMR_{mid}^{top} \rangle = 0.988$ and $\langle SMR_{bot}^{mid} \rangle = 0.983$, that is reflected in $\langle \eta_{spectral} \rangle = 0.980 \pm 0.3\%$.

As a conclusion, the set of moments chosen for calibration should be SMR non-biased, i.e. they should be chosen in such a way that their SMR distributions are symmetric, balanced around one in both SMR dimensions. This could be avoided reducing at minimum the value of tolerance around $SMRs=1$, but we need to guarantee a filter whose tolerance assures a minimum number of spectra to reduce the uncertainty (the standard error of the mean depends on the inverse of the square root of the number of measurements). In this sense, the tolerance proposed in the IEC 62670-3 (2.5%) is a tradeoff between data and bias, but symmetry should also be taken into account to reduce the bias to the minimum.

2.4.3 SPECTRAL BIAS DUE TO DIFFERENT TECHNOLOGY TO FILTER SPECTRAL CONDITIONS

Up to now, the analysis carried out has been focused on the relationship between a MJ solar cell and the component cells of the same technology based on the fact that both have identical relative spectral response. However in several cases we cannot have access to component cells of the same technology than the MJ solar cell under analysis, therefore they present different spectral response. In this situation the condition $SMR_{mid}^{top}=1$ and $SMR_{bot}^{mid}=1$ (the reference SMR condition) does not produce the same metameric spectra for a MJ solar cell with different technology because the photocurrent balance may differ, introducing another source of bias due to technological mismatch.

Figure 2.8 represents the spectral distribution in SMR dimensions and its $\langle \eta_{spectral} \rangle$ associated to several different MJ technologies: the same LM-Ge as it has been presented previously in this section, two different upright and one inverted metamorphic (UMM^A, UMM^B and IMM) and lattice-matched with dilute nitride (LM-DN) (see Appendix III for more details) versus the SMR filtering based on LM-Ge. The considered period is a single day of spring 2014 in Madrid, and the data are obtained from synthetic spectra calculated with SMARTS from the AERONET station in Madrid and considering $\varepsilon=2.5\%$. The graphical representation is similar to Figure 2.7 but simplified to show all the technologies together, so only the contour and the SMR barycenter of the point cloud are plotted. The corresponding $\langle \eta_{spectral} \rangle$ with their dispersions are also shown.

Figure 2.8 Spectral distribution in SMR dimensions (SMR_{mid}^{top} and SMR_{bot}^{mid}) associated to LM-Ge technology in SMR (SMR_{mid}^{top} and SMR_{bot}^{mid}) dimensions of three days of June 2014 in Madrid considering SMRs (SMR_{mid}^{top} and SMR_{bot}^{mid}) filters using LM-Ge, UMM^B, LM-DN and IMM technologies with a 2.5% tolerance. The spectral data have been obtained synthetically considering the Madrid AERONET station using SMARTS. The graphical distribution of each MJ technology is simplified considering its contour and barycenter.

As a general remark, an additional bias appears when a different MJ technology is used for filtering. However the concrete variation on the $\langle \eta_{spectral} \rangle$ is very dependent on the chosen period since the different changes in spectrum affect in different ways to the MJ technologies. In the case presented in Figure 2.8, all the solar cells present the similar bias in SMR ($\langle SMR_{mid}^{top} \rangle = 1.01$ and $\langle SMR_{bot}^{mid} \rangle = 1.00$), however the effect on $\langle \eta_{spectral} \rangle$ is different depending the technology of the MJ solar cell. For example, the case of a UMM^B solar cell, a very low bias in spectral efficiency is found, $\langle \eta_{spectral} \rangle = 1.000 \pm 1\%$, even if the UMM^B QE is the most different with respect LM-Ge. However UMM^A and IMM solar cells have a $\langle \eta_{spectral} \rangle = 0.995 \pm 1\%$.

In the case the data are clearly shifted, the bias can grow. Even so, the spectral bias in the case of technological mismatch is fairly low when the tolerance is low, at least for the considered MJ technologies.

2.4.4 SPECTRAL SENSITIVITY OF A MJ SOLAR CELL

The concrete impact of any kind of spectral bias is going to be strongly affected by the sensitivity of the spectral efficiency of the concrete MJ solar cell that is being calibrated. As example, a representative annual dataset that fills a large portion of the $SMRs$ diagram is used as a representation of the spectral sensitivity of two MJ technologies: LM-Ge and UMM as a pair of technologies with a very different spectral sensitivity as is shown in Figure 2.9. The dataset is also obtained from synthetic spectra comprising a full year and the information given in this figure is actually equivalent to the one in Figure 2.5, but with a different distribution of axes.

Figure 2.9 Spectral distribution in SMR dimensions (SMR_{mid}^{top} and SMR_{bot}^{mid}) with their corresponding spectral efficiency of a whole year in Madrid from synthetic data obtained with SMARTS from AERONET station considering several SMR (SMR_{mid}^{top} and SMR_{bot}^{mid}) filtering with a 2.5%, 5% and 10% of tolerance as in Figure 2.9. LM-Ge technology (left) and IMM technology (right). Black dots represent a day chosen for calibration.

The actual impact on spectral efficiency on the two MJ solar cells can be seen in black dots, which are the moments of a day chosen for calibration. In this case, considering again 2.5% as tolerance, even if the dataset is pretty symmetric and the bias in SMR_{bot}^{mid} is very similar for both technologies, there are differences of 1% (LM-Ge $\langle\eta_{spectral}\rangle=1.01\pm0.5\%$, UMM $\langle\eta_{spectral}\rangle=1.00\pm0.6\%$). This difference in $\langle\eta_{spectral}\rangle$ is attributable to the concrete spectral sensitivity of each MJ solar cell (Domínguez et al. 2016).

2.5 CPV POWER RATING: SPECTRAL FILTERING BY MEANS OF SMRS

A CPV system is composed not only of MJ solar cells, but also optics. Hence, spectral effects caused by the optics (Lorenzo 1981; Annen et al. 2011) (chromatic aberration, material transmittance) may play an important role that cannot be neglected. Additionally, there are temperature effects that also have a significant impact. In the first place, the operating cell temperature of the MJ solar cells will be different than that of the component cells, which affects the spectral response of the devices. In the second place, the lens temperature may significantly affect its effective focal distance and color mixing (Steve Askins et al. 2011; Rumyantsev et al. 2010; Hornung, Steiner, and Nitz 2012; Victoria et al. 2013) which also affects the light spectrum over the cell. Obviously the impact of these issues depends on the type of CPV module, mainly its optical design (refractive vs. reflective, number of stages, geometrical concentration, etc).

Taking into account that SMRs are obtained by means of bare component cells and the effects described above, the condition $SMR_{mid}^{top} = 1$ and $SMR_{bot}^{mid} = 1$ (the reference SMR condition) does not produce equivalent spectra to the reference one for a CPV module because the photocurrent balance may differ due to optical and temperature effects, in the same way that different MJ solar cell technologies differ from each other. But the question that we are trying to answer is whether that condition could ensure repeatable spectral conditions for the CPV module and consequently repeatable power rating of the CPV module under that condition. As seen before, the reference SMR condition leads to solar spectra that resemble very much the reference AM1.5D-G173-03 if the requirement of DNI close to $900 \text{ W}\cdot\text{m}^{-2}$ is added, but not necessarily if the DNI range is wider.

For rating of CPV modules and systems, the approach currently used by several laboratories (S. Askins et al. 2010; Siefer et al. 2014) consists in keeping the pyrheliometer as reference instrument to account for the incoming DNI and use the component cells to determine prevailing spectral conditions by filtering SMR_{mid}^{top} and SMR_{bot}^{mid} values around one. This approach is also currently included in the draft of the IEC 62670-3 standard (IEC committee 2015) focused on the performance measurements and power rating of CPV modules.

The analysis we will show is based on a 15 kWp CPV array installed in Madrid, using two-stage refractive optics and 3J solar cells working above 800X (Nagai et al. 2014). First, we will focus on the power rating of the array at Concentrator Standard Operating Conditions (CSOC) (IEC committee 2013). The objective is to rate the power of the array at CSOC in the short term, carried out for only a few days after its installation and set-up. Figure 2.10 shows the current at the maximum power point normalized by DNI for a couple of days with different filters applied. The current at maximum power point has been represented instead of power itself to avoid further data correction due to temperature issues. It must not be forgotten that the spectral distribution of the irradiance at the entrance aperture of the CPV modules will influence the fill factor FF and thus the power of the MJ solar cell (McMahon et al. 2008). The current at maximum power point accounts at least partially for this effect and is much less sensitive to temperature variations than voltage and consequently power. Nevertheless, for the example case detailed above, relatively constant cell temperatures are expected for the filtered data which obtained in steady state conditions and with relatively constant ambient temperature and wind conditions during the two days, so power will be also analyzed for comparison.

Figure 2.10. Normalized DC current at the maximum power point of a CPV system I_{DC}/B_{NIP} as a function of the direct normal irradiance (DNI) measured with a pyrheliometer B_{NIP} . Two days of data are shown. Black dots correspond to the clear condition filter ($DNI > 700 \text{ W}\cdot\text{m}^{-2}$). Brown triangles represent the addition of the condition $SMR_{mid}^{top} = 1 \pm 1\%$. The requirement $SMR_{bot}^{mid} = 1 \pm 1\%$ has been added for green marks.

Table 2.4 collects the average values and their dispersion obtained for the rated current and power at the maximum power point. Both Figure 2.10 and Table 2.4 show the high dispersion of rated values when the only condition of clear sky ($DNI > 700 \text{ W}\cdot\text{m}^{-2}$) is applied (red dots). If the spectral filters are added, based on $SMRs$ obtained from spectroheliometer data, standard deviation are decreased to values as low as 0.7% and 0.2% for one (blue circles) or two (green markers) SMR conditions of $\pm 1\%$ respectively. Even for the case of SMR filters of $\pm 2.5\%$, the

dispersion achieved in the rated current is well below $\pm 1\%$. Regarding power dispersion, results are very similar, proving that FF variations caused by spectral changes mostly affect the current at maximum power.

Table 2.4. Results of a short-term (2 days of data measurement) rating of a 15 kWp CPV array based on a two stage refractive optics working above 800X installed in Madrid. Both average value and standard deviation for the normalized current and power at the maximum power point (A/W) are detailed for each filtering condition.

Filtering condition	<i>DNI > 700</i> No SMR filt.		<i>DNI > 700</i> $SMR_{mid}^{top} = 1 \pm \epsilon\%$		<i>DNI > 700</i> $SMR_{mid}^{top} = 1 \pm \epsilon\%$ $SMR_{bot}^{mid} = 1 \pm \epsilon\%$	
$\epsilon = 1\%$ for <i>SMRs</i> when applicable	I_{DC_norm} Avg = 24.53 Std = $\pm 7.5\%$	P_{DC_norm} Avg = 13721 Std = $\pm 8.0\%$	I_{DC_norm} Avg = 25.21 Std = $\pm 0.7\%$	P_{DC_norm} Avg = 14137 Std = $\pm 0.7\%$	I_{DC_norm} Avg = 25.32 Std = $\pm 0.2\%$	P_{DC_norm} Avg = 14209 Std = $\pm 0.3\%$
$\epsilon = 2.5\%$ for <i>SMRs</i> when applicable			I_{DC_norm} Avg = 25.18 Std = $\pm 0.8\%$	P_{DC_norm} Avg = 14119 Std = $\pm 0.8\%$	I_{DC_norm} Avg = 25.28 Std = $\pm 0.6\%$	P_{DC_norm} Avg = 14165 Std = $\pm 0.6\%$

The same analysis has been carried out over a longer period to better show the strength of the *SMR* filters. Results of one year data are shown in Figure 2.11 and Table 2.5. It should be noted that data are affected by the soiling in the array, since array cleaning happened only through natural washing by rain, which may limit the evolution of the dispersion values. Despite this limitation, the reduction in the dispersion of the rated values when using *SMR* filters is clearly observable in Figure 2.11.

Figure 2.11. Normalized DC current at the maximum power point of a CPV system I_{DC}/B_{NIP} as a function of the direct normal irradiance (*DNI*) measured with a pyrheliometer B_{NIP} . One year of data are shown. Red dots correspond to the clear condition filter ($DNI > 700 \text{ W}\cdot\text{m}^{-2}$). Blue dots represent data filtered adding the condition $SMR_{mid}^{top} = 1 \pm 1\%$ in the left and $SMR_{mid}^{top} = 1 \pm 2.5\%$ in the right. The requirement $SMR_{bot}^{mid} = 1 \pm 1\%$ or $1 \pm 2.5\%$ has also been added in green dots.

Table 2.5. Results of a long-term (1 year of data measurement) rating of a 15 kWp CPV array based on a two stage refractive optics working above 800X installed in Madrid. Both average value and standard deviation for the normalized current and power at the maximum power point (A/W) are detailed for each filtering condition.

Filtering condition	<i>DNI</i> > 700 No <i>SMR</i> filt.		<i>DNI</i> > 700 $SMR_{mid}^{top} = 1 \pm \epsilon\%$		<i>DNI</i> > 700 $SMR_{mid}^{top} = 1 \pm \epsilon\%$ $SMR_{bot}^{mid} = 1 \pm \epsilon\%$	
	I_{DC_norm} Avg = 23.20 Std = $\pm 12.6\%$	P_{DC_norm} Avg = 13046 Std = $\pm 12.9\%$	I_{DC_norm} Avg = 24.69 Std = $\pm 3.6\%$	P_{DC_norm} Avg = 13921 Std = $\pm 3.5\%$	I_{DC_norm} Avg = 24.46 Std = $\pm 2.4\%$	P_{DC_norm} Avg = 13847 Std = $\pm 3.3\%$
$\epsilon = 1\%$ for <i>SMRs</i> when applicable						
$\epsilon = 2.5\%$ for <i>SMRs</i> when applicable						

2.6 CONCLUSIONS

A set of component cells has been presented as a simple and effective instrument to quantify the spectral variation of the *DNI* and its influence on MJ solar cells and CPV systems. They can be used together with collimating tubes to compose an instrument (spectroheliometer) that provides experimental data to obtain the *SMRs*, a set of spectral indexes that quantifies any particular spectra by comparing it to a reference spectrum.

The main use of these *SMR* indexes is filtering of operating conditions, providing a simple way to determine prevailing spectral conditions by keeping *SMR* values around one. This approach has proved a significant reduction in the dispersion of the rated current of CPV cells, modules and systems based on MJ cells. The study of the site of Madrid has revealed the probability of the occurrence of the prevailing spectral conditions according the range of the *SMR* filters for several MJ solar cell technologies, which is one of the open questions in the CPV community.

A detailed study about spectral calibration of MJ solar cells has shown several sources of bias: the use of a *SMR*=1 tolerance not narrow enough; the non-symmetry of the data and the spectral mismatch between the cell and the component cells. Nevertheless it has been shown that the real impact on the calibration value is dependent on the spectral sensitivity of the MJ solar cell under calibration.

In the case of CPV systems, ranges of $\pm 1\%$ for the *SMR* filters showed dispersion values of the rated current at the maximum power point as low as $\pm 0.2\%$ for a 15 kWp CPV array during a rating period of two clear-sky days, while simple clear sky condition of *DNI* higher than 700 $\text{W}\cdot\text{m}^{-2}$ leaded to dispersion values as high as $\pm 7\%$. Higher ranges of *SMRs* $\pm 2.5\%$ showed also very good results ($\pm 0.6\%$), with the clear advantage of a much higher probability of occurrence, but it should be accompanied of further conditions to avoid possible bias errors during the spectral calibration.

2.7 APPENDIX I - UNCERTAINTY ESTIMATION OF A SPECTROHELIOMETER

In this appendix we intend to estimate the uncertainty of SMR values as measured with a spectroheliometer. According to the ISO “*Guide to the Expression of Uncertainty in Measurement*” (JCGM 2008) evaluation of the sources of uncertainty are categorized in type A (uncertainty estimated using statistics, i.e., obtained from repeated observations) and type B (uncertainty estimated from any other source, e.g., calibration certificates, manufacturer’s specifications, previous experience with similar measurements...)

On the one hand, type A evaluation of uncertainty is based on statistical analysis of series observation. The short-circuit current produced by every component cell $I_{L,subcell\ i}$ is obtained through the measured voltage V_i and the shunt resistance R_i , while the instrument is placed in a meteorological sun tracker and the data are collected by a datalogger, and therefore type A analysis may be used for this parameter. When repeatability conditions are imposed (clean windows, irradiation over $700\text{ W}\cdot\text{m}^{-2}$ and DNI stability, as defined in Section 2.2.2), the type A uncertainty for the short-circuit current of a component cell has been found to be lower than 0.2%.

On the other hand, the main contribution to type B uncertainty for the short-circuit current of a component cell $U_{I_{L,subcell\ i}}$ is the tolerance of the shunt resistances (0.1%) U_{R_i} . The additional contributions to uncertainty caused by the pointing accuracy of the tracker (0.1° for a solar tracker for radiation measuring instruments) and the resolution of the data acquisition instruments (20 bits and 10 V full scale) can be considered negligible.

Taking into account both A and B contributions, total uncertainty when measuring short-circuit current of a component cell can be estimated as $U_{I_{L,subcell\ i}} = 0.22\%$, according to (JCGM 2008).

To determine the uncertainty of the short-circuit current of every subcell under the reference spectrum $U_{L,subcell\ i\ ref}$ we should consider the uncertainty of the calibration provided by the manufacturer (3% for all the component cells) and the uncertainty of the protective window transmissivity U_{Window} , (maximum value of the three component cells 0.35%). Then $U_{I_{L,subcell\ i\ ref}} = 3.02\%$ (before rounding to two significant digits as stated in (JCGM 2008)). Errors due to the differences in the spectral response of the component cells at different temperatures have been neglected.

The uncertainty in the determination of SMR U_{SMR} is calculated based on the definition of SMR given in Eq. (2.1):

$$U_{SMR} = \sqrt{\left(\frac{\partial SMR}{\partial I_{L,subcell\ i}} U_{I_{L,subcell\ i}}\right)^2 + \left(\frac{\partial SMR}{\partial I_{L,subcell\ j}} U_{I_{L,subcell\ j}}\right)^2 + \left(\frac{\partial SMR}{\partial I_{L,subcell\ i_{ref}}} U_{I_{L,subcell\ i_{ref}}}\right)^2 + \left(\frac{\partial SMR}{\partial I_{L,subcell\ j_{ref}}} U_{I_{L,subcell\ j_{ref}}}\right)^2} \quad (2.8)$$

We have determined $U_{SMR} = 4.3\%$, demonstrating that *SMR* uncertainty is basically determined by the uncertainty of the calibration of the component cells at reference conditions.

2.8 APPENDIX II - SPECTRAL PARAMETERS

Spectral parameters refer mainly to components present in the atmosphere that affect the solar spectrum (atmospheric parameters) or to a parameter that describe the path of the solar spectrum through the atmosphere (AM). The atmospheric parameters are responsible of absorption and scattering of solar radiation, including Rayleigh and Mie scattering (due to gases and particles respectively) while the common way to express this attenuation of solar light is through the corresponding attenuation coefficient (τ) corrected by air mass (AM) according to the Beer-Lamber law.

$$I = I_0 \cdot e^{-AM \cdot \sum_i \tau_i(\lambda)} \quad (2.9)$$

where I_0, I are the extraterrestrial and terrestrial irradiance and τ_i is the spectrally-resolved optical thickness or depth of each atmospheric parameter.

2.8.1 AIR MASS

The most relevant spectral parameter is the one that is not an atmospheric one. Air mass (AM) describes the path length in the terrestrial atmosphere that solar radiation has to traverse, normalized by the zenith path length (the minimum path length) at sea level. When the incidence is close to normal (at midday) a low AM is expected, whereas if the incidence angle is almost parallel the AM increases dramatically (sunrise/sunset).

Since the normalization is given at sea level, the actual value of AM is dependent on the air pressure (directly linked to altitude). If no air pressure correction is applied, the AM is considered to be relative and when it is taken into account the AM is absolute. The absolute AM is the one that really expresses the amount of atmosphere that the sunlight passes, consequently it is also the only that makes sense to use for the determination of MJ solar cell photocurrents. A well accepted formulation is the one given by Kasten and Young (Kasten and Young 1989):

$$AM = \left(\frac{1}{\cos(Zz) + 0.50572 \cdot (96.07995 - Zz)^{-1.6364}} \right) \cdot e^{-0.1184 \cdot altitude} \quad (2.10)$$

where Zz refers to the solar zenith angle in degrees and altitude is in km.

2.8.2 AEROSOL OPTICAL DEPTH

Aerosols concentration and optical characteristics is function of place and the moment of measurement, severally influenced by the meteorological circumstances (Muneer et al. 2004). They can have either of natural origin (soil dust, sand particles, sea salt, forest fires, volcanic dust..) or from anthropogenic as pollution or biomass burning.

Aerosols' spectral relationship formulated in 1929 by Ångström (Ångström 1929) establishes the dependence of aerosol optical depth (*AOD*) on wavelength:

$$\tau_{\lambda_1} = \beta \cdot \lambda_1^{-\alpha} \quad (2.11)$$

where

- τ =optical thickness/depth (*AOT/AOD*)
- α =Ångström exponent

This parameter expresses the aerosol size distribution. Depends on climate and typical worldwide value is 1.3 ± 0.5

- β =Ångström turbidity coefficient

It is related to the amount of aerosols and is equivalent to *AOD* at wavelength equals to 1 μm . $\beta < 0.1$ are related to clean atmospheres and $\beta > 0.1$ to turbid ones.

- λ =wavelegnth

The spectral dependence of the *AOD* at different wavelengths is actually a generalization of the previous equation and can be used to estimate the Ångström exponent.

$$\frac{\tau_{\lambda_1}}{\tau_{\lambda_2}} = \left(\frac{\lambda_1}{\lambda_2} \right)^{-\alpha} \quad (2.12)$$

It is usual that the *AOD* is expressed at only one wavelength, or even in the form of Ångström turbidity coefficient (β). In fact SMARTS tool can accept *AOD* at 500 and 550 nm and the β (that equals to *AOD* at 1000 nm). A related concept is the *visibility* expressed as the distance at which an object can be seen, typical in traffic, especially at airports.

2.8.3 PRECIPITABLE WATER

Precipitable water (*PW*) refers to the amount of water (in the form of vapor) contained in a column of the atmosphere. This means that If all the *PW* were precipitated, the height of the water in that column will be equivalent to the amount measured by the *PW* parameter, usually expressed in cm.

It is strongly influenced by the absolute level of humidity in the atmosphere, so ambient temperature and relative humidity of a given site influence the level of *PW*.

2.8.4 OTHER PARAMETERS

Other less relevant atmospheric parameters are ozone (O_3), carbon dioxide (CO_2) and nitrogen dioxide (NO_2). Their much lesser impact on the amount of spectral irradiance allows ignoring them in the determination of MJ solar cell photocurrents.

2.9 APPENDIX III- MJ SOLAR CELL TECHNOLOGIES

In Table 2.6 and Figure 2.12 can be found the description and QE of the five MJ solar cell technologies used in this thesis.

Table 2.6. Description of the five MJ solar cell technologies.

Cell technology	Layers	Band gaps	Ref.
Lattice matched germanium	InGaP/InGaAs/Ge	1.88 / 1.4 / 0.67 eV	LM-Ge
Upright Metamorphic - A	InGaP/InGaAs/Ge	1.82 / 1.33 / 0.67 eV	UMM ^A
Upright Metamorphic - B	InGaP/InGaAs/Ge	1.82 / 1.24 / 0.67 eV	UMM ^B
Inverted Metamorphic	InGaP/GaAs/InGaAs	1.89 / 1.41 / 1.0 eV	IMM
Lattice matched dilute nitride	InGaP/GaAs/InGaAsNSb	1.89 / 1.41 / 1.0 eV	LM-DN

Figure 2.12. Quantum efficiencies of the five MJ solar cell technologies.

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CHAPTER 3 – SPECTRAL CLASSIFICATION OF WORLDWIDE LOCATIONS BASED ON SMR INDEXES

3.1 INTRODUCTION

Concentrator PV (CPV) systems are based on multijunction (MJ) solar cells that are composed of several subcells connected in series. The benefit of MJ solar cells with respect single junction broadband cells is that each MJ subcell is optimized to a specific range of the solar spectrum and usually the MJ cell can absorb a broader spectral range. However due to the series connection, any change in solar spectrum with respect the reference spectrum (AM1.5D-G173-03 (Committee G03 2012)) is going to provoke a current mismatch among the subcells and the MJ solar cell is only generating the minimum of the subcells currents. In fact, the most common scenario is that the photocurrent ratios (I_{ratios}) obtained at reference spectrum are only accomplished a very few times during a day or even not occurring. So the optimum I_{ratios} that maximize every harvesting at a certain location may not be the ones that maximize the current of the device under AM1.5D-G173-03.

It can be useful to define a representative spectrum for a place, so this spectrum could be used to optimize a MJ solar cell and therefore a CPV module, for example, by tuning the photocurrents generated by every subcell (Lumb et al. 2010; Araki and Yamaguchi 2003; Kinsey and Edmondson 2009) or by adjusting the optical design (Marta Victoria et al. 2013). However this spectral information is scarce and is found only for a few places.

A procedure for the spectral characterization of a particular site based on SMR indexes is proposed and then used to characterize spectrally worldwide locations. This information

reveals how the annual energy weighted spectrum of the site compares to the reference spectrum and provides useful information for the optimization of a particular MJ technology for that site. To quantify the spectral losses due to spectral mismatch of a location with regard to reference spectrum, the derived spectral efficiency computes the losses associated to such spectral variations. Moreover, its integration over days, months or years for a specific site reveals the spectral losses to be expected in such site for a particular MJ technology, which can be used in the modeling and energy forecast of CPV systems.

The foundations of the analysis based on spectroheliometers are first presented for a single case of Madrid, then applied to a small spectral network in Europe and then extended to a global scope considering synthetic spectra generated with SMARTS (Gueymard 2001) using atmospheric data from AERONET (Holben et al. 1998) stations. Furthermore the underlying objective is to be able to correlate geographic and atmospheric features characteristic of a climate or region with SMR values, so MJ solar cells and CPV modules could be spectrally tuned to a concrete location.

3.2 ANNUAL SPECTRAL ENERGY DISTRIBUTION VERSUS SMR

Strongly influenced by local climate, the majority of the energy may be found at SMR values different from one, e.g., at high altitude locations with clear sky the most probable situation is $SMR_{mid}^{top} > 1$. Therefore the middle subcell would limit the current of the device most of the time. As a consequence, the $I_{ratio_{mid,ref}}^{top}$ value that maximizes the annually harvested energy for that particular location would be lower than one.

The SMRs representative for a place can be calculated by integrating the SMRs weighted by the direct normal irradiation E_{DNI} , over the whole year

$$\overline{SMR}_{subcell_j}^{subcell_i} = \frac{\int_{year} SMR_{subcell_j}^{subcell_i}(t) \cdot E_{DNI}(t) dt}{\int_{year} E_{DNI}(t) dt} \quad (3.1)$$

The distribution of the annual direct normal irradiation as a function of SMR_{mid}^{top} and SMR_{bot}^{mid} is shown in Figure 3.1 for Madrid in 2013 with minute resolution. Both SMRs define a mesh whose size is 100x100 bins with a resolution of 0.05x0.05. The color map represents an indication of the direct normal irradiation that is received in Madrid for every combination of SMR values.

The black dot in Figure 3.1 indicates the SMRs barycenter, that is, the annually DNI-weighted in spectral coordinates ($\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$) which are respectively 0.96 and 1.00. It must be pointed out that both values are very close or equal to one, which indicates that the reference spectrum AM1.5D-G173-03 is quite suitable to optimize a LM GaInP/GaInAs/Ge MJ solar cell for the climate of Madrid.

Figure 3.1 Spectral distribution of direct normal irradiation in Madrid throughout 2013 expressed as a function of spectral matching ratios (SMR_{mid}^{top} and SMR_{bot}^{mid}). The black dot indicates the barycenter, i.e. the energy weighted SMR values that minimize the annually integrated spectral losses.

A graphical representation of the distribution of the annual DNI as a function of SMR_{mid}^{top} and SMR_{bot}^{mid} has been proposed (Núñez et al. 2015) for the spectral characterization of a particular site for CPV applications, whose coordinates $\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$ reveal how well matched is a particular MJ technology to that site and the current balance correction needed to optimize that technology to the site.

3.2.1 ANNUAL REPEATABILITY

In order to estimate the repeatability of the annually DNI-weighted SMRs, the years 2012, 2014 and 2015 have been also analyzed for the case of Madrid. It is found out that the spectral graphs have similar shape as can be seen in Figure 3.2. Looking into the energy distributions a concrete pattern is arising. Basically the energy is concentrated at high values of SMR_{mid}^{top} and this is mainly due to the long clear days of Madrid in summer.

The annually DNI-weighted SMRs mean and its dispersion among the four years (2012, 2013, 2014 and 2015) is $\overline{SMR}_{mid}^{top} = 0.97 \pm 0.56\%$ and $\overline{SMR}_{bot}^{mid} = 1.00 \pm 0.66\%$. We can conclude that the expected variability of the annually DNI-weighted SMRs for Madrid and places with a similar latitude and climate is delimited to 0.5-1%.

Figure 3.2. Spectral diagrams of Madrid to show repeatability from year 2012 until 2015. Energy levels are the same as shown in the color map in Figure 3.1 for comparison purposes.

3.3 SPECTRAL OPTIMIZATION OF A MJ SOLAR CELL FOR A PARTICULAR LOCATION

The most direct way to optimize a MJ solar cell consists in tuning the subcell bandgaps so that the current ratio $I_{ratio_{subcell_j}^{subcell_i}}^{ref}$ equals one under the reference spectrum.

Alternatively, some authors (Araki and Yamaguchi 2003; Kinsey and Edmondson 2009; Lumb et al. 2010; Philipps et al. 2010; Jaus and Gueymard 2012) have used a set of spectra representative for a particular location to determine the ratio that maximize the current produced by that MJ solar cell throughout the year. Instead, we propose here to use measurements obtained with a spectroheliometer to determine the optimum $I_{ratio_{subcell_j}^{subcell_i}}$.

The annually DNI-weighted $\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$ can be used to estimate the $I_{ratio_{subcell_j}^{subcell_i}}$ that would maximize the current generated by the corresponding MJ solar cell technology throughout the year in a certain location.

The set of $\overline{SMR}_{subcell_j}^{subcell_i}$ can be calculated following the definition of SMR as a fraction of the subcells current ratio and the subcells ratio at spectral reference conditions (ASTM G173 AM1.5D). Then, we can obtain an expression where $\overline{SMR}_{subcell_j}^{subcell_i}$ depends only on the annually energy weighted current ratio between subcell i and j ($\overline{I_{ratio_{subcell_j}^{subcell_i}}}$) and the current ratio of the same subcells under the reference spectrum ($\overline{I_{ratio_{subcell_j}^{subcell_i}}^{ref}}$), according to:

$$\overline{SMR}_{subcell_j}^{subcell_i} = \frac{\int_{year} I_{ratio_{subcell_j}^{subcell_i}}(t) \cdot E_{DNI}(t)}{\int_{year} E_{DNI}(t)} \cdot \frac{1}{I_{ratio_{subcell_j_{ref}}^{subcell_i}}} = \frac{\overline{I_{ratio_{subcell_j}^{subcell_i}}}}{I_{ratio_{subcell_j_{ref}}^{subcell_i}}} \quad (3.2)$$

Maximizing the current generated annually in a particular place implies making $\overline{I_{ratio_{subcell_j}^{subcell_i}}}$ equals to one.² Hence, the optimum value for the subcell photocurrent ratio under the reference spectrum for that particular location $I_{ratio_optimum_{subcell_j_{ref}}^{subcell_i}}$, should accomplish:

$$\overline{SMR}_{subcell_j}^{subcell_i} \cdot I_{ratio_optimum_{subcell_j_{ref}}^{subcell_i}} = 1 \quad (3.3)$$

This can be understood as follows. For the sake of clarity the discussion is based on the top and middle subcells photocurrent ratio but it will be equivalent for the middle and bottom. If for a certain location and MJ solar cell technology $\overline{SMR}_{mid}^{top}$ is higher than one, it means that the direct normal irradiation is, in average, blue-shifted and the MJ current is most of the time limited by the middle subcell. In this situation it would be convenient to tune the $I_{ratio_{mid_{ref}}^{top}}$ to a value lower than one so the time throughout the year when the middle subcell is limiting would be reduced.

This optimization of $I_{ratio_{subcell_j_{ref}}^{subcell_i}}$ presented here ignores some aspects that should certainly be considered to optimize the energy annually harvested by a CPV system. Among them, the most important are the effects of the optics transmittance and its temperature dependence (Hornung, Steiner, and Nitz 2012; Askins et al. 2011; Rumyantsev et al. 2010; M. Victoria et al. 2010; Helmers, Schachtner, and Bett 2013; Fernández et al. 2016). Bare cells are commonly optimized to have top/mid current ratio as close as possible to one under the reference spectrum, so the optics should inversely compensate $\overline{SMR}_{mid}^{top}$. It must be pointed out that many CPV optics transmits better in the middle range than in the top which worsen even more the top/mid current ratio, so this approach is not always possible. Alternatively the cell itself can be optimized according to the $\overline{SMR}_{mid}^{top}$ value of the site and considering the spectral effect of the optics.

The impact of cell temperature on the spectral response (Aiken et al. 2002) is studied later in this chapter and at annual analysis can be neglected in the majority of cases.

² This condition is better accomplished when the dataset of SMR values are symmetric and close to one. The actual value of $I_{ratio_optimum_{subcell_j_{ref}}^{subcell_i}}$ should be understood as a very close approximation for locations whose atmosphere is not extreme. Anyway in real-case scenarios more factors account for estimating the optimal current ratio, therefore in this chapter $\overline{SMR}_{subcell_j}^{subcell_i}$ is intended only for classification purposes.

3.4 ENERGY LOSSES DUE TO SPECTRAL VARIATION

Several authors have analyzed the effect of spectral variation on the annual current produced by a MJ solar cell in a particular location using some representative spectra (Emery, Myers, and Kurtz 2002; McMahon et al. 2002) or radiative models as MODTRAN (Armijo et al. 2014), SPCTRAL2 (Araki and Yamaguchi 2003; Faine et al. 1991) or SMARTS (Jaus and Gueymard 2012; Philipps et al. 2010; Kinsey and Edmondson 2009; Lumb et al. 2010). However all these models have the limitation that they use as inputs the atmospheric parameters whose measurement are complex and require expensive instrumentation. As it was remarked in Chapter 2, the spectral efficiency $\eta_{spectral}$ is a simpler approach based in MJ subcells photocurrents.

The spectral efficiency $\eta_{spectral}$ accounts for the photocurrent losses caused by the differences between the spectral distribution of the DNI at every moment and the reference spectrum. When the spectral efficiency is integrated over a period of time t , an estimation of the collected energy despite the spectral mismatch $\eta_{spectral,t}$ can be calculated as:

$$\eta_{spectral,t} = \frac{\int_t B_{MJ}(t)dt}{\int_t B_{NIP}(t)dt} \quad (3.4)$$

The evolution of the spectral efficiency throughout a sunny day was also presented in Chapter 2. The ratio between DNI and spectrally corrected DNI (B_{MJ}) integrated over a period represents the losses in the current of a MJ solar cell due to spectral variation over that period of time. For example, for the day represented in Figure 4 of Chapter 2, $\eta_{spectral,day}$ is 94.2%, so the current losses due to changes in the solar spectrum, compared to the reference spectrum AM1.5D-G173-03, are 5.8%.

The atmosphere changes throughout the day and the year, usually showing periodical patterns caused by local characteristics. Monthly averages of $\eta_{spectral}$ can be obtained for a certain location and solar cell technology if enough experimental data are available. This information can be applied to CPV modeling and energy prediction for a specific location (Faine et al. 1991; Jaus and Gueymard 2012; Emery, Myers, and Kurtz 2002; McMahon et al. 2002; Araki and Yamaguchi 2003; Philipps et al. 2010), and it could be used together with irradiation values provided in radiation databases to forecast the energy harvested by a CPV system, as it is proposed in Chapter 5. Figure 3.3 shows the spectral efficiency in Madrid integrated over every month for four years (2012-2015) and the synthetic series for 2013 generated with SMARTS and data from a photometer station (AERONET) in Madrid for comparison. Table 3.1 presents these values, including the annually-integrated value per year.

Along this chapter, experimental values from spectroheliometers are used when they are available, but for wider analyses where they are not accessible, synthetic data are employed.

Figure 3.3. Evolution of the spectral efficiency integrated over every month $\eta_{spectral,month}$ and the annually-integrated values for the years 2012-2015 and the synthetic series obtained from AERONET data of 2013 in Madrid. $\eta_{spectral,month}$ gives an idea of the expected current losses due to spectral mismatch for a lattice-matched (LM) GaInP/GaInAs/Ge triple-junction (3J) solar cell.

The annual average for the four years is 0.947, so around 5% of annual current losses in Madrid for that particular MJ solar cell technology are caused by spectral mismatch. For the complete CPV system the change in the transmittance of the optics may increase or reduce these losses.

Table 3.1. Spectral efficiency integrated over every month $\eta_{spectral,month}$ and annually-integrated value for the years 2012-2015 and synthetic values obtained using SMARTS and AERONET station data in Madrid.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2012	0.890	0.897	0.940	0.953	0.960	0.960	0.965	0.983	0.983	0.973	0.947	0.876	0.949
2013	0.898	0.927	0.936	0.957	0.930	0.953	0.957	0.963	0.982	0.964	0.925	0.878	0.945
2014	0.925	0.922	0.928	0.970	0.946	0.956	0.955	0.971	0.978	0.971	0.938	0.866	0.949
2015	0.879	0.925	0.934	0.948	0.989	0.953	0.963	0.967	0.960	0.951	0.894	0.870	0.946
Synthetic	0.911	0.928	0.941	0.955	0.963	0.965	0.960	0.960	0.956	0.974	0.947	0.911	0.952

3.5 EUROPEAN SPECTRAL NETWORK

Although first experiences based on component cells approach have shown very good results (Siefer et al. 2014; Antón et al. 2012) and component cells and derived spectral parameters (Núñez et al. 2016) are gaining prominence in the CPV community, geographical data are not available for the evaluation of the potential generation of CPV systems, a gap that this section intends to fill based on the SMR and DNI annual series.

Under the SOPHIA European project (Malbranche 2011), several partners have been collecting spectral data using spectroheliometers for at least one year, 2014. In Figure 3.4 we can see the location of the institutions that are involved: Madrid (Spain, IES-UPM), Bourget-du-Lac (France, CEA-INES), Freiburg³ (Germany, Fraunhofer ISE) and Portici (ENEA).

Figure 3.4 European map showing the institutions that are measuring using spectroheliometers composing the SOPHIA spectral network.

The corresponding spectral graphs can be seen in Figure 3.5 and the shapes and sizes are already giving an idea that similar geographical conditions (especially latitude) are shaping in similar ways the spectral graphs. Just considering the energy distribution paying attention to colors, Portici and Madrid have a similar pattern as Freiburg and Bourget do, representing both groups two different climates.

³ Fraunhofer ISE's component cells are a LM-Ge slightly different version than the used by other partners. To be able to compare both sets, a data translation has been applied using the method explained in Chapter 4 to model a set of component cells from another.

Figure 3.5 Spectral diagrams of Freiburg (left), Portici (center) and Bourget-du-Lac (right). Energy levels are the same as shown in the color map in Figure 3.1 for comparison purposes.

3.5.1 SPECTRAL GEOGRAPHICAL ANALYSIS IN SMR DIMENSIONS

In Figure 3.6 the annually DNI-weighted SMR ($\overline{SMR}$ s) of the different locations are plotted together with their corresponding annual spectral efficiency. The first conclusion is that all the places are reddish from an annual energetic point of view, basically due to the low level of AOD used to define the ASTM G173-03 reference spectrum. We can quickly compare spectrally different locations plotting the $\overline{SMR}$ s of each place. First let us remember the atmospheric factors that mainly influence on each SMR. SMR_{mid}^{top} is affected by AM and AOD , so the lower is AM (affected by latitude and altitude) and AOD (pollution, dust, soot ...), the higher is SMR_{mid}^{top} (Núñez et al. 2014). Similarly SMR_{bot}^{mid} is affected mainly by PW and AOD , so the closeness to mass of waters increases the SMR_{bot}^{mid} while it is also reduced by AOD (Núñez et al. 2014). This can be seen in Figure 3.6 in the analyzed locations. For example, we can compare Madrid and Portici, with similar latitudes and Mediterranean climates. These similarities can be seen directly in the spectral graph of both places (see both spectral diagrams in Figure 3.1 and Figure 3.5), quite comparable in shape and distribution of energy. However we see in Figure 3.6 that Madrid presents higher values of $\overline{SMR}_{mid}^{top}$, due to its higher altitude (695 m vs. 0 m) and Portici has higher $\overline{SMR}_{bot}^{mid}$ due to be sited at sea level, presenting higher level of vapor of water in its atmosphere.

Regarding the annual spectral efficiency, the closer a location is to $\overline{SMR}s=1$, the lower are the expected annual spectral losses for cell optimized for AM1.5D G173-03, specially on

$\overline{SMR}_{mid}^{top}$ dimension, since in top and middle spectral bands are where the most of the energy of DNI spectrum is distributed.

Figure 3.6 Annual SMRs of the locations of the SOPHIA spectral network representing how the direct normal irradiation is shifted with respect the reference spectrum AM1.5D G173-03 ($\overline{SMR}_{mid}^{top} = \overline{SMR}_{bot}^{mid} = 1$).

3.6 SYNTHETIC WORLD SPECTRAL NETWORK

A more generic analysis should include extra locations from different worldwide climates. Since nowadays the amount of deployed spectroheliometers around the globe is quite reduced, another approach considering synthetic spectra can be an interesting option for the atmosphere characterization, especially when this information is already available. We propose an approach that involves the use of atmospheric radiative transfer models (Chan, Brindley, and Ekins-Daukes 2014), such as SMARTS (Gueymard 2001), SPECTRAL2 (Faine et al. 1991), and MODTRAN (Armijo et al. 2014), which synthesize spectrally resolved DNI and GNI (Global Normal Irradiance) upon a particular atmospheric and environmental condition. The spectrally-resolved DNI is obtained by starting with the extraterrestrial irradiance, corrected by actual sun-earth distance, and considering atmospheric factors with a known impact on transmittance, namely, Rayleigh scattering, absorption by ozone, nitrogen dioxide, uniformly mixed gases and water vapor, and aerosol extinction. Among those factors, the sunlight path length, which is function of Sun's zenith angle and altitude, the aerosol extinction and water vapor absorption are considered to be the principle impact factors (Gueymard 2009; Faine et al. 1991; Philipps et al. 2010; Emery, Delcueto, and Zaaïman 2002; Osterwald, Emery, and Muller 2014; Fernández et al. 2014).

Therefore, based on a set of input parameters, primarily air mass (AM), aerosol optical depth (AOD), and precipitable water (PW), as well as geographical information (mainly

altitude), radiative transfer models can provide the spectrally resolved DNI at a specific moment and location. Furthermore, a representative number of simulated spectral irradiance distributions can be used for estimating the average effect of the spectral variations in the performance of a MJ solar cell in periods of days, months, or a whole year for a specific site. This information is then used in this section for the optimization of the current balance between subcells within a MJ solar cell under the standard reference spectrum, which will depend on the site.

The advantage of this approach is that satellite sources (MODIS (Hubanks et al. 2008) and SOLIS model (Mueller et al. 2004; Behrendt et al. 2013)) and a worldwide ground network with higher accuracy, AERONET (AERosol RObotic NETwork) (Holben et al. 1998), which provide the required atmospheric data are already available. AERONET is a network of ground-based sun photometers established by NASA and PHOTONS (PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire) and it is greatly expanded by cooperation of research centers and individual scientists. The historical data and the wide geographical representation of the locations in the AERONET database have great value for the evaluation of part of the spectral variability relevant to MJ solar cells and consequently to CPV. These spectral data considering the locations with the most complete representative annual series are used in this section to estimate representative information of different climates and regions around the world.

The set of spectrally-resolved DNI for a number of sites and years, modeled with SMARTS from AERONET data, has been used to obtain SMR spectral indexes (Jaus and Gueymard 2012; Núñez et al. 2014) used in CPV considering a representative operation cell temperature of 90 °C. A second variant is considered at 25 °C to estimate the spectral variation on MJ solar cell photocurrent due to thermal drift. Nevertheless an analysis of the influence in a concrete CPV system should also consider the effect of the optics on the spectral distribution on the MJ cell (M. Victoria et al. 2010; Fernández et al. 2014), the change on the transmittance due to temperature variations on the optics (Hornung, Steiner, and Nitz 2012; Askins et al. 2011) and ambient temperature fluctuations.

3.6.1 DATA DESCRIPTION

3.6.1.1 AERONET data

The AERONET network is based on the instrument CIMEL Electronique 318A, which is a sky spectral sun photometer (Bayat, Masoumi, and Khalesifard 2011; Shaw 1983; Estellés et al. 2006). A sensor head fitted with collimators is attached to a robot base which

systematically points the sensor at the sun disc and sky positions according to a programmed routine (Holben et al. 1998).

The radiometer makes two basic measurements, either sun disk or sky, both within several programmed sequences (Holben et al. 1998). For the case of direct sunlight, the spectral irradiance at wavelengths of 340, 380, 440, 500, 670, 870, 940 and 1020 nm are measured (a sequence of three measurements are taken, creating a triplet per wavelength). The 940 nm channel is used for the determination of the atmospheric content of precipitable water (*PW*). Additionally, the attenuation induced by Rayleigh scattering and absorption by ozone and gaseous pollutants is estimated and removed to isolate the aerosol optical depth (*AOD*). This measurement is realized to screen the cases of influence of clouds. The typical time interval between measured data is 15 minutes.

3.6.1.2 Data quality

The associated data published in the database of AERONET have three different levels, namely, level 1.0, level 1.5 and level 2.0 ordered by increasing level of data quality and reliability, but reducing the amount of available data.

In order to have a trade-off between reliable and representative results, data at level 1.5 (automatic cloud screened but no manual data inspection) are used for this study, considering one natural year as the time period unit. However, the data quality of each available location of AERONET is quite different considering the measurement frequency and the lack of data in a relatively long period, so a site analysis has been conducted to ensure very high data quality of the selected sites. It must be pointed out that the sun photometer does not generate data in cloudy conditions, so a lack of data caused by long cloudy periods or reliability and maintenance issues are indistinguishable. Nevertheless, these periods are of little relevance for CPV, as diffuse light is wasted.

Representative locations have been first selected according to data at level 2.0 because they are available on a single database (1.5 level data must be downloaded for each location separately). The database contains level 2.0 data of more than 800 locations, whose measured atmospheric parameters have different level of quality for each location and every year. The site and period selection criteria are set to be:

- A particular year must have at least a certain number of data points, fixed at 10,000;
- Data must be available during each month of a year. All the sites are expected to have at least one sunny day per month even in winter conditions;

- Altitude of the site not exceeding 2000 m;
- Latitude of site not exceeding 50 degrees.

To avoid a too limited set of sites, we have not considered an annual DNI threshold (even if some of them cannot be suitable for CPV). Nevertheless all of them provide valuable information about spectral differences. Under these criteria, 34 locations with at least one year of data were selected, covering a wide range of climate conditions. The final set of locations can be seen in Figure 3.7 (the detailed list of selected locations is in the Appendix):

Figure 3.7 Worldwide distribution of selected AERONET locations. Note: numbers inside circles identify locations and can be found in Appendix.

3.6.2 SYNTHETIC SPECTRAL ANALYSIS OF A LOCATION

Based on the solar spectral irradiance obtained with SMARTS on the basis of the AERONET data and the quantum efficiencies (QE) of the MJ cells, a series of photocurrents for each subcell and the corresponding SMR_{bot}^{top} and SMR_{bot}^{mid} can be calculated for each selected location with the time resolution of the AERONET data (variable, maximum 15 minutes) and over a relevant period of time, namely one year at least filtering those whose SMR have no physical significance ($0 < SMR < 1.5$). Since QE are dependent on cell temperature, unless otherwise stated, hereafter a cell temperature of 90 °C, closer to operation temperatures of MJ solar cells in a CPV module, will be considered. In addition, to characterize the spectral irradiance at a specific site, the synthetic equivalent average SMRs weighted by incident DNI for each location are calculated according to the following equations:

$$\overline{SMR}_{subcell_j}^{subcell_i} = \frac{\sum_{year} SMR_{subcell_j}^{subcell_i}(t) \cdot DNI_{P,AERONET}(t)}{\sum_{year} DNI_{P,AERONET}(t)} \quad (3.5)$$

$$DNI_{P,AERONET}(t) = \frac{\sum DNI_{AERONET}(t)}{\Delta t} \quad (3.6)$$

where $\overline{SMR}_{subcell_j}^{subcell_i}$ is the annually DNI-weighted average $SMR_{subcell_j}^{subcell_i}$; $DNI_{P,AERONET}$ stands for the representative DNI at the particular time period modeled with SMARTS from AERONET data; Δt is the time resolution, which is calculated by the time difference between two consecutive measurements; usually 15 minutes but can be lower (i.e. it is assumed that the spectral irradiance $DNI_{P,AERONET}$ stays stable between samples).

Figure 3.8 Schema of an example of sampling blocks from AERONET data series. Red areas indicate the time of sample that is considered not to have actual information.

Since the time resolution is variable and calculated as the difference between two samples, any lack of data of the AERONET station caused by overcast, instrument failure or any other reason could be interpreted as longer periods with extra irradiation. As a result time intervals exceeding 15 minutes are constrained to 15 minutes, assuring that only actual measurements count to estimate the annually DNI-weighted SMRs (see example in Figure 3.8). For that reason the total considered energy per site in this study (from now on AERONET annual DNI) is going to be limited by AERONET availability. Although previous filters have constrained the set of sites to those with the highest amount of data, the total annual DNI measured by AERONET is going to be lower than if it was measured by a pyrheliometer.

Annually DNI-weighted average atmospheric parameters have been calculated using the same procedure. The results of these annually DNI-weighted average atmospheric parameters ($\overline{AM}$, $\overline{AOD}$, and $\overline{PW}$) and annually DNI-weighted average SMR ($\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$) for all listed locations are detailed in the Appendix.

3.6.2.1 Experimental validation. Case study: Madrid

IES-UPM has been collecting spectroheliometer SMR data at a site that is only 200 m distant from an AERONET station maintained by the Spanish state meteorological agency (AEMET). Both instruments see virtually the same sky (when no clouds are present in the low-étage), which represents a convenient scenario for comparing both spectral data sources.

As an example of the aforementioned graphical representation, Figure 3.9 shows the spectral distribution of DNI in Madrid for the year 2013, obtained from the spectroheliometer (previously presented in Figure 3.1) and AERONET data processed with SMARTS. Considering that AERONET stations usually have a sampling frequency of 15 minutes and the spectroheliometer is sampled every minute, the spectroheliometer dataset has been interpolated to the time array of the AERONET data. Regarding data screening, AERONET level 2.0 data quality has been selected, therefore it assures cloud screening plus manual quality verification (Holben et al. 2006). The coordinates $\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$ are respectively 0.94 and 1.00 obtained from the spectroheliometer measurements and 0.94 and 0.98 from the AERONET atmospheric data and simulated spectrally resolved DNI, which shows a reasonably good agreement between both procedures.

Figure 3.9 Spectral distribution of the direct normal irradiation in Madrid throughout 2013 expressed as a function of spectral matching ratios ($\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$). The black dot indicates the barycenter, i.e. the annual DNI-weighted mean SMR values. (Left) SMR and DNI determined from experimental measurements with spectroheliometer and pyrliometer, respectively. (Right) SMR and DNI are integrated from a “synthetic” spectrum generated with SMARTS fed with AERONET data.

3.6.3 MAPPING THE SOLAR RESOURCE WITH THE SPECTRAL CHARACTERISTICS OF WORLDWIDE LOCATIONS

The aim of this section is to show the capability of a set of SMR indexes, namely two SMRs for the case of triple junction solar cells, to characterize a particular atmospheric condition for that MJ solar cell technology. Among the atmospheric parameters, air mass (AM) corrected with site elevation (Kasten and Young 1989), aerosol optical depth (AOD), and precipitable water (PW) are considered to be the main factors impacting DNI spectrum, while others such as ambient temperature, air pressure, ozone and others have a minor

impact (Muller et al. 2010). Therefore, for the case of MJ cells, a particular atmospheric condition can be determined by means of the triplet (AM , AOD , PW). Nevertheless, the impact of such atmospheric condition on the MJ device performance cannot be directly calculated, but it is necessary to estimate the spectral distribution of DNI first by means of a radiative transfer model and then calculate the performance of the device through its spectral response. Alternatively, SMR indexes allow the direct estimation of the impact on the MJ performance since they account for the variations in current ratios among the subcells of the device. Thus, it would be helpful to determine relationships between the atmospheric indexes (AM , AOD , PW) and the spectral indexes ($SMRs$).

The selected sites (see Appendix for details), which cover a wide range of climatic conditions, will be used to determine the correlation between both atmospheric and SMR indexes. We shall start studying the atmospheric parameters that affects each SMR index, not only for the case of instantaneous SMR values but also the annual DNI-weighted averages $\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$. For this second case, we shall use the annual DNI-weighted averages of the atmospheric parameters as input values, i.e. $\overline{AM}$, $\overline{AOD}$, and $\overline{PW}$, instead of their instant values.

3.6.3.1 Annually DNI-weighted top-middle SMR vs. geographic parameters

Figure 3.10 World distribution of selected AERONET locations showing both their annual DNI-weighted mean spectral matching ratio between top and middle subcells ($\overline{SMR}_{mid}^{top}$) and their annual DNI-weighted mean aerosol optical depth $\overline{AOD}$. $\overline{SMR}_{mid}^{top}$ is represented in a color scale while a diameter scale is used for $\overline{AOD}$. Note: numbers inside circles identify locations and can be found in Appendix.

The $\overline{SMR}_{mid}^{top}$ index covers the top and middle subcell spectral regions, i.e., from 350 to 900 nm, so it is mainly affected by AM and AOD (Núñez et al. 2014). The lower the latitude, the lower the mean air mass, which result in higher values of $\overline{SMR}_{mid}^{top}$. The 34 values of $\overline{SMR}_{mid}^{top}$ for the studied sites are represented in a global map (Figure 3.10) as circles with a color scale together with the corresponding $\overline{AOD}$ through the circle diameter, showing a clear

relationship between both parameters. In general, low $\overline{AOD}$ sites (small dots) show higher $\overline{SMR}_{mid}^{top}$ values (blue dots) as Lanai in Hawaii (19) or Cordoba (4) in Argentina, while high $\overline{AOD}$ sites (large dots) show low $\overline{SMR}_{mid}^{top}$ values (red dots) as the Arabian Desert (1, 5, 23 and 29) or Yonsei-University (34) in Seoul (a polluted big city due to anthropogenic reasons (Park et al. 2015)). A distinctive site is Tamanrasset (31) in Algeria, in the middle of the Sahara desert, which shows a unexpected low $\overline{AOD}$ due to its particular local conditions such as a dry-cool season with low mean AOD (Guirado et al. 2014), plus a relative high altitude (1377 m) that increases its $\overline{AM}$. All these effects together are reflected in a unpredicted high level of $\overline{SMR}_{mid}^{top}$ for a desert location. Other notable examples related to altitude are in the North American South West, where several locations (25, 28, 30 and 33) have an altitude over 1200 m (see Appendix) leading to higher $\overline{AM}$ values that along with a lower $\overline{AOD}$ than other sites of similar latitudes is reflected in higher levels of $\overline{SMR}_{mid}^{top}$.

3.6.3.2 Annually DNI-weighted middle-bottom SMR vs. geographic parameters

Figure 3.11 World distribution of selected AERONET locations showing both their annually DNI-weighted Spectral Matching Ratio between Middle and Bottom subcells ($\overline{SMR}_{bot}^{mid}$) and their annually DNI-weighted precipitable water ($\overline{PW}$). $\overline{SMR}_{bot}^{mid}$ is represented in a color scale while a diameter scale is used for $\overline{PW}$. Note: numbers inside circles identify locations and can be found in Appendix.

The relationship of $\overline{SMR}_{bot}^{mid}$ with $\overline{PW}$ is pointed out in Figure 3.11. The higher the $\overline{PW}$, the stronger the absorption of the DNI in the infrared region, more important in the bottom subcell region than in the middle one, leading to high $\overline{SMR}_{bot}^{mid}$ values. Consequently, the proximity of big masses of water (as in the case of islands and coastal sites) increases the level of $\overline{SMR}_{bot}^{mid}$; some example cases are Lanai (19) in Hawaii and Jabiru (14) and Lake Argyle (18) in Australia. On the other hand, especially dry sites, such as the North

American South West (25, 28, 30 and 33) or in inner deserts show very low $\overline{SMR}_{bot}^{mid}$, with Tamanrasset (31) being a good example.

Again Yonsei-University (34) is an interesting special case that is worth noticing due to the influence of the East Asian monsoon in its climate with a humid summer and a dry winter (Yoon, Lee, and Choi 2007). Since precipitations are correlated with less irradiation, the annual DNI-weighted values of Seoul are prone to spectral conditions of winter, i.e. low PW and therefore low $\overline{SMR}_{bot}^{mid}$, decreased even further by its high level of $\overline{AOD}$.

3.6.3.3 Relationship between spectral parameters and SMRs

The relationships between the SMR indexes and atmospheric parameters were determined based on experimental instantaneous data measured in Madrid throughout the year 2013 (Núñez et al. 2014). This relationship can be obtained from a set of places that can be considered to be representative of the areas where CPV is prone to be installed among the selected sites from AERONET network, i.e. those whose $\overline{AOD}$ is lower than 0.15 and $\overline{PW}$ is between 0.7 and 2. This group needs also to be filtered by the AERONET annual DNI, but as it was pointed out previously, we cannot consider AERONET annual DNI as an absolute reference. Therefore, we take as threshold the median energy of the group that drops sites that clearly are not target for CPV as Toronto (32), Halifax (11) or Egbert (6), all in Canada. In the end, 13 sites are selected as base for the model whose names are highlighted in bold in the tables of the Appendix.

The proposed model is linear plus some products that account for parameters that affect similar spectral regions:

$$SMR_{mid}^{top} = 1.14 - 0.09 \cdot AM - 0.19 \cdot AOD + 0.02 \cdot PW - 0.15 \cdot AM \cdot AOD \quad (3.7)$$

$$SMR_{bot}^{mid} = 0.92 - 0.30 \cdot AOD + 0.07 \cdot PW - 0.06 \cdot AOD \cdot PW \quad (3.8)$$

This instantaneous SMR model is applied to all sites, including those who were not selected to create the model. The accuracy of the model for each location can be evaluated looking at the residuals that should be approximately normally distributed, where a low standard distribution shows a good fitting and a zero centered distribution stands for an unbiased estimation. In Figure 3.12 mean value and standard deviation (in percentage) of residuals are plotted for each location. Outliers, defined here as those moments of every location whose residuals are larger than 0.1, were filtered out (they represent less than 1% of the total of the moments). The figure shows a better fitting for the 13 selected sites (round dots), while other climates with lower potential for CPV show higher dispersion

and bias in the residuals, taking into account always that the model is an approximation of several non-linear effects. Even for climates with very high AOD values not suited for CPV installations, such as Bahrain (1) or and Yonsei-University (34) in Seoul, the model works reasonably well and is able to show the strong correlation between SMR indexes and atmospheric parameters.

Figure 3.12 (Left) Mean and standard deviation of residuals of the 34 sites selected from AERONET applying the model proposed in Eq. 3.7 and 3.8 that relates atmospheric parameters (air mass, aerosols and precipitable water) and spectral matching ratios (SMR_{mid}^{top} and SMR_{bot}^{mid}). **(Right)** Detail of residuals distributions of a CPV site selected in model (Railroad_Valley (25)) and two outlier sites (Yonsei_University (34) and Bahrain (1)).

As stated above, the $\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$ are the spectral coordinates that reveal how well matched is a particular MJ technology to the spectral conditions of a site. In this sense, the relationship between the local annually DNI-weighted average atmospheric parameters to such coordinates would provide a fast way to determine the potential of a particular site for a particular MJ technology. Similar equations to the instantaneous model are revealed but with slightly different coefficients, as is shown in Eq. 3.9 and 3.10. Again, only the 13 CPV-prone sites have been used to determine this time the fit parameters of an annual model. This model is based on annual DNI-weighted averages of the atmospheric parameters as input values, i.e. $\overline{AM}$, $\overline{AOD}$, and $\overline{PW}$, instead of their corresponding instant values:

$$\overline{SMR}_{mid}^{top} = 1.14 - 0.10 \cdot \overline{AM} - 0.43 \cdot \overline{AOD} + 0.03 \cdot \overline{PW} - 0.19 \cdot \overline{AM} \cdot \overline{AOD} \quad (3.9)$$

$$\overline{SMR}_{bot}^{mid} = 0.91 - 0.34 \cdot \overline{AOD} + 0.07 \cdot \overline{PW} + 0.25 \cdot \overline{AOD} \cdot \overline{PW} \quad (3.10)$$

Even though $\overline{PW}$ has been included in the Eq. (3.9), its influence in $\overline{SMR}_{mid}^{top}$ is less than 3%, so from here on it will be neglected in the graph (but not in the model) to ease the graphical representation of the involved spectral parameters.

In Figure 3.13, the annual DNI-weighted average $\overline{SMR}_{mid}^{top}$ for the 34 selected locations using AERONET network are represented as a function of $\overline{AM}$ and $\overline{AOD}$. The black dashed lines represent simplified Eq. (3.9) for a constant $\overline{PW}$ value (mean annual value for model sites: 1.28 cm). Accordingly, dots of the same color should be superimposed onto their corresponding black dashed line.

Figure 3.13 Spectral Matching Ratio between top and middle subcells ($\overline{SMR}_{mid}^{top}$) versus atmospheric parameters of the annual DNI-weighted averages of the 34 selected locations around the world using AERONET network. To ease the representation, only the two main factors are considered (air mass $\overline{AM}$ and aerosol optical depth $\overline{AOD}$). Black dashed lines represent the fitting model. Note: numbers inside circles identify locations and can be found in Appendix.

The figure shows a clear relationship between the values of $\overline{SMR}_{mid}^{top}$ and $\overline{AM}$ and $\overline{AOD}$, the higher the $\overline{AM}$ and $\overline{AOD}$, the lower the level of $\overline{SMR}_{mid}^{top}$. Residuals considering the full model of Eq. (3.9) are normally distributed and the standard error of estimate is 0.55%. Error increases to 1.28% if $\overline{PW}$ is neglected and decreases to 0.12% when the model is applied only to the 13 sites used to build the model.

A similar analysis can be carried out considering $\overline{SMR}_{bot}^{mid}$ and the atmospheric parameters that mainly affect it, namely $\overline{PW}$ and $\overline{AOD}$. In Figure 3.14, $\overline{SMR}_{bot}^{mid}$ versus $\overline{PW}$ and $\overline{AOD}$ is plotted for the 34 sites, as well as the fitting model in black dashed lines.

Figure 3.14 Spectral matching ratios between middle and bottom subcells ($\overline{SMR}_{bot}^{mid}$) versus relevant spectral parameters (PW and AOD). Black dashed lines represent the fitting model. Annual DNI-weighted averages of the 34 selected locations around the world using AERONET network. Note: numbers inside circles identify locations and can be found in Appendix.

As in the previous case, there is a high correlation between $\overline{SMR}_{bot}^{mid}$ and the atmospheric parameters with a standard error of estimate of 1.20% for the 34 sites and 0.23% for the 13 sites that feed the model. Furthermore, it is interesting to notice that for the spectral ranges of the QE of LM-Ge 3J cell technology, air mass does not significantly contribute to $\overline{SMR}_{bot}^{mid}$, and consequently it was ignored in Eq. (3.10).

3.7 GLOBAL ANALYSIS OF SPECTRAL INFLUENCE FOR SEVERAL KINDS OF TRIPLE JUNCTION CELLS

The analyses in previous section were conducted on LM GaInP/GaInAs/Ge triple junction solar cells, hereafter LM-Ge. The aim of this part is to compare these data with those obtained for other triple junction technologies, including various types of lattice-matched and metamorphic triple-junction solar cells. Table 3.2 shows the materials and bandgaps of the cells used in the study, covering on the one hand lattice-matched 3J solar cells, both traditional cells based on germanium substrates and cells based on dilute nitrides, and on the other hand metamorphic 3J solar cells, both upright and inverted grown. The details about QE can be found in the Appendix III in Chapter 2 (Note: UMM in this study is UMM^A from that list).

Table 3.2 Description of the four cell technologies considered in this study.

Cell technology	Layers	BandGaps	Ref.
Lattice matched germanium	InGaP/InGaAs/Ge	1.88 / 1.4 / 0.67 eV	LM-Ge
Upright Metamorphic	InGaP/InGaAs/Ge	1.82 / 1.33 / 0.67 eV	UMM
Inverted Metamorphic	InGaP/GaAs/InGaAs	1.89 / 1.41 / 1.0 eV	IMM
Lattice matched dilute nitride	InGaP/GaAs/InGaAsNSb	1.89 / 1.41 / 1.0 eV	LM-DN

The same calculation detailed above for LM-Ge has been carried out for the other three types of solar cells (UMM, IMM and LM-DN). An entire year of AERONET data obtained for the 34 sites is used for the simulation, by means of SMARTS, of the spectrally resolved DNI. Then, for the four MJ technologies of the table, the photocurrents of the three subcells and the corresponding instantaneous values of SMR_{bot}^{top} and SMR_{bot}^{mid} are calculated for each location over the course of the year with the time resolution of the AERONET data (15 min). Finally, the annually DNI-weighted values of $\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$ are calculated and compared. Numeric results are listed in the Table 3.5 of the Appendix and graphical comparisons are shown in Figure 3.15.

Figure 3.15 shows $\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$ for the four cell technologies. The differences between the cell technologies is observed to be relatively low compared to the strong differences between locations, which is a consequence of the high degree of similarity between the spectral range of top, middle and bottom subcells for the four technologies. Some sites have geographic parameters in common and form clusters that have similar levels of annual DNI-weighted spectral parameters relevant to highlight as those in deserts, close to big masses of water and North-American South-West.

Regarding $\overline{SMR}_{mid}^{top}$ the differences among the technologies are below 1% for half of the sites and between 1% and 2% for the other half, while the differences among sites range about 20%, from 0.82 to 1.03. A second conclusion is that $\overline{SMR}_{mid}^{top}$ is below one for most of the locations, which means that the average spectral irradiance is red-shifted, i.e., the bare cells would work under top current limitation on average (the spectral influence of the optics is not considered here). This apparent mismatch between annual DNI-weighted SMR_{mid}^{top} ($\overline{SMR}_{mid}^{top} < 1$) and spectral reference ($SMR_{mid}^{top} = 1$) is explained by the fact that the total integrated irradiance of the AM1.5D-G173-03 spectrum was chosen to match standard reporting condition irradiance (900 W·m⁻², typical at midday) and with very concrete atmospheric parameters, i.e. AOD (0.084) and PW (1.42 cm). Therefore while the

spectral reference is representative usually of midday clear-sky conditions, DNI distribution over the year is mainly below the standard value. Consequently the main reason for this mismatch is that DNI during sunrise and sunset, even if they don't contribute as much as the values at midday, on average push down the $\overline{SMR}_{mid}^{top}$.

The results suggest that the CPV module optimization should increase top current for the four technologies and most of the sites, which can be made at the cell level or by means of the optics, as for example promoting short wavelength focusing or tuning the antireflective coating (Marta Victoria et al. 2013).

Figure 3.15 Annually DNI-weighted Spectral Matching Ratio between top and middle subcells ($\overline{SMR}_{mid}^{top}$) and between middle and bottom subcells ($\overline{SMR}_{bot}^{mid}$) for the selected locations considering four different MJ technologies: Lattice matched based on Germanium (LM-Ge), Upright Metamorphic (UMM), Inverted Metamorphic (IMM) and Lattice matched dilute nitride (LM-DN). Some sites have geographic parameters in common and form groups that have similar levels of annual DNI-weighted spectral parameters relevant to highlight as those in deserts (desert), close to big masses of water (~water) and North-American South-West (NA-SW). Note: numbers inside circles identify locations and can be found in Appendix.

In a similar way, Figure 3.15 also shows $\overline{SMR}_{bot}^{mid}$ for the 34 sites in the horizontal axis. In this case the differences among the 4 cell technologies are higher which correspond with the greater differences in the spectral responses of the 4 bottom subcells. About 60% of the sites show differences below 2%, while the others have values up to 4.5%. Nevertheless the differences among sites are again much higher and vary more than 20%.

A majority of sites show also a $\overline{SMR}_{bot}^{mid}$ value below one but in this case there are many sites with values close to one or above. Nevertheless, the impact of the $\overline{SMR}_{bot}^{mid}$ depends very much on the cell technology, since the current of the bottom subcells exceeds the other two from only about 7% for the case of the LM-DN cells to more than 40% for the LM-Ge subcells. For this last technology, in any single location the bottom subcell will not limit the current of the device, but this may not be the case for the other technologies in specific sites.

It is worth making the point that the distance among SMR coordinates of different technologies of a given site is related to the closeness of its atmosphere to AM1.5D-G173-03 conditions. The closer is a location to the ideal situation ($\overline{SMR}_{mid}^{top}=1$ and $\overline{SMR}_{bot}^{mid}=1$), the closer are the four SMR coordinates. Sites with high/low $\overline{AOD}/\overline{PW}$ as Yonsey_University (34) ($\overline{AOD}=0.33$, $\overline{PW}=0.96$) and low/high $\overline{AOD}/\overline{PW}$ as Lanai (19) ($\overline{AOD}=0.08$, $\overline{PW}=2.87$) highlight those differences which are caused by the combination of the cut-off wavelengths of the subcells and the dominant levels of atmospheric components of a site.

3.8 ANNUAL SPECTRAL EFFICIENCY

The conclusion seen in the European spectral network studied above is valid also in the global analysis, i.e. the further a location is placed in the spectral diagram, the larger are the expected spectral losses, regardless of the MJ solar cell technology, as Figure 3.16 proves. The data are presented in Table 3.4 in the Appendix.

Figure 3.16 Annually DNI-weighted Spectral Matching Ratio between Top and Middle subcells ($\overline{SMR}_{mid}^{top}$) and between Middle and Bottom subcells ($\overline{SMR}_{bot}^{mid}$) for the selected locations considering four different MJ technologies: lattice matched based on germanium (LM-Ge), upright metamorphic (UMM), inverted metamorphic (IMM) and lattice matched dilute nitride (LM-DN). Color expresses the annual spectral efficiency ($\eta_{\text{spectral,year}}$). Note: numbers inside circles identify locations and can be found in Appendix.

Regarding the technologies, differences are not so obvious for locations whose $\overline{SMR}$ s are close to one. However, those places that are not spectrally matching the current ratio at reference conditions present notable spectral losses that are more pronounced in the case of lattice matched technologies (LM-Ge and LM-DN). Metamorphic ones (UMM and IMM) are therefore more tolerant. For example, the worst-case, Yonsey University (34), has very different values among the technologies ($\eta_{\text{spectral,annual}} [\text{LM-Ge}] = 0.833$, $\eta_{\text{spectral,annual}} [\text{UMM}] = 0.893$, $\eta_{\text{spectral,annual}} [\text{IMM}] = 0.910$, $\eta_{\text{spectral,annual}} [\text{LM-DN}] = 0.827$).

A special case occurs for places whose atmosphere in general terms are clear and are close to water masses, as Lanai (19). In this case ($\eta_{\text{spectral,annual}} [\text{LM-Ge}] = 1.01$, $\eta_{\text{spectral,annual}} [\text{UMM}] = 0.99$, $\eta_{\text{spectral,annual}} [\text{IMM}] = 0.998$, $\eta_{\text{spectral,annual}} [\text{LM-DN}] = 0.976$) the annual spectral losses are virtually zero or even over one for LM-Ge. This indicates that the MJ solar cell calibrated at AM1.5D-G173-03 produces more current than expected by the DNI measured with the pyrheliometer. For the case of LM-Ge technology, this happens when $\overline{SMR}_{mid}^{top}$ is close to one and both, top and middle subcell spectral regions have higher irradiance than the reference while the bottom region irradiance is lower. This usually happens when $I_{ratio_{mid}}^{top}$ is close to one (Lanai's atmosphere is clear, so frequently $\overline{SMR}_{mid}^{top} \geq 1$) and the atmosphere has a high water content (Lanai's PW is usually higher than the reference

value 1.42 cm, so $SMR_{bot}^{mid} \geq 1$). As a consequence, the decrease in the DNI mainly affects the bottom subcell region that in this case is not limiting.

3.9 SPECTRAL THERMAL DRIFT

The cell temperature impacts on the spectral response of MJ solar cells (Aiken et al. 2002) and therefore on their current subcells and related SMR values. As it was pointed above, all the previous analyses considered a cell temperature of 90 °C, closer to operation temperatures of MJ solar cells in a CPV module. QE of a solar cell tend to expand due to temperature, so depending on the cut-off levels of each subcell with respect solar spectrum, thermal changes can lead to different evolutions depending on the technology. Figure 3.17 shows the spectral coordinates for the four technologies at 25 °C and 90 °C revealing that most of thermal drifts are below 0.01 in both $\overline{SMR}$ dimensions. Data for both temperatures for the four technologies are collected in Table 3.5 of the Appendix.

Figure 3.17 Annually DNI-weighted Spectral Matching Ratio between Top and Middle subcells ($\overline{SMR}_{mid}^{top}$) and between Middle and Bottom subcells ($\overline{SMR}_{bot}^{mid}$) for the selected locations at 25 °C and 90 °C considering four different MJ technologies: lattice matched based on germanium (LM-Ge), upright metamorphic (UMM), inverted metamorphic (IMM) and lattice matched dilute nitride (LM-DN). Note: numbers inside circles identify locations and can be found in Appendix.

While the change due to temperature is negligible in IMM and LM-DN, the most sensitive technology is UMM, where in some extreme cases as Lanai (19) the thermal drift is almost 0.02. This is explained by the fact that the cut-off wavelengths of middle and bottom subcells are exactly at the first main water-absorption peak of terrestrial solar spectrum

around 940 nm. The abrupt change of irradiance in this spectral area makes this technology more sensitive than the others to QE changes and so on to temperature.

3.10 CONCLUSIONS

SMR indexes have been used to characterize the solar resource at a specific site through their annual DNI-weighted average values related to a MJ solar cell technology. This provides the spectral information that gives most of the necessary information for optimizing the spectral response of a CPV module (whose response at a reference site is known) for a new location. This may be carried out by tuning the current ratio of the receiver multi-junction cells by a factor corresponding to the difference in SMR between the known site and the new site or considering external factors as optics. In addition, the estimation of the spectral losses due to current mismatch is obtained through the integrated value of the spectral efficiency in a year. As a general remark, the further are the SMR coordinates from reference spectrum, the larger are the spectral losses.

Later the relationships between SMR indexes and atmosphere parameters, mainly AM, AOD, and PW have been determined not only for instantaneous values, but also for annual DNI-weighted averages, which allows the prediction of the SMR indexes if some geographic and atmosphere parameters of a site are known. The capability of the AERONET network to provide such needed parameters has been exploited in this study, selecting 34 worldwide sites with the best data quality and covering many different climate conditions.

Finally, the site characterization by means of SMR indexes has been extended to several triple-junction technologies, covering lattice-matched cells based on germanium and dilute nitrides and both inverted and upright metamorphic cells. The comparative analysis shows large differences in the performance of the devices between the selected locations, while the differences among the technologies were much less significant. Impact of solar cells temperature has been shown to be negligible in this analysis.

3.11 APPENDIX

Table 3.3 lists the 34 AERONET stations selected in this work, including geographic data, AERONET annual DNI and annual DNI-weighted spectral parameters for each location. Table 3.4 has a list of the annual spectral efficiencies for the four MJ solar cell technologies of the 34 locations. Table 3.5 gives the annual DNI-weighted SMR indexes of the same list of locations for the different considered technologies at solar cell temperature of 25 °C and 90 °C.

Table 3.3 List of the 34 AERONET stations selected in this work, including geographic data, AERONET annual DNI and annual DNI-weighted spectral parameters. Sites highlighted in bold are those used in the model in section 3.6.3.3.

No	Location	Latitude [°]	Longitude [°]	Altitude [m]	AERONET annual DNI [kWh]	$\overline{AM}$	$\overline{AOD}$	$\overline{PW}$ [cm]
1	Bahrain	26.21	50.61	25	1318	1.54	0.35	1.87
2	Bari_University	41.11	16.88	12	1539	1.83	0.19	2.13
3	Burjassot	39.51	-0.42	30	1250	1.97	0.17	1.92
4	Cordoba-CETT	-31.52	-64.46	730	1548	1.75	0.09	1.45
5	Dhadnah	25.51	56.33	81	1368	1.67	0.36	2.26
6	Egbert	44.23	-79.75	264	960	1.89	0.13	1.37
7	Evora	38.57	-7.91	293	1549	1.91	0.10	1.44
8	Fresno	36.78	-119.77	0	1798	1.83	0.13	1.57
9	Fresno_2	36.79	-119.77	100	1735	1.81	0.12	1.52
10	Granada	37.16	-3.61	680	1576	1.77	0.15	1.31
11	Halifax	44.64	-63.59	65	996	2.00	0.11	1.45
12	IMAA_Potenza	40.60	15.72	820	1209	1.68	0.15	1.39
13	IMS-METU-ERDEMLI	36.57	34.26	3	1477	1.76	0.24	2.08
14	Jabiru	-12.66	132.89	30	1430	1.73	0.14	2.66
15	Kelowna	49.96	-119.37	344	1047	2.02	0.11	1.29
16	Kelowna_UAS	49.94	-119.40	456	1002	1.88	0.10	1.39
17	Kirtland_AFB	34.95	-106.51	1711	2035	1.58	0.08	0.83
18	Lake_Argyle	-16.11	128.75	150	2137	1.71	0.09	1.66
19	Lanai	20.74	-156.92	20	1530	1.76	0.08	2.87
20	Malaga	36.72	-4.48	40	1554	1.88	0.15	1.67
21	Maricopa	33.07	-111.97	360	1670	1.80	0.09	1.37
22	Mongu	-15.25	23.15	1107	1488	1.55	0.22	1.65
23	Mussafa	24.37	54.47	10	1357	1.74	0.35	2.07
24	Pretoria_CSIR-DPSS	-25.76	28.28	1449	1511	1.59	0.17	1.11
25	Railroad_Valley	38.50	-115.96	1435	1974	1.63	0.06	0.71
26	Santa_Cruz_Tenerife	30.86	34.78	480	1922	1.67	0.17	1.42
27	SEDE_BOKER	28.47	-16.25	52	1483	1.69	0.16	1.95
28	Sevilleta	34.36	-106.89	1477	1830	1.58	0.08	0.91

29	Solar_Village	24.91	46.40	764	1754	1.57	0.31	1.13
30	Table_Mountain	40.13	-105.24	1689	1428	1.68	0.08	0.89
31	Tamanrasset_INM	22.79	5.53	1377	1998	1.51	0.16	0.65
32	Toronto	43.97	-79.47	300	951	1.92	0.14	1.18
33	White_Sands_HELSTF	32.64	-106.34	1207	1740	1.69	0.08	0.98
34	Yonsei_University	37.56	126.94	88	681	2.04	0.33	0.96

Table 3.4 List of the 34 AERONET stations selected in this work, including their annual spectral efficiency ($\eta_{spectral,annual}$). Sites highlighted in bold are those used in the model in section 3.6.3.3.

No	Location	$\eta_{spectral,annual}$ [LM-Ge]	$\eta_{spectral,annual}$ [UMM]	$\eta_{spectral,annual}$ [IMM]	$\eta_{spectral,annual}$ [LM-DN]
1	Bahrain	0.912	0.965	0.976	0.909
2	Bari_University	0.955	0.981	0.995	0.947
3	Burjassot	0.953	0.987	1.000	0.947
4	Cordoba-CETT	0.972	0.987	0.992	0.963
5	Dhadnah	0.907	0.958	0.970	0.903
6	Egbert	0.949	0.980	0.987	0.943
7	Evora	0.965	0.986	0.994	0.955
8	Fresno	0.961	0.981	0.989	0.953
9	Fresno_2	0.967	0.986	0.993	0.958
10	Granada	0.944	0.975	0.981	0.937
11	Halifax	0.954	0.983	0.994	0.946
12	IMAA_Potenza	0.955	0.984	0.989	0.949
13	IMS-METU-ERDEMLI	0.939	0.977	0.990	0.934
14	Jabiru	0.988	0.987	0.994	0.968
15	Kelowna	0.946	0.977	0.987	0.939
16	Kelowna_UAS	0.965	0.988	0.994	0.958
17	Kirtland_AFB	0.956	0.978	0.973	0.947
18	Lake_Argyle	0.982	0.987	0.989	0.968
19	Lanai	1.010	0.990	0.998	0.976
20	Malaga	0.959	0.988	0.997	0.952
21	Maricopa	0.968	0.987	0.988	0.956
22	Mongu	0.934	0.956	0.963	0.922
23	Mussafa	0.899	0.953	0.965	0.895
24	Pretoria_CSIR-DPSS	0.933	0.968	0.970	0.927
25	Railroad_Valley	0.956	0.979	0.972	0.947
26	Santa_Cruz_Tenerife	0.948	0.974	0.978	0.941
27	SEDE_BOKER	0.970	0.982	0.992	0.960
28	Sevilleta	0.957	0.978	0.973	0.948
29	Solar_Village	0.891	0.947	0.951	0.888
30	Table_Mountain	0.952	0.978	0.976	0.943

31	Tamanrasset_INM	0.925	0.962	0.952	0.919
32	Toronto	0.935	0.973	0.980	0.929
33	White_Sands_HELSTF	0.960	0.982	0.979	0.952
34	Yonsei_University	0.833	0.893	0.910	0.827

Table 3.5 List of the 34 AERONET stations selected in this work, including annually DNI-weighted ($\overline{SMR}$ s) for each location at solar cell temperature of 25 °C and 90 °C (Analysis has considered 90 °C values). Sites highlighted in bold are those used in the model in section 3.6.3.3.

No	Location	LM-Ge				UMM				IMM				LM-DN			
		$\overline{SMR}_{mid}^{top}$		$\overline{SMR}_{bot}^{mid}$		$\overline{SMR}_{mid}^{top}$		$\overline{SMR}_{bot}^{mid}$		$\overline{SMR}_{mid}^{top}$		$\overline{SMR}_{bot}^{mid}$		$\overline{SMR}_{mid}^{top}$		$\overline{SMR}_{bot}^{mid}$	
		25 °C	90 °C	25 °C	90 °C	25 °C	90 °C	25 °C	90 °C	25 °C	90 °C	25 °C	90 °C	25 °C	90 °C	25 °C	90 °C
1	Bahrain	0.896	0.896	0.935	0.932	0.895	0.897	0.932	0.928	0.898	0.898	0.960	0.960	0.894	0.894	0.953	0.955
2	Bari_University	0.929	0.930	0.996	0.991	0.933	0.940	0.987	0.976	0.930	0.932	1.011	1.011	0.926	0.927	1.000	1.004
3	Burjassot	0.921	0.923	0.994	0.990	0.925	0.930	0.987	0.977	0.923	0.924	1.006	1.007	0.919	0.919	0.998	1.002
4	Cordoba-CETT	0.971	0.971	0.994	0.994	0.971	0.971	0.993	0.992	0.971	0.971	0.996	0.997	0.970	0.970	0.995	0.997
5	Dhadnah	0.883	0.884	0.944	0.939	0.885	0.890	0.937	0.927	0.886	0.886	0.973	0.973	0.881	0.881	0.962	0.965
6	Egbert	0.936	0.936	0.966	0.967	0.934	0.933	0.967	0.969	0.938	0.937	0.974	0.976	0.934	0.935	0.974	0.976
7	Evora	0.952	0.953	0.991	0.991	0.952	0.954	0.990	0.988	0.953	0.954	0.995	0.996	0.950	0.951	0.993	0.995
8	Fresno	0.947	0.948	0.988	0.987	0.948	0.951	0.985	0.982	0.949	0.949	0.995	0.996	0.946	0.946	0.992	0.994
9	Fresno_2	0.955	0.956	0.989	0.989	0.956	0.957	0.988	0.985	0.956	0.957	0.995	0.996	0.954	0.954	0.993	0.995
10	Granada	0.936	0.936	0.959	0.960	0.934	0.933	0.961	0.963	0.938	0.937	0.969	0.970	0.935	0.935	0.969	0.970
11	Halifax	0.935	0.935	0.978	0.978	0.934	0.935	0.978	0.978	0.937	0.937	0.984	0.986	0.933	0.933	0.983	0.985
12	IMAA_Potenza	0.947	0.946	0.969	0.969	0.946	0.945	0.969	0.970	0.948	0.947	0.977	0.978	0.946	0.946	0.976	0.978
13	IMS-METU-ERDEMLI	0.914	0.916	0.973	0.970	0.917	0.922	0.967	0.958	0.917	0.917	0.992	0.992	0.912	0.913	0.983	0.986
14	Jabiru	0.971	0.974	1.038	1.031	0.980	0.990	1.024	1.007	0.972	0.975	1.048	1.048	0.970	0.971	1.034	1.038
15	Kelowna	0.926	0.926	0.973	0.974	0.925	0.925	0.974	0.973	0.928	0.927	0.979	0.981	0.923	0.924	0.978	0.981
16	Kelowna_UAS	0.950	0.950	0.987	0.987	0.950	0.951	0.986	0.985	0.951	0.951	0.991	0.993	0.948	0.949	0.990	0.992
17	Kirtland_AFB	0.976	0.974	0.941	0.946	0.969	0.960	0.950	0.963	0.976	0.974	0.944	0.946	0.977	0.976	0.954	0.952
18	Lake_Argyle	0.984	0.984	1.002	1.001	0.985	0.986	1.000	0.998	0.984	0.985	1.005	1.006	0.983	0.984	1.003	1.004
19	Lanai	1.003	1.007	1.081	1.071	1.015	1.029	1.062	1.039	1.003	1.006	1.084	1.084	1.001	1.003	1.067	1.072
20	Malaga	0.939	0.939	0.989	0.987	0.940	0.943	0.985	0.980	0.940	0.941	0.997	0.998	0.937	0.937	0.993	0.995
21	Maricopa	0.964	0.963	0.982	0.983	0.962	0.961	0.983	0.985	0.964	0.964	0.985	0.986	0.962	0.963	0.986	0.987
22	Mongu	0.937	0.937	0.958	0.957	0.937	0.938	0.956	0.954	0.938	0.938	0.973	0.973	0.936	0.936	0.969	0.971
23	Mussafa	0.873	0.874	0.937	0.933	0.874	0.879	0.931	0.922	0.876	0.876	0.966	0.967	0.871	0.871	0.956	0.959
24	Pretoria_CSIR-DPSS	0.938	0.936	0.934	0.937	0.933	0.928	0.940	0.946	0.939	0.938	0.946	0.947	0.938	0.937	0.949	0.950
25	Railroad_Valley	0.978	0.975	0.936	0.943	0.970	0.959	0.948	0.963	0.978	0.976	0.939	0.941	0.979	0.978	0.950	0.949
26	Santa_Cruz_Tenerife	0.941	0.941	0.961	0.962	0.940	0.940	0.962	0.963	0.943	0.942	0.972	0.973	0.941	0.941	0.971	0.972
27	SEDE_BOKER	0.959	0.960	1.003	1.000	0.962	0.967	0.996	0.988	0.960	0.961	1.012	1.013	0.957	0.958	1.005	1.008
28	Sevilleta	0.976	0.974	0.944	0.949	0.970	0.962	0.953	0.965	0.977	0.975	0.948	0.950	0.977	0.976	0.957	0.956
29	Solar_Village	0.889	0.887	0.895	0.897	0.883	0.878	0.901	0.908	0.892	0.890	0.917	0.918	0.888	0.887	0.919	0.920
30	Table_Mountain	0.965	0.963	0.944	0.948	0.958	0.950	0.953	0.964	0.965	0.963	0.947	0.949	0.965	0.964	0.956	0.955
31	Tamanrasset_INM	0.949	0.945	0.894	0.900	0.939	0.925	0.907	0.925	0.950	0.947	0.907	0.909	0.950	0.949	0.919	0.917
32	Toronto	0.923	0.922	0.943	0.946	0.918	0.915	0.948	0.954	0.924	0.923	0.953	0.955	0.921	0.921	0.956	0.958
33	White_Sands_HELSTF	0.969	0.967	0.952	0.956	0.964	0.957	0.959	0.969	0.969	0.968	0.955	0.957	0.969	0.968	0.962	0.962
34	Yonsei_University	0.823	0.820	0.846	0.851	0.813	0.805	0.856	0.868	0.827	0.824	0.876	0.879	0.820	0.819	0.881	0.882

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CHAPTER 4 – SPECTRAL UNIQUENESS OF SOLAR SPECTRA AND SUITABILITY OF SMR AS SPECTRAL INDEX

4.1 INTRODUCTION

Solar spectrum changes slightly with sun-Earth distance (up to 6.6% in total integrated irradiance), but the main modification is done by the terrestrial atmosphere. On the one hand, the solar elevation and the altitude of the site both characterized by the air mass (*AM*) determine the optical length that the sunlight has to pass through when it reaches Earth's surface. On the other hand, the components that are contained within the atmosphere, mostly aerosols (*AOD*) and precipitable water (*PW*), affect the spectrum at different spectral ranges and modulate the spectrum that finally reaches the ground.

The effect of the atmospheric content on the behavior of solar cells depends on the range and width of its spectral response. In the case of a multijunction (MJ) solar cell, the spectral band is divided by the number of junctions; the variations in each sub-band modulate the spectral effect on the resultant photocurrent for its corresponding subcell. That is why, in the early procedures for current and power calibration of solar cells, the reported calibration values were adjusted based on atmospheric conditions (NASATech 1977) and accounted for *AM*, turbidity, *PW* and ozone. More recently, other authors (Emery, Myers, and Kurtz 2002) have proposed a more representative spectrum for evaluating concentrator solar cells that suggests the same parameters, but considers *AOD* instead of turbidity. This work has led to the current standard (Committee G03 2012) that is implemented synthetically using the SMARTS model, (Gueymard 1995) where the same main parameters are used in addition to some others that this model takes into account.

The main atmospheric parameters for spectral characterization of MJ solar cells are AM , AOD and PW . While other atmospheric components affect the solar spectrum, for spectral MJ applications they can usually be neglected, provided that air pressure is the most influential among them. Considering a variation of $\pm 3\%$ in atmospheric pressure (99% of the time, air pressure in Madrid fluctuates $\pm 2.1\%$), SMARTS simulations show that the B_{TOP} (top is the subcell most affected by air pressure changes) varies less than 0.35%.

The most important factors that moderate a solar spectrum are AM , along with AOD and PW . Here, they are considered spectral parameters. This means that if we know the corresponding values at a given moment, we can describe the spectrum. Therefore, a tuple (AM, AOD, PW) is a simple but sufficiently accurate way to identify spectral uniqueness under the effects on an MJ solar cell.

Consequently, these spectral parameters can be understood as spectral indexes, i.e. values that have a one-to-one correspondence with solar spectra. In this case, the spectral parameters will be ideal spectral indexes. Here the number of metameric spectra (as defined in Chapter 2) under this spectral index would be one. In a real-world scenario, however, practical (meaning that a minimum tolerance is unavoidable) spectral indexes such as those proposed in this chapter identify a few metameric spectra and the suitability of fit obtained from residuals is not zero, but it is low enough to be indistinguishable for CPV's purposes.

4.1.1 METHODOLOGY

The main source of data for the analysis in this chapter is a set of synthetic direct spectra generated with SMARTS using spectral parameters from the AERONET network (Holben et al. 1998) for a period of one year. The main station of the analysis is in Madrid. However, other places with atmospheres that are especially peculiar due to extremely high or low levels of AOD or PW are sometimes considered, along with some sites of high annual direct irradiation. In general, SMARTS has been configured based on an urban model for aerosol; in the specific case of Madrid, an altitude 695 m and an average air pressure of 933 hPa have been used. Other SMARTS parameters with negligible influence on this analysis, such as ozone and CO_2 , have been set to reference spectrum conditions.

In the cases where validating simulations with measurements makes sense, data have been obtained from a spectroheliometer (see Chapter 2) and a pyrheliometer installed on the roof of the IES-UPM building in Madrid. This spectroheliometer is collecting SMR data from 2011 at just 200 m distance from an AERONET station, which has been working since mid-2012 and is maintained by the Spanish State Meteorological Agency (AEMET). Both

instruments see virtually the same sky, so conditions are perfect for comparing the spectral data sources.

The thermal effects on photocurrent are ignored, so whenever synthetic and measured spectral indexes are compared, we are supposing that the "simulated" component cell has the same temperature as the real component cell. Nevertheless, the impact on *SMR* values is negligible if the current sensitivities to temperature of the subcells involved in the *SMR* are very similar since *SMR* is a ratio of those subcell currents. And when the sensitivities to temperature are not identical this approach is valid for the typical ranges of ambient temperature in most of the MJ technologies, as it was shown in Chapter 3, in the thermal effects paragraph, with cell temperature differences of 65 °C.

4.2 MODELING UNIQUENESS OF (DIRECT NORMAL⁴) SOLAR SPECTRA

4.2.1 DEFINITION OF SPECTRAL UNIQUENESS

A solar spectrum is computed as an array of irradiance for each wavelength in the solar spectral range. For example, the AM1.5D G173-03 (Committee G03 2012) reference spectrum is represented by 2002 samples that range from 280 to 4000 nm. Therefore, the number of possible solar spectra that could potentially be described with that resolution is enormous.⁵ Nevertheless, as pointed out above, only a few spectral parameters influence solar spectra, suggesting that solar spectra can be described with a similar amount of independent variables.

To prove this hypothesis, we first need to check the expected variance of solar spectra at all wavelengths, considering a representative collection of spectra during a given year. In Figure 4.1, a set of synthetic spectra generated by SMARTS using the Madrid AERONET station 2014 data is represented by the mean value of the spectra and three standard deviations for each wavelength.

⁴ While all the analyses are based on direct solar spectra, the following procedures and conclusions are also valid for global solar spectra.

⁵ Considering 2002 samples per spectrum and a resolution of eight bits per sample, there are 256^{2002} different options, a tremendous number of possible spectra.

Figure 4.1. Mean spectrum and the variance (represented with 3σ) of the set of synthetic spectra obtained with SMARTS and 2014 data from the Madrid AERONET station.

Principal Component Analysis (PCA) is a statistical method (Jolliffe 2002) that translates a set of specimens to another set based on independent variables called principal components (*PCs*) that are ordered by their contribution to the total variance. If most of the variance can be explained by the most important *PCs*, the dimensionality of a collection of specimens is reduced and the set is described with a negligible loss by the minimum number of necessary variables. For the case of the solar spectra presented in Figure 4.1, the eigenvectors (*PC_vec*) of each PC contain the contributions per wavelength (shown in Figure 4.2) and the corresponding eigenvalues (*PC_val*) are the numbers that describe any spectra under the eigenvectors. This method is used, among other disciplines, in spectroscopy for chemical spectra discrimination. (Wold, Esbensen, and Geladi 1987; He, Li, and Deng 2007) Therefore, it can be a satisfactory option for solar spectra identification.

Figure 4.2. Mean spectrum and the first three PC of the set of synthetic spectra obtained with SMARTS and data from AERONET station for 2014 in Madrid.

A PCA on the set previously presented shows that the first *PC* is responsible for the 93.9% of the variance and the second and third *PCs* contribute 4.4% and 1.5%, respectively. These three independent variables explain 99.8% of the variance.

Since PCA is also a space transformation, we can obtain the eigenvalues that describe the *i* spectrum in the *PC* space. To recompose the corresponding spectrum we simply need to use the *PC* eigenvectors as is specified in Equation (4.1):

$$spectrum_i(\lambda) = \overline{spectra}(\lambda) + \sum_i PC_vec_i(\lambda) \cdot PC_val_i \quad (4.1)$$

The PCA transformation that uses the whole number of *PCs* will be able to recompose all the spectra with no differences between the original and the reconstructed spectra (perfect uniqueness). Nevertheless, if the less significant *PCs* are discarded, an error is expected, so the goodness of fit must be checked to determine the number of *PCs* needed for a limited error. Figure 4.3 shows the mean spectrum of the previous set of spectra plus three times the standard deviation of residuals, taking into account a PCA transformation considering only the first three *PCs*.

Figure 4.3. Mean spectrum of the set of synthetic spectra obtained with SMARTS and 2014 data from the AERONET station in Madrid. Red shows the dispersion with 3σ of residuals of the PCA per wavelength and in blue the dispersion measured in *nRMSE*.

4.2.1.1 Goodness of fit

The goodness of fit of the PCA can be measured by looking into the residuals: ideal residuals should be zero, which indicates uniqueness, i.e., that spectra and fitting are the same. A typical measure of goodness of fit is the root-mean-square error (*RMSE*) that quantifies the degree of residual dispersion. Since *RMSE* is scale-dependent, normalized *RMSE* by range (maximum - minimum) or by the mean (also called the coefficient of

variation of the $RMSE$, CV_RMSE) when data are around one are preferred to compare datasets with different scales. In the current case, an $RMSE$ is obtained for every wavelength of the spectral irradiance:

$$nRMSE = \frac{RMSE_{spectrum(\lambda)}}{range_{spectrum(\lambda)}} = \frac{\sqrt{\frac{\sum_{i=1}^n (\widehat{spectrum}_i(\lambda) - spectrum_i(\lambda))^2}{n}}}{spectrum(\lambda)_{max} - spectrum(\lambda)_{min}} \quad (4.2)$$

$$CV_RMSE = \frac{RMSE_{spectrum(\lambda)}}{mean_{spectrum(\lambda)}} = \frac{\sqrt{\frac{\sum_{i=1}^n (spectrum_i(\lambda) - spectrum_i(\lambda))^2}{n}}}{mean(spectrum(\lambda))} \quad (4.3)$$

where i refers to the i th spectrum and range and mean are obtained from the set of spectra.

However, for practical reasons, we consider a representative value of the whole spectrum and take the mean of all of the $nRMSE$, but ignoring those wavelengths where the signal is very low (mainly due to water absorption peaks) and the error mostly comes from resolution. Consequently, when a spectrum is recovered from the three characteristic eigenvalues and corresponding eigenvectors, the result is highly similar, as can be seen in Figure 4.3. Specifically, for the synthetic dataset of Madrid 2014, the direct PCA transformation has a mean value of the $nRMSE$ ($\overline{nRMSE}$) of 1.37%.

Table 4.1 List of worldwide locations described by their altitude and annually DNI-weighted spectral parameters (AM , AOD and PW). The $\overline{nRMSE}$ column expresses the mean $nRMSE$ of the PCA transformation of the set of spectra from every AERONET station of each location.

	Altitude (m)	$\overline{AM}_{annual}$	$\overline{AOD}_{annual}$	$\overline{PW}_{annual}$ [cm]	$\overline{nRMSE}$
Madrid	695	1.91	0.11	1.32	1.37%
Granada (Similar to Madrid)	680	1.92	0.15	1.31	1.53%
Maricopa (SW USA)	360	1.89	0.09	1.37	1.44%
Tamanrasset (Desert, +dry, +altitude)	1377	1.77	0.16	0.65	1.63%
Lanai (Island, + PW)	20	1.75	0.08	2.87	1.35%
Mussafa (Desert, close to sea, + AOD)	10	1.74	0.35	2.07	1.57%
Combined	-	-	-	-	1.69%

If we extend this analysis to other locations with more extreme spectral variations (Table 4.1), we observe that the $\overline{nRMSE}$ value is below 1.7% for any location or the combination of all of them.

4.2.2 SPECTRAL INDEXES FOR SPECTRAL UNIQUENESS

An ideal set of spectral indexes would be the one that allows biunivocal (also known in mathematics as bijective) identification of a spectrum with a unique set of values, which ensures spectral uniqueness. In other words, a set of spectral indexes corresponds to a spectrum, but only one, and the reciprocal must also be true: a spectrum corresponds to one and only one set of spectral indexes.

A single spectral index is not enough to guarantee the spectral uniqueness, as is proved above in the paragraph 4.2.1, but it can be valid under certain dispersion thresholds (Minemoto et al. 2009; M. Norton, Amillo, and Galleano 2015). Since spectral parameters (AM , AOD and PW) are actually the independent physical variables responsible of changes in solar spectrum, they can directly be used as a set of values that have the property of uniqueness. However, excluding AM , the rest of the spectral parameters (AOD and PW) should be obtained using photometers such as the ones used in the AERONET network (Holben et al. 1998), or must rely on high uncertain satellite data (Mueller et al. 2004; Hubanks et al. 2008).

Several spectral indexes have been proposed, mainly to evaluate the spectral effects on multi-junction solar cells. Consequently, a spectral mismatch could be corrected when estimating cell performance. Spectral indexes can be estimated directly through sensor photocurrents or indirectly through spectral irradiance (and some also need spectral response, as they are device dependent). The main objective of any definition of spectral indexes for PV or CPV applications is to estimate the spectral mismatch, i.e., the difference in performance under any spectrum and the reference spectrum for a particular cell technology, even if these are not ideal spectral indexes as defined above. Common spectral indexes, mostly defined for single-junction solar cells, are:

- AM can be considered a rudimentary spectral index, valid enough for single-junction, solar-cell devices. However, it is location and time dependant (Emery, Delcueto, and Zaiman 2002; Osterwald, Emery, and Muller 2014), since it ignores atmospheric components.
- Useful Fraction (UF) expresses the ratio of the observed spectral irradiation in the useful spectral range of the PV device to the total observed irradiation (Gottschalg, Infield, and Kearney 2003; Gottschalg et al. 2005; Gottschalg et al. 2002). It is

therefore device dependent and intended for single-junction solar cells. A spectroradiometer is necessary in order to obtain the spectrally resolved irradiance.

$$UF = \frac{1}{DNI} \int_0^{\lambda[E_g]} DNI(\lambda) d\lambda \quad (4.4)$$

- Spectral Factor (SF or SF^{-1}) is aimed at estimating the spectral differences of a given solar cell's performance (Pérez-López, Fabero, and Chenlo 2007; Tetsuyuki, Otani, and Takashima 2011; Nofuentes et al. 2014). It is equivalent to the Mismatch Factor (MMF/MM) ("IEC 60904-7 Computation of the Spectral Mismatch Correction for Measurements of Photovoltaic Devices" 2008) and used to correct spectral mismatches when a cell is being calibrated with a spectrum other than the reference spectrum (Mülleijans et al. 2005). It is therefore device dependent and intended for single-junction solar cells; a spectroradiometer is necessary in order to obtain the spectrally resolved irradiance.

$$SF = \frac{\int_0^{\lambda} DNI_{ref}(\lambda) \cdot SR(\lambda) d\lambda / \int_0^{\lambda} DNI_{ref}(\lambda) d\lambda}{\int_0^{\lambda} DNI(\lambda) \cdot SR(\lambda) d\lambda / \int_0^{\lambda} DNI(\lambda) d\lambda} \quad (4.5)$$

- Average Photon Energy (APE) is intended to describe the energetic distribution of an irradiance spectrum (Tetsuyuki, Otani, and Takashima 2011; Nofuentes et al. 2014; Minemoto et al. 2009; Betts et al. 2003; Chantana et al. 2015; Matthew Norton, Dobbin, and Georghiou 2011; Ishii et al. 2013; M. Norton, Amillo, and Galleano 2015). It is obtained by dividing the irradiance by the photon flux density, meaning that higher values represent bluish spectra. It has physical units (eV), and it is device-independent; however, a spectroradiometer is necessary in order to obtain the spectrally resolved irradiance.

$$APE = \frac{\int_0^{\lambda} DNI(\lambda) d\lambda}{q \cdot \int_0^{\lambda} \phi(\lambda) d\lambda} \quad (4.6)$$

- SMR (Domínguez et al. 2013; Núñez et al. 2016) and Z -parameter (Peharz, Siefer, and Bett 2009) describe the spectral mismatch between subcells in a MJ solar cell. They are similar to SF but account for subcell ratios. They are device dependent and

when they are obtained directly from component cells they do not require the spectrally resolved *DNI* (measured with a spectroradiometer).

4.3 UNIQUENESS OF SMR INDEXES

Discarding the spectral indexes that are based on spectroradiometers to save the cost of an expensive instrument and to avoid continuous maintenance and regular calibration, those based on component cells as *SMRs* are a practical option, especially for MJ solar cells and CPV applications.

4.3.1 UNIQUENESS AT BROADBAND LEVEL

The idea of uniqueness is indeed very powerful. It means that we could ideally substitute the representation of a solar spectrum given by an array of wavelengths with a set of three values. Insofar as a different set of values is independent, we can expect, in principle, a satisfactory level of uniqueness, at least for broadband applications, including those relevant to CPV.

As pointed out above, three independent parameters can describe solar spectra with high accuracy. However, we cannot expect low error in all individual wavelengths. Nevertheless MJ cells require a resolution in the range of subcell spectral bands, around 150 nm. If the photocurrent generated by a subcell under a spectrum is virtually the same as the photocurrent under the regenerated spectrum, this procedure is valid for both that subcell and for that spectrum. And we can also consider equivalent irradiances as defined in Chapter 2, since they are proportional to the photocurrents.

Our proposal is to use equivalent irradiances values (or *SMRs* when only spectral shapes are needed) to estimate other spectral variables based in the assumption of spectral uniqueness, expecting low fitting errors.

4.3.2 CORRELATION OF SMR AND SPECTRAL PARAMETERS

As noted above, spectral parameters (*AM*, *AOD* and *PW*) define a spectrum and therefore any broadband variable derived from spectra. We can try to model *SMRs* from these parameters empirically using a whole year of data from a spectroheliometer and an atmospheric source such as the AERONET station in Madrid close to IES-UPM.

Accounting for the part of the spectrum that the atmospheric parameters affect and the spectral response of the three component cells, we can already guess some basic relations that orient the analysis below. *AM* and *AOD* affect mainly top subcell as SMR_{mid}^{top} does. *PW* has a greater effect on the bottom because most of the water absorptions peaks are located in this spectral part, so *PW* will be related to SMR_{bot}^{mid} .

In Figure 4.4 we observe how a simple linear relationship between AM and SMR_{mid}^{top} can be obtained if the AOD value is fixed. The slope of the linear relationship is modulated by AOD , showing that these parameters correlate in a second order fit.

Figure 4.4. Spectral Matching Ratio between top and middle subcells (SMR_{mid}^{top}) based on aerosol optical depth (AOD) and AM for Madrid in 2014.

Using the data from spectroheliometer and the AERONET station, taking into account the previous relationships and filtering the values to those where 90% of accumulated energy is located in Madrid, ($0.96 > AM > 2.24$, $0.19 > AOD > 0.02$, $0.45 > PW > 1.75$) we have found a simple second order fit for the three main atmospheric parameters with the SMR_{mid}^{top} (a similar expression has been obtained in Chapter 3, but for a set of global locations):

$$SMR_{mid}^{top}[Madrid] = 1.16 - 0.09 \cdot AM - 0.06 \cdot AOD + 0.03 \cdot PW - 0.34 \cdot AM \cdot AOD \quad (4.8)$$

Figure 4.5 shows the fitting considering only AM and $AM \& AOD$ as inputs for the model. It is clear that AM cannot offer a complete explanation of SMR_{mid}^{top} , which presents a non-centered zero fitting. The addition of AOD provides a fitting with residual distribution centered in zero, while PW improves the standard deviation slightly. In relative terms, the CV_RMSE of the three cases are presented in Table 4.2.

Figure 4.5. Histogram of residuals model-measurements for different models for SMR_{mid}^{top} considering AM , AOD and PW for Madrid in 2014.

Table 4.2. SMR_{mid}^{top} fitting goodness considering CV_RMSE using different spectral parameters

Fitting parameters	CV_RMSE
$f(AM)$	4.27%
$f(AM, AOD)$	2.16%
$f(AM, AOD, PW)$	1.68%

A similar fit has been found for SMR_{bot}^{mid} :

$$SMR_{bot}^{mid}[Madrid] = 0.92 - 0.15 \cdot AOD + 0.08 \cdot PW - 0.09 \cdot AOD \cdot PW \quad (4.9)$$

Notice the lack of AM term, which is due to the low correlation coefficient between SMR_{bot}^{mid} and AM . This is mainly caused by a low influence of AM in the bottom subcell spectral region.

Figure 4.6. Histogram of residuals model-measurements for different models for SMR_{bot}^{mid} considering AOD and PW for Madrid in 2014.

Figure 4.6 shows the residual distribution of two fits, considering or not AOD , both showing symmetry and low dispersion in residuals. The CV_RMSE values are presented in Table 4.3.

Table 4.3. SMR_{bot}^{mid} fitting goodness using different spectral parameters

Fitting parameters	CV_RMSE
$f(PW)$	2.60%
$f(AOD, PW)$	1.52%

It can be concluded that SMR_{mid}^{top} is strongly correlated to AM and AOD , since both affect basically the top subcell region and SMR_{bot}^{mid} can be used to explain the PW in the atmosphere, in this case due to the fact that most of the water absorption peaks are located in the bottom region.

4.3.3 CORRELATION OF EQUIVALENT IRRADIANCES AND DNI

Integrated spectrum of direct irradiance is actually the DNI seen by a spectroheliometer. Therefore, considering the condition of uniqueness noted above, the DNI can be deducted from equivalent irradiances. The data measured from the spectroheliometer and the pyrliometer reveal the following expression:

$$DNI_{Spectroheliometer} = 0.51 \cdot B_{top} + 0.10 \cdot B_{mid} + 0.39 \cdot B_{bot} \quad (4.10)$$

And the goodness of fit of $DNI_{Spectroheliometer}$ to $DNI_{Pyrliometer}$, estimated by $nRMSE$, is 1.91%.

This relation can be also cross-checked with synthetic spectral data from the AERONET station in Madrid. In that case, the nRMSE between $DNI_{AERONET}$ and the $DNI_{Spectroheliometer}$ is 0.5%. From other AERONET stations, we can check how well this expression fits to the locations seen in the paragraph 4.2 (Granada, Mariopa, Tamanrasset, Lanai and Mussafa) with different atmospheres and the nRMSE are under 0.6% in all cases.

A caveat about measuring DNI from a spectroheliometer is necessary. Spectroheliometer uncertainty (about 3% per component cell (Núñez et al. 2016)) is not comparable to pyrliometer uncertainty (around 1% (Reda, Myers, and Stoffel 2010)), so spectroheliometers cannot be considered suitable substitutes. However, this relationship can be used to cross-check both instruments, to validate the equivalent irradiances and DNI measured at the same time and place.

4.3.4 CORRELATION OF SMR OF DIFFERENT MJ TECHNOLOGIES

Perhaps the most interesting correlation is among different MJ solar cell technologies. Quantum efficiencies of any current MJ technology share a large part of wavelength ranges, so we can expect satisfactory correlations between their B_{eqvs} .

In this analysis, we will consider other MJ cell technologies beyond the LM-Ge solar cell, such as two versions of upright metamorphic (UMMA^A and UMM^B), an inverted metamorphic (IMM) and a lattice-match based on dilute nitrides (LM-DN). Their corresponding quantum efficiencies (QEs) can be seen in the Appendix of Chapter 2.

A simple model based on linear relations of equivalent irradiances of the *origin* technology is proposed to estimate the equivalent irradiances of the *destiny* technology, $B_{xxx_destiny} = f(B_{top_origin}, B_{mid_origin}, B_{bot_origin})$, based again on the previously-introduced concept that three independent variables are enough to define any solar spectrum (and spectral broadband variables) with a high degree of uniqueness. A similar problem was solved using fitting equations but based in only one current per subcell in (Jaus, J. 2011).

$$B_{top_des} = c_{top_des} \cdot B_{top_ori} + c_{top_des} \cdot B_{mid_ori} + c_{top_des} \cdot B_{bot_ori} + k_{top_des} \quad (4.11)$$

$$B_{mid_des} = c_{mid_des} \cdot B_{top_ori} + c_{mid_des} \cdot B_{mid_ori} + c_{mid_des} \cdot B_{bot_ori} + k_{mid_des} \quad (4.12)$$

$$B_{bot_des} = c_{bot_des} \cdot B_{top_ori} + c_{bot_des} \cdot B_{mid_ori} + c_{bot_des} \cdot B_{bot_ori} + k_{bot_des} \quad (4.13)$$

From these modeled equivalent irradiances we can obtain the corresponding SMR_{mid}^{top} and SMR_{bot}^{mid} , as ratios of B_{eqvs} . A simpler and more straightforward way would be to directly model an SMR destiny from $SMRs$ of origin. However, the fit is worse, mainly due to the

smaller number of independent parameters used in the model: two $SMRs$ as opposed to three B_{eqvs} .

In Table 4.4, we present the CV_RMSE of the model of $SMRs$ of each technology based on other technology ($SMR_{xxx_destiny}^{xxx} = f(B_{top_origin}, B_{mid_origin}, B_{bot_origin})$) versus the directly-calculated values both from the same annual synthetic spectra obtained with SMARTS and the data from the AERONET station in Madrid.

Table 4.4. Goodness of fit measured with the CV_RMSE of modeled $SMRs$ of several MJ technologies using different options as origin variables.

		Destiny				
<div>CV_RMSE $[SMR_{mid}^{top}/SMR_{bot}^{mid}]$</div>		LM-Ge	UMMA ^A	UMMB ^B	IMM	LM-DN
Origin	LM-Ge	-	0.44%/0.21%	0.34%/0.50%	0.04%/0.35%	0.11%/0.18%
	UMMA ^A	0.46%/0.26%	-	0.24%/0.37%	0.42%/0.67%	0.49%/0.40%
	UMMB ^B	0.67%/1.10%	0.45%/0.66%	-	0.62%/1.75%	0.74%/1.16%
	IMM	0.04%/0.28%	0.40%/0.40%	0.16%/0.53%	-	0.14%/0.14%
	LM-DN	0.11%/0.21%	0.44%/0.34%	0.20%/0.51%	0.12%/0.19%	-

As a main conclusion, the closer the QEs of two MJ solar cells of different technologies are, the better the goodness of the fit between their $SMRs$ and the modeled $SMRs$ is. Even if the technologies with similar QEs have better fit, all the modeled $SMRs$ with any technology are below 1.20%. Most, in fact, are below 0.8%. This means that we can virtually simulate any current 3J solar cell using the component cells of any other 3J technology.

4.3.4.1 Detailed analysis and experimental validation

When measuring an MJ solar cell, component cells with the same spectral response are commonly used to determine the spectrum variations of the light, as is presented in Chapter 2. Nevertheless, as we have seen above, any MJ technology can be modeled using any other with a low error of fit that can be used to calibrate any MJ cell with any set of component cells. This could lead to use of only one kind of component cell set as a "universal" MJ spectral reference.

The paragraphs below describe two cases. The first case is based on cell technologies with similar bandgaps, so the use of component cells of different technology has low impact and modeled component cells improve very little. The other case examines what happens when spectral responses are much different and the spectral changes using component

cells of different technology lead to a strong bias in the estimation of photocurrent limitation.

4.3.4.1.1 Similar spectral responses case

Let us look at an example of two technologies with similar spectral responses simulating spectra and comparing the SMRs of two sets of component cells. That is the case of two MJ solar cells based on LM-Ge and UMM^A, the QEs of which can be seen in Figure 4.7.

Figure 4.7. Quantum efficiencies of LM-Ge and UMM^A plus the AM1.5D G173-03 reference spectrum.

We will compare the results of the two approaches explained above. On the one hand, Figure 4.8 shows the direct model of *SMRs* of UMM^A (destiny) from *SMRs* of LM-Ge (origin) in red, i.e. using origin as destiny directly. On the other hand, the *SMRs* of UMM^A modeled using LM-Ge component cells ($UMM^A_m = f(LM-Ge)$), that use the equivalent irradiances of Eq. (4.11) to (4.13), are represented in blue.

Figure 4.8. Correlation of SMR_{mid}^{top} and SMR_{bot}^{mid} of UMM^A technology versus UMM^A_m directly considering LM-Ge (red dots) or considering a $UMM^A_m = f(LM-Ge)$ (blue dots) model. The origin of the data is from simulated spectra using SMARTS and AERONET Madrid station.

For both SMR_{mid}^{top} and SMR_{bot}^{mid} ($CV_RMSE=0.68\%$ and 1.14% , respectively), the correlation is fairly good between LM-Ge and UMM^A (red dots) at all the levels of SMRs obtained over the course of a year using data from AERONET station of Madrid. However, the results are even better in the case of applying the model ($UMM^A_m = f(LM-Ge)$, blue dots), so the CV_RMSE is lowered to 0.44% and 0.21% , as it was presented in Table 4.4. However, the figure shows that direct modeling of destination SMRs from origin SMRs is sufficient when the subcell gaps and, consequently, the spectral bands of each subcell are similar, as in the case of LM-Ge and UMM^A .

The same analysis is presented in Figure 4.9, in this case using real measurements made with two sets of component cells, one of LM-Ge and the other of UMM. The measurement campaign was carried out in Madrid during several days in the summer, so the SMR_{mid}^{top} achieves high values due to low values of AM typical in this season. The SMR_{bot}^{mid} range is more limited due to its dependence on local PW , which is typically low and constant during summer.

Figure 4.9. Correlation of SMR_{mid}^{top} and SMR_{bot}^{mid} of UMM^A technology versus model (UMM^A_m) considering directly LM-Ge (red dots) or considering a model $UMM^A_m = f(LM-Ge)$ (blue dots); the origin of the data is a measurement campaign carried out in Madrid during several days in summer from two sets of component cells.

In this case, the CV_{RMSE} of direct SMRs are 0.87% and 0.90%, while when applying the model ($UMM^A_m = f(LM-Ge)$), the values are reduced to 0.58% and 0.65%. The improvement is restricted mainly due to the reduced spectral variations found during the time of the comparison.

Another interesting example is the case considering the technology LM-DN presented in Figure 4.10; while there is a significant difference in the band gap of the bottom cell compared to LM-Ge, the cut-off frequencies are similar in both cases.

Figure 4.10. Correlation of SMR_{mid}^{top} and SMR_{bot}^{mid} of LM-DN technology versus model ($LM-DN_m$) considering directly LM-Ge (red dots) or considering a model $LM-DN_m = f(LM-Ge)$ (blue dots); the data are obtained from simulated spectra using SMARTS and AERONET Madrid station.

In this case, we can see also that LM-Ge is compatible for SMR_{mid}^{top} with very low CV_RMSE (0.50%), which is reduced to 0.11% using the model ($LM-DN_m = f(LM-Ge)$). For SMR_{bot}^{mid} , there is a clear bias at low values, although by definition these values are still valid for reference conditions (as any technology calibrated at the same spectral reference conditions), since both cross $SMR_{bot}^{mid}=1$. The CV_RMSE is 1.21% and applying the model improves it to 0.18%, quite low due to the high density of moments around $SMR_{bot}^{mid}=1$.

4.3.4.1.2 Non-similar spectral responses case

In an analogous way, we can simulate SMR values for other technologies with more disparate spectral responses. This is the case presented in the graph of Figure 4.11, where, using an UMM architecture, middle subcell quantum efficiency has been expanded, so the bottom is reduced. The most relevant consequence of the differences between the QEs of LM-Ge and UMM^B is that UMM^B's middle component cell sees the water peak around 900 nm that is seen by the bottom cell of LM-Ge technology.

Figure 4.11. Quantum efficiencies of LM-Ge and UMM^B plus the AM1.5D G173-03 reference spectrum.

When comparing SMR_{mid}^{top} of UMM^B and UMM^B_m (see Figure 4.12), we see a high dispersion mainly due to the change of QE at top-middle transition around 900 nm. This affects the correlation of both technologies, with $CV_RMSE=2.36\%$. This leads to situations in which the inability to estimate spectral reference conditions can be unaffordable. Regarding SMR_{bot}^{mid} , the situation is similar, but since the middle subcell of UMM^B technology sees the first main water peak of absorption, the impact is even stronger (high bias and 3.22% of dispersion measured in CV_RMSE).

Figure 4.12. Correlation of SMR_{mid}^{top} and SMR_{bot}^{mid} of UMM^B technology versus model (UMM^B_m) considering directly LM-Ge (red dots) or considering a model $UMM^B_m = f(LM-Ge)$ (blue dots); the origin of the data is from simulated spectra using SMARTS and AERONET Madrid station.

Applying the $UMM^B_m = f(LM-Ge)$ model, again the CV_{RMSE} is reduced, and this time the improvement in dispersion is notable, 0.34% and 0.50%.

4.4 CONCLUSIONS

A PC analysis about solar spectrum uniqueness has shown that with just three independent parameters more than 99% of the variability is explained. In terms of goodness of fitting, the main three *PC* eigenvectors can recover spectra with a $\overline{nRMSE}$ lower than 1.7% for most of the annual datasets representative of several locations with very different spectral conditions.

It is concluded that a single spectral index is clearly insufficient to establish spectral uniqueness and that three independent indexes are close to the biunivocal spectral identification. Following the pervious result, a possibility for *SMRs* as spectral indexes is deepened and based on this idea the use of *SMR* to establish correlations among different MJ cell technologies and other devices is suggested.

SMR values of a technology were simulated by a reference set of component cells with a substantial reduction of the CV_{RMSE} compared with the direct use of the *SMR* values of the reference technology for annual spectral datasets. The reduction is especially notable for technologies whose QEs are more different with respect the reference, with cases with a reduction from 3.22% to 0.5% in terms of CV_{RMSE} . In some cases the conclusions are confirmed by direct outdoors side-by-side comparison of two sets of component cells.

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CHAPTER 5 – SPECIFIC ISSUES OF CPV SYSTEMS MODELING

5.1 INTRODUCTION

Estimating the energy yield with a low uncertainty of any renewable energy-based plant or photovoltaics (PV) in concrete (Dirnberger, Müller, and Reise 2015; Suri et al. 2007; Makrides et al. 2013; Thevenard and Pelland 2013) is a key step to achieve bankability, and concentrator PV (CPV) plants are no exception. To achieve low uncertainty in the calculation of the expected energy of systems whose inputs are random by nature, a good understanding of the CPV system behavior and meteorological resources is mandatory.

CPV is affected by the same ambient resources as PV: solar irradiation, spectrum, ambient temperature and wind, but their influence on CPV systems is different, namely CPV is more sensitive. A simple diagram with the influences and approximate weights of the resource on CPV is shown in Figure 5.1.

Figure 5.1 Schema of the energy modeling based on resource and CPV system modeling. Width of the lines indicates an approximation of the influence of an ambient resource on the electrical variables of a CPV system.

In fact, when compared with PV modeling, several specific issues should be given extra attention in the case of CPV. In particular, these are the use of assumptions in PV models that cannot always be applied to CPV:

- In the case of *DNI*, special attention should be given to expanded time series, and only realistic daily profiles should be used.
- Spectral influence is especially relevant in CPV, and a local model that describes the atmosphere should be taken into account.
- Natural convection has stronger influence on CPV than PV; therefore, wind should be taken into account more often.
- Optics can be strongly influenced by the ambient temperature.
- CPV soiling sensitivity is greater than PV sensitivity. A more detailed high temporal resolution model should reflect this issue in concrete, rather than a simple annual value.

Based on these two submodels (CPV system and resources), there are three main steps to forecast the energy produced by a CPV system. The first is to determine the power of a CPV system or plant at concentrator standard operation conditions (CSOC, see Table 5.1), i.e. the power rating of a single system or an entire plant, as defined in the draft of standard IEC62670-3 (IEC committee 2015). However, when enough data that have been monitored over a period of time is available together with operating conditions, applying filters that delimit a narrow band around CSOC conditions is a straightforward way to obtain it without extrapolating.

Table 5.1 CPV standard conditions as defined in IEC 62670-1 (IEC committee 2013).

Conditions	Irradiance <i>DNI</i> [W·m ⁻²]	Temperature [°C]	Wind speed [m·s ⁻¹]	Spectrum
CSOC [concentrator standard operation conditions]	900	20 [Ambient temperature]	2	Direct normal AM1.5 spectral irradiance distribution consistent with conditions described in IEC 60904-3 ⁶
CSTC [concentrator standard test conditions]	1000	25 [Cell temperature]	None	

The next step is to determine the influence of operating conditions on the power of the plant, such as *DNI* and its spectral distribution, ambient temperature and wind (see width of lines in Figure 5.1), which lead to a power model as a function of the operating conditions and consequently an energy model if the power is integrated over time, following the physical MJ solar cell model of these variables (C. Domínguez, Anton, and Sala 2010). The objective is to determine dependencies and coefficients that could be used for an energy prediction model, avoiding any variable that is not commonly available. For example, although open-circuit voltage (V_{oc}) is highly correlated with cell temperature, this parameter is not available at the system or plant level connected to an inverter, so it cannot be used in the model. Back-side module temperature (usually on the heatsink) that is easily measurable is preferred, therefore the dependence of this temperature with V_{oc} should be found. Again, if enough data are available, these dependences can be deduced directly from high temporal resolution data from the monitoring of the plant and the operating conditions; otherwise, some cell or module models should be extended at plant level. At this stage, the model can be applied to analyze the power of a CPV system or plant in order to determine its evolution over time in identifying tracker or inverter malfunctions, soiling effects, degradation or any cause that contributes to power degradation.

Finally, the energy forecast model can be implemented, based on the CPV system and resources models.

⁶ The reference spectrum defined by the IEC standard is entirely equivalent to the one defined by ASTM, both obtained synthetically by SMARTS with the same input parameters.

5.1.1 ENERGY FORECAST SOFTWARE

Software to estimate the annual yield of a PV system is a quotidian tool in energy yield estimation, in particular for the planning, financing and operation of PV power plants. While most of these tools rely on equations to estimate the PV production, some incorporate a CPV section that may include models of the factors that are especially affecting a CPV system, including spectral changes and estimation of realistic operation conditions such as cell temperature, optical acceptance or soiling.

Regarding resource modeling, modern software uses high-resolution data, obtained mainly hourly or even minutely, due to the high computing power of present-day computers. When no hourly data are available, some models that expand time resolution are used.

Listed below are two tools with widespread use in PV academic and industrial sectors and that include some CPV modeling.⁷

5.1.1.1 System Advisor Model

System Advisor Model (SAM) (Blair et al. 2014) is a public-use software that is based on a performance model designed by NREL to estimate the energy yield of several systems relying on renewable technologies, including PV and CPV (Ghosal et al. 2014). It also includes a financial analysis that considers the cost of energy estimates.

SAM's resource input is a typical meteorological year (TMY), i.e. an annual series of meteorological values with hourly resolution that includes *DNI*, ambient temperature and wind speed. If a TMY is not available for the location, it should be provided since there are no models that expand monthly mean values or perform similar procedures.

It uses air mass (*AM*) functions to estimate the spectral correction that should be estimated for every location, as it is shown in the next paragraph.

The rest of the CPV-specific add-ons are currently limited. Furthermore, the estimation of the cell temperature is made through an empirical model that takes into account the wind speed and uses the thermal gap between heatsink and cell temperature. However, the model coefficients should be obtained empirically from data, since the model is not physical.

⁷ The PV_LIB (Stein 2012; Andrews et al. 2014) is a initiative lead by Sandia National Laboratories that facilities a collaborative group of PV professionals whose aim is to improve the accuracy of PV models. While there are no CPV sections yet, it is a very promising proposal to pay attention in the future.

5.1.1.2 PVsyst

PVsyst software (Cottier et al. 1996) is one of the standards in PV solar simulation, and its recent versions include CPV add-ons that have already been used in CPV modeling by some manufacturers, including Soitec (Gerstmaier et al. 2010; Gerstmaier et al. 2011) and Semprius (Fisher et al. 2014; Ghosal et al. 2014). In general, the level of detail in modeling PV systems is very high, allowing several meteorological inputs and even expanding synthetic series from monthly values.

For CPV modeling it includes three CPV utilization factors versus *DNI*, *AM* and ambient temperature. Of particular relevance is the ambient temperature function that allows modeling the lens dependence on ambient temperature, appreciable in most of the CPV lens configurations and especially in silicon-on-glass. However, in general, this software currently solves some other CPV particularities roughly.

One of these is related to *DNI* modeling, since PVsyst is not enforcing that the daily profiles of the *DNI* series are realistic and it allows *DNI* estimation based on synthetically expanded averaging values from monthly mean irradiation values. The bias introduced by this approach is analyzed in the next section.

The other main issue is that the spectral correction is based only on the *AM* utilization factor and it cannot be generalized to any location. The cell temperature estimation is based on an energy balance using heat transfer coefficients (one that is constant and another to account for wind convection).

5.2 METEOROLOGICAL RESOURCE MODELS

A more in-depth description of the state of the art in meteorological variables relevant for CPV is given in this section, with special emphasis on the modeling of variables that energy forecast software does not currently successfully resolve.

5.2.1 SOLAR RESOURCE MODEL

Among meteorological input variables, solar radiation exerts by far the most influence on the yield of a CPV system and, consequently, it is the one that needs more accurate modeling.

There are two different approaches to estimate the direct irradiation: radiative models (Gueymard 2008; Bird and Hulstrom 1981) that are based on atmospheric transmittance whose formulation is developed with physical equations, and empirical models based on relationships among other types of irradiances such as global or those that have a low time resolution that should be expanded. The radiative models need atmospheric

parameters such as aerosols or water vapor, whose measurement is complex so the global availability is limited. Furthermore, the broadband irradiation is calculated through the integration of the spectral irradiation that is obtained from a very complex set of equations, requiring a considerable amount of computing time. It is for these reasons that it is very common to estimate the *DNI* series for energy forecasts from non-radiative empirical models that just expand the time resolution or decompose the global irradiation into direct and diffuse parts.

The ideal input to estimate the energy yield of a solar-based system is a TMY (Hall et al. 1978), a time-series of meteorological data that consists of individual months of data sets selected from different years over the available data period, usually about thirty years (Wilcox and Marion 2008). The concrete selection of months is such that they are representative of the typical dispersion of the site while the mean monthly and annual energies are kept. The time resolution is hourly.

Considering that a TMY is directly an hourly time series, the energy yield is straightforward, as the integrated values of hourly power obtained from the CPV system model with the particularity that a TMY is the average series of the expected irradiation, so the best estimation for the expected operation life is obtained, without bias.

Most of the time, the availability of TMYs is limited. The next, more representative, set of data is an annual time series from the site. In this case, one cannot be sure that there is no bias (especially since *DNI* presents more dispersion than global (Mohammed et al. 2013)) and a solution involves "calibrating" the monthly irradiation using the monthly long time averages, adding or removing days in a month until the monthly averages are matched (Fernández-Peruchena, Blanco, and Bernardos 2014).

Up until now, we are supposing that *DNI* data are available following the shape of a meteorological time series, which is not as usual as a global radiation series. For CPV, only *DNI* is valid as a resource, so in the case that global is the only radiation variable available, *DNI* can be obtained indirectly by the application of decomposition models (Batlles et al. 2000; Skartveit and Olseth 1987; Erbs, Klein, and Duffie 1982; Maxwell 1987; Perez, Ineichen, and Maxwell 1992). Decomposition of global radiation into its components, direct and diffuse, allows it to obtain a *DNI* series but with an obvious increase in the corresponding uncertainty with respect to directly measured values. Most of the models define a relationship between the k_D (diffuse ratio) and k_T (clearness index) as:

$$k_D = \frac{D(0)}{G(0)} \quad (5.1)$$

$$k_T = \frac{G(0)}{B_o(0)} \quad (5.2)$$

where the B_o represents the extraterrestrial irradiation. A moment as determined by a concrete pair of indexes (k_D , k_T) presents a more or less turbid atmosphere and cloudy sky. Using both indexes is possible to obtain the diffuse irradiation and therefore the *DNI*.

The next level in the quality of data would be the monthly average series, much more available than the hourly series, usually of global horizontal irradiation. In this case, a model that generates the daily irradiance profile is necessary, increasing the time resolution from daily to hourly values but augmenting the uncertainty of the final values. Among the models for global irradiation that relate the daily and hourly irradiation, the most common model is that proposed by Liu and Jordan (Liu and Jordan 1960). A key aspect at this level is how the *DNI* daily profiles are built. Most of these methods distribute the monthly average energy along the typical day, assuming that all days of the month are equal and that radiation extends from sunrise to sunset. However, this approach generates daily profiles with very low *DNI* at the central hours of the day that are not representative for direct irradiation.

CPV energy modeling requires models that generate realistic daily *DNI* profiles. Those that synthetically (Beyer et al. 2010; Graham and Hollands 1990; Knight, Klein, and Duffie 1991; Silva-Pérez et al. 2014) generate a distribution of hours in a day can be found, such as those based on neural networks (J. Rodrigo et al. 2012) or ones based on autoregressive moving-average models (R. Aguiar and Collares-Pereira 1992). If there is also a need for a series of stochastic days, they can be generated with Markov transition matrices (R. J. Aguiar, Collares-Pereira, and Conde 1988). Another approach is to use clear-sky models based on monthly values, where the distribution of the monthly energy is done by the number of clear days (Fernández-Peruchena, Blanco, and Bernardos 2014). This is the case that is developed in Section 5.5.1 and is applied to a CPV system to forecast its energy production.

5.2.1.1 Clear-sky *DNI* models

DNI clear-sky and averaged models are differentiated by the way they distribute the monthly irradiation. A clear-sky model generates a representative clear-sky day and creates as many days as needed to reach the monthly energy level. In contrast, an

averaged model assumes that all the irradiation is distributed equally among all the days of the month, so the typical day presents a daily profile lower than that of a clear-sky day. In summary, the clear-sky model assumes a limited number of full days while the non clear-sky model presupposes that all the days are sunny but with reduced *DNI*.

Figure 5.2 Schema representing the distribution of monthly irradiation for (above) clear-sky model and (below) averaged model. Both models distribute the same amount of monthly irradiation.

$$\sum DNI_{clear-sky} = \sum DNI_{averaged} \quad (5.3)$$

5.2.1.1.1 Energy yield bias due to averaged *DNI* models

Figure 5.3 shows the daily distribution of *DNI* of an averaged model versus a typical clear December day in Madrid, Spain. Even if the total of irradiation for the month is the sum of the original averaged data, the model clearly cannot reproduce the real profile of direct irradiation. A CPV system fed with this modeled irradiation would be clearly far off from its real operational conditions that, furthermore, will not ever occur. Because the efficiency and temperature of the cells strongly depend on the irradiance, the model will expect a lower current and cell temperature translated to higher voltage. For the example given in Figure 5.3, the temperature of the cell can be up to 39 °C below the estimated value based on actual measurements. The changes in operation conditions can also distort the operation point of the inverter, whose efficiency is a function of the input voltage.

Figure 5.3 An averaged model and measured profiles of Direct Normal Irradiance and estimated cell temperature of a CPV module of a clear December day in Madrid. An averaged model distributes the total monthly energy and considers all the days to be identical, estimating 39 °C below the real value.

Consider, for example, the case of the CPV plant that is used as an example in Section 5.4 further in this chapter: both models can be applied and the impact on the energy forecast can be evaluated. The final result is 1.8% higher in the case of the averaged model, mainly due to the fact that a lower *DNI* produces a lower cell temperature and that is reflected in higher levels of voltage. The actual impact on a CPV system depends, therefore, on the actual value of the beta parameter and the thermal resistance of the CPV system.

5.2.1.2 *DNI* frequency distribution

The main reason for the unsuitability of averaged models for direct irradiation is that the *DNI* distribution over the course of a day is roughly constant and only attenuated by the length of atmosphere that sunlight has to pass through, so *DNI* is mainly distributed in high irradiation values. On the other hand, global irradiation is balanced by diffuse contribution, so over different days, several levels of irradiation are possible. These patterns can be checked in the histograms for Madrid in 2013 as represented in Figure 5.4.

Figure 5.4 Histograms of global horizontal irradiation and Direct Normal Irradiation (DNI) of Madrid for 2013. While global irradiation shows an almost uniform pattern at every level of irradiation, DNI has a clear skew, mainly at high levels of irradiation.

5.2.2 SPECTRAL RESOURCE MODEL

The sensitivity of the multijunction (MJ) solar cells to the spectrum is well known: the photocurrent produced by MJ cells is reduced due to spectral mismatch because of the series connection of its subcells.

In the case of the current triple junction (3J) technologies based on germanium, the top subcell exhibits a limiting factor at the beginning and at the end of the day and the middle/bottom subcell does likewise during midday. However, despite this clear trend, it is impossible to establish exact hourly models that are universal and valid for any location without using a radiative model based on spectral parameters. This is because the randomness of atmosphere contents as aerosols and precipitable water of any location.

5.2.2.1 Air mass function for spectral correction

The best approach of current CPV modeling software is to model spectral losses using an *AM* function (Osterwald, Emery, and Muller 2014). However, these functions are mainly intended for PV flat panels, whose spectral sensitivity is relatively low because most of them are based on only one type of broadband junction solar cell. Moreover, the *AM* functions ignore the variations in the atmospheric components; consequently, they are location-dependent (as is highlighted in (Osterwald, Emery, and Muller 2014)). The fact is that the use of *AM* functions for the estimation of spectral effects on CPV modules can produce a large bias, especially if the considered period is not representative of the local atmosphere (periods of time less than one year). Figure 5.5 shows the air mass functions derived from normalized currents of a silicon and a MJ solar cells obtained by synthesizing spectra from the Madrid AERONET station (data from 2013).

Figure 5.5 Air mass functions derived from normalized currents of silicon and MJ solar cells. The silicon cell is ideal in the sense that it considers a quantum efficiency (QE) equal to 100% and the MJ cell corresponds to a lattice-match (LM), with a bottom based on germanium. The considered data represent Madrid 2013, obtained from AERONET station.

The ideal silicon cell corresponds to perfect quantum efficiency (QE) as a representative case of a flat-panel module and, as can be seen, the dispersion is relatively low so the fit is representative enough of the evolution of spectral effects versus the *AM*. Furthermore, the MJ solar cell is much more affected by spectral variations. The fit is manifestly limited and the larger dispersion is due to atmospheric parameters, mainly the aerosols. Moreover, it should be noted that, for example, at *AM*=1.5 (the reference condition), the variation is about 20% so the *AM* function will clearly give erroneous spectral corrections for instantaneous values. In the case of a full annual period it will work as the best representative linear fit, since the *AM* is the main factor of the spectral change of the solar spectrum, and the atmospheric components as aerosols also follow an annual pattern, but with notable dispersion.

However, *AM* functions are highly sensitive to location due to different levels of atmospheric components at different locations. For example, when the *AM* function from Figure 5.5 (calculated for Madrid) is applied to the same MJ solar cell but under a different atmosphere, the bias is evident. In the case of Lanai (Hawaii), whose atmosphere is strongly influenced by its proximity to the sea, the difference on an annual basis is about a 6% decrease, or in the case of Tamanrasset (Algeria, sited in the Sahara desert) it is about 5%.

A better fitting function should also take into account atmospheric parameters, at least the most influential ones such as aerosols and precipitable water. Another solution involves indirectly estimating the spectral losses through the spectral efficiency (η_{spectral}) using

component cells, as is proposed in the next section. In this case, the correction is also place-dependent, but the dispersion is very much reduced since the component cells reproduce the same behavior as the corresponding MJ solar cell, aggregating the effects of all the spectral components, including *AM*, aerosols and precipitable water.

5.2.2.2 Component cells for spectral correction

Based on the spectral efficiency defined in Chapter 2, an estimate of the energy loss due to spectral mismatch is easy to obtain. Every instant has a corresponding value of $\eta_{spectral}$ that can be obtained from the photocurrents of component cells.

The $\eta_{spectral}$ should be applied to the current of the CPV module, giving an idea of the effective irradiance in terms of spectrum, or applied to the MJ solar cell that is inside, when the differences on spectral variations between the MJ solar cell and the CPV system can be considered negligible (César Domínguez et al. 2013). Nevertheless the spectral variation of the atmosphere is the responsible of the most of the spectral impact on CPV systems and optics contribution is already included in the power rating at CSOC.

This method is defined at a high time resolution (minutes) but since the spectral effect has a medium impact on annual energy estimation, monthly resolution to quantify this effect in a location is enough. Monthly values of four years in Madrid proved to have quite a good repeatability (the concrete values can be checked in Chapter 3, Section 3.4).

When no measurement of spectral data is available from a spectroheliometer, the spectral influence can be obtained from quantum efficiencies of the MJ solar cell and synthetic spectra that have been generated with radiative models such as SMARTS (Gueymard 2001) using atmospheric parameters (aerosols and precipitable water) from sources that include AERONET (Holben et al. 1998), which contains annual data from sites worldwide.

5.2.3 AMBIENT TEMPERATURE RESOURCE MODEL

With less impact than solar irradiation, ambient temperature is indirectly affecting the energy yield through voltage (as PV systems), and the current through the optics. As with direct radiation, an hourly series of ambient temperature for the representative day of every month is necessary and the ideal input would be a TMY.

Regarding modeling, there are methods based on neuronal networks (Altan Dombaycı and Gölcü 2009) that generate stochastic series, however a methodology for estimating the average profiles of daily ambient temperature based on double-cosine methods as presented in the European Solar Radiation Atlas (ESRA) (Huld et al. 2006) is considered simple and sufficiently valid for annual energy models, mainly due to the high inertia of

ambient temperature. The only necessary data are a monthly series of average temperatures of mean daily minimum and maximum temperatures, which can be obtained from meteorological databases (e.g., WWIS⁸ from the World Meteorological Organization).

5.2.4 WIND RESOURCE MODEL

Wind influence on CPV systems is relatively low but it has a higher impact on CPV than on PV systems. This is due, firstly, to the higher sensitivity of the cell temperature and, secondly, the requirement of a tracker. CPV trackers have a very low tracking accuracy (0.1°) and it is common for the tracker to move to stow position over a threshold.

A TMY with wind data available is, again, the best source of data. If this information is not available, there are autoregressive models (Brown, Katz, and Murphy 1984) that generate time series or models based on Markov chains (Sahin and Sen 2001; Shamshad et al. 2005). However, wind follows a Weibull distribution, which is characterized by a scale parameter that measures the dispersion and a form factor that measures the skewness. From the characterized distribution, a stochastic model can generate daily profiles (Yu and Tuzuner 2008), or even simpler sampling can be considered for CPV forecasting.

5.2.5 SOILING MODEL

Most of the CPV systems use a lens to concentrate the sunlight and focus it onto the solar cells. Soiling blocks sunlight as in flat panel PV, but the effect of scattering is especially important; most times it will provoke light losses due to CPV low optical acceptance. The result is that CPV systems are much more sensitive to soiling than flat panel PV systems (Vivar et al. 2010).

In order to better estimate the soiling effect, an ad hoc characterization is advised. Since the accumulation of soil causes a reduction of the generated power, which is recovered when the system is cleaned, an adequate model needs to take into account the pattern of natural or forced cleanings. In addition, an estimate of the length of time for the effect of soiling to saturate is necessary.

5.2.6 SUMMARY OF METEOROLOGICAL INPUT VARIABLES

In Table 5.2 there is a summary of the input variables that affect the yield of a CPV system with the corresponding symbol used in this chapter. The effect of wind speed is distributed among convection and tracking factors and the shading factor refers mainly to the self shading among trackers.

⁸ <http://worldweather.wmo.int/>

Table 5.2 List of meteorological variables that affect a CPV system.

Variable	Symbol
Direct normal irradiance	DNI
Ambient temperature	T_{amb}
Spectral efficiency	$\eta_{spectral}$
Convection factor	$F_{convection}$
Tracking factor	$F_{tracking}$
Soiling factor	$F_{soiling}$
Shading factor	$F_{shading}$

5.3 CPV SYSTEM MODEL

While some models estimate the CPV plant behavior based primarily on statistical models (Almonacid et al. 2013), the majority of the proposed methods for CPV modeling are based on physical models, mainly the Shockley model of a solar cell. This means that the expected power of the plant under standard reference conditions (e.g., CSOC-Concentrator Standard Operating Conditions as defined in IEC 62670-1 (IEC committee 2013)) is converted by the means of translation models based on equations (Kinsey and Edmondson 2009; Bowman, Jensen, and Melia 2012; Fernández et al. 2013; Nishioka et al. 2006; Philipps et al. 2010) or equivalent SPICE diode models (Chan et al. 2013; Young 2010; Steiner et al. 2015).

5.3.1 TRANSLATION EQUATIONS-BASED MODEL

Translating current-voltage (IV) characteristics of a solar cell useful for CPV modeling can be performed using a lumped diode model for concentrator MJ solar cells (César Domínguez, Antón, and Sala 2010). The model of a plant can be obtained by extending those equations while considering the aggregation of cells in modules, modules in trackers, and trackers in a plant (Kinsey and Edmondson 2009; Bowman, Jensen, and Melia 2012; Nishioka et al. 2006; Philipps et al. 2010). Additionally, several extra equations are necessary to model the cell temperature (see Appendix I) and the effects on the lens module.

5.3.2 SPICE-BASED MODEL

SPICE (Simulation Program with Integrated Circuit Emphasis) has been used widely in electronics to predict circuit behavior. The modeling of solar cells as electrical circuits has allowed the power of SPICE to be used on photovoltaics, including CPV (Chan et al. 2013; Young 2010; Steiner, Siefer, and Bett 2014).

SPICE can also be considered to be an equations-based model, which has the idiosyncrasy that its models are especially complex regarding details. The main benefit of SPICE modeling is that it provides an *IV* curve. However, the level of complexity (and computing time) increases dramatically when several CPV modules are considered.

Using the SPICE model of the module from Appendix II as a unit, the modeling can be extended to a full CPV plant. Beyond the electrical interconnection of the modules to form trackers, and the interconnection of trackers to form a plant, it is relevant to consider variations in current due to changes in *DNI* and spectrum, and variation in voltage due to changes in ambient temperature and *DNI*. Thermal resistances modulated by wind speed previously characterized are also necessary to estimate the cell temperature.

5.4 EXAMPLE OF POWER ESTIMATION OF A CPV PLANT

As a case of study, the model based in equations of a CPV plant along with the resource models will be compared with the power of an experimental 50 kWp CPV plant to validate them and to thoroughly understand the influence of ambient variables on CPV systems.

5.4.1 DESCRIPTION OF THE CPV CASE PLANT

The CPV plant is located in La Villa de Don Fadrique, a village in the Castilla La Mancha region of Spain 125 km south of Madrid, from November 2012 until November 2014 under the European Union-Japan project NGCPV (López et al. 2012). The CPV technology of this plant is based on a two-stage optical system working at 820X, consisting of dome-shaped Fresnel lenses made of polymethyl methacrylate (PMMA) as primary optics, and an inverted truncated pyramid made of glass as secondary optics, which focuses light on three junctions (3J) lattice-matched (LM) GaInP – InGaAs – Ge solar cells. The plant can be seen in Figure 5.6, comprised of five arrays of 48 modules, with each array consisting of eight branches connected in a parallel of six series-connected modules. The five arrays are connected in parallel to a single inverter with a unique maximum power point tracking (MPPT) system.

Figure 5.6 Photography of the CPV plant composed of five arrays in independent trackers.

The monitoring system of the plant oversees power and energy generated by the trackers, and a meteorological station (see Figure 5.7) measures wind speed and direction; ambient temperature; relative humidity; global, diffuse and direct irradiance; and spectral irradiance with a tri-band spectroheliometer (César Domínguez et al. 2013) based in LM component cells with a similar spectral response as the plant modules.

Figure 5.7 Photograph of the meteorological station inside the plant. The next variables are measured: ambient temperature; relative humidity; wind speed and direction; global, diffuse and direct solar irradiance; and spectral irradiance by the means of a spectroheliometer, an instrument based on component cells.

Detailed characteristics of the plant, such as module and tracker dimensions or tracker distances, are shown in Table 5.3.

Table 5.3 Features of the module, the array and the field of La Villa de Don Fadrique CPV plant.

Module dimensions (net input area)	1 m ²
Cells in the module	25 (MJ, 3 subcells), in series
Array (rows x columns)	48 modules/array (6 series x 8 parallel)
Height tracker	6.2 m
Longitude tracker (parallel to ground)	8.8 m
Distances between pedestals (north-south / east-west)	17.65 m (north-south), 22.20 m (east-west)

5.4.2 MEASUREMENT PROCEDURES

The power rating of a plant under any particular conditions and in concrete in CSOC can be obtained simply by recording the involved variables by time and applying suitable filters for the operating conditions. After a few days or weeks of plant operation, all the CSOC conditions have been matched several times and there is ample data with sufficient

statistical significance to estimate the relationship of electrical versus ambient variables without extrapolating or creating external hypotheses.

Another simpler and shorter procedure is to consider a single sunny day and the application of translational equations of a physical base (César Domínguez, Antón, and Sala 2010). This method has been employed previously for acceptance of plants and arrays with various technologies (Antón et al. 2012), and it is a very suitable method for the reception of a plant that allows for very quick identification of the CSOC power (and even CSTC). However, it is not possible to determine the thermal characteristics of the array with sufficient certainty to predict its performance.

5.4.3 DETERMINATION OF P_{CSOC}

The main source of uncertainty in the modeling of the energy production of a CPV plant is the determination of the power of the plant at nominal operating conditions at CSOC. The maturity of the technology does not allow to simply add the power of the modules declared by the manufacturer, which is commonly based on flash test on the production line at CSTC and translated to CSOC. Considering the low angular tolerance of CPV modules (below 1°), an important source of power loss is the degree of misalignments among the modules in an array, both caused by difference in the pointing vector of the modules (due to manufacturing tolerances and errors) and by the bending of the tacking structure (caused by manufacturing errors and bending under load conditions), to add to the dispersion on power values among modules. As a consequence, the array is the minimum unit to determine the nominal power of a CPV technology.

The determination of the nominal power of a CPV array or plant at CSOC involves the characterization of the technology during at least several days or weeks, assuring CSOC conditions are achieved. The array must be biased at the maximum power point (i.e., connected to the inverter) to ensure that electrical power is extracted and does not add an extra and very significant thermal load, considering that typical efficiencies of a CPV systems are above 25-30%. During the characterization process both DC and AC power are monitored, ideally with current and voltage variables separated.

Since the power determination is made outdoors during several days and with the array connected to the inverter, there are other unavoidable losses that are included in the nominal power of the array or plant beyond the array itself. These additional losses are: power point tracking losses caused by the inverter, pointing losses caused by the tracker which must be carefully aimed and a certain degree of soiling which depends of the cleaning strategy carried out during the characterization. For the example case, there was

not any cleaning routine in the plant, and the initial characterization of the power at CSOC was carried out several months after the plant set-up, which means that part measured power is very affected by the degree of soiling at that moment.

Besides monitoring the electrical variables from the plant, the ambient variables that directly influence the performance of the CPV system should also be recorded simultaneously: direct solar irradiance, wind speed, ambient temperature and spectral variation. Additionally, given the importance of thermal effects, heatsink module temperature from a cell of a representative module should be also recorded (Núñez et al. 2014).

If sufficient data are available, filtering by CSOC conditions will directly provide power (as shown in Figure 5.8), voltage and current in these circumstances, but not introduce extra uncertainty since no extrapolation is needed. The losses that can introduce the inverter and the DC/DC converter in a maximum power point (P_{MP}) are already included in the estimation of the DC power at CSOC (P_{CSOC}).

Figure 5.8 DC power versus Direct Normal Irradiance (DNI) filtered under Concentrator Standard Operation Conditions (CSOC) where the DNI variable is not fixed to CSOC conditions to show the correlation. At CSOC ($DNI=900 \text{ W}\cdot\text{m}^{-2}$), the power is obtained filtered from several days of operation. Initial soiling conditions are considered during the period of operation of the plant.

As stated above, the rated power is very affected by the soiling of the arrays. Considering that the rating was carried out ten months after the installation of the plant, the nominal power of the plant, considering that one of the nominal conditions “clean” is:

$$P_{CSOC(clean)} = \frac{P_{CSOC(initial)}}{F_{soiling(initial)}} \quad (5.4)$$

where $F_{soiling(initial)}$ was estimated in 0.91. Consequently, the nominal power of the plant is $P_{CSOC(clean)}=48.75$ kW.

5.4.4 TRANSLATING FACTORS

Electrical parameters (current and voltage) are corrected to CSOC conditions by means of the following parameters and using direct irradiation and ambient temperature directly or considering the thermal expansion of the lens material of the CPV modules' primary optics.

The short-circuit current variation of MJ solar cells with temperature (α) is small, and in the case of CPV is masked with the variations on current due to thermal changes in optics (a contribution usually relevant for CPV and detailed later).

5.4.4.1 Factor of current and voltage as a function of irradiance

This factor reflects the proportionality of the photocurrent to the irradiance, plus its effect on voltage.

$$F_{IV}(DNI) = \frac{DNI}{DNI_{CSOC}} + k \cdot \ln\left(\frac{DNI}{DNI_{CSOC}}\right) \quad (5.5)$$

where $k = 3n \cdot V_t(T)$, n is commonly known as ideality or quality factor and its value ranges from 1 to 2, $V_t(T)$ is the thermal voltage and the 3 stands for the fact that the cells are triple junction solar cells. The DNI_{CSOC} is defined in the IEC 62670-1 (IEC committee 2013) document as $900 \text{ W}\cdot\text{m}^{-2}$.

The second term accounts for the logarithmic dependence of the voltage with DNI , while the first is related to the quasi linear dependence of current and DNI . However variations on voltage due to direct irradiance are limited to a range of $200\text{-}300 \text{ W}\cdot\text{m}^{-2}$ during operation because of the quasi-constant daily profile of DNI , so this term can be negligible in the majority of the cases.

Nevertheless the current of a MJ solar cell-based system is not actually linear with DNI because of the strong spectral dependence of MJ cells. Spectral differences from standard spectrum (ASTM AM1.5D G173) are accounted for by an extra spectral factor that will be introduced in the following subsections.

5.4.4.2 Factor of voltage as a function of ambient temperature

In the same manner as described in the determination of P_{CSOC} , and thanks to the volume of collected data, correction equations can also be estimated from fitting. These equations account for voltage and current dependent of irradiance and temperature, so basically

descriptive parameters such as beta (voltage vs. temperature) or their array equivalents are obtained.

The correction factor with temperature needs an equivalent beta parameter (in this case, referred to as maximum power point voltage) for the entire CPV plant that is estimated using a representative heatsink module temperature that is easily measureable, unlike the actual cell temperature. This relationship is shown in Figure 5.9.

Figure 5.9: DC voltage of the CPV plant versus module temperature (measured on the backplane) and filtered under Concentrator Standard Operation Conditions (CSOC), where the ambient temperature variable is not fixed to CSOC conditions to show the correlation. A $\beta_{\text{plant_DC}}$ parameter (but referred to V_{DC}) similar to the one of solar cells but representative of the system is obtained. This parameter is useful for modeling the thermal influence on the CPV plant's voltage.

The following equation provides the variation of the voltage versus the difference relative to heatsink module temperature at CSOC conditions. N_s refers to the total number of cells in the series (150 in this case) and $\beta_{\text{plant_DC}}$ is the equivalent beta parameter per cell representative of the plant at DC (maximum power point).

$$F_V(T_{\text{module}}) = \left[1 + \frac{N_s \cdot \beta_{\text{plant_DC}}}{V_{\text{CSOC}}} \cdot (T_{\text{mod,CSOC}} - T_{\text{module}}) \right] \quad (5.6)$$

This expression requires, then, the obtainment of a representative heatsink module temperature that should be a function of the meteorological variables model: ambient temperature and direct irradiation.

$$T_{\text{module}} = T_{\text{amb}} + DNI \cdot (\eta_{\text{opt}} - \eta_{\text{DC}}) \cdot R_{\text{th m}_a} \quad (5.7)$$

where, for the plant of La Villa de Don Fadrique: (optical efficiency of the primary lens) $\eta_{opt}=0.85$, (thermal resistance between module and ambient) $R_{th\ m_a}=0.069\ ^\circ\text{C}/(\text{W}\cdot\text{m}^{-2})$, estimated previously from measurements of the heatsink module temperature (on the backplane, directly behind the solar cell, see Appendix I). $\eta_{DC} = \eta_{opt}\cdot\eta_{cell}$ is the DC efficiency of the CPV module.

Eq. (5.7) is implicit since η_{DC} depends on T_{module} . Nevertheless, it results almost invariable after two iterations, starting from the η_{DC} obtained at CSOC. A rough but many times good approximation is considering η_{DC} constant and equal to $\eta_{DC(CSOC)}$.

This expression has been evaluated with the mean value of the measurements of heatsink module temperatures of the five trackers of the plant, showing a good correlation in Figure 5.10 with an affordable dispersion, RMSE=2.3 $^\circ\text{C}$.

Figure 5.10 Correlation of estimated module temperature from ambient temperature and direct normal irradiance (DNI) versus measured (obtained directly from the heat sink).

5.4.4.3 Factor of the optics effects on current

Temperature affects the photogenerated current of a CPV cell through two effects. On the one hand, the well-known dependence of the current of a PV cell caused by the sensitivity of the bandgap to the temperature, which is commonly modeled, in single junction solar cells, with the linear temperature variation coefficient of the short circuit current (α). However, this dependence is not linear for the case of MJ solar cell, considering that the current generated by the device is the minimum of the currents generated by each subcell at a given operating condition. In addition, optic elements show a strong focal dependence on temperature which affects the generated current of the cell. CPV optics are exposed to ambient temperature and a thermal load in the module which on the one hand, change the

effective focal distance due to thermal expansion, and on the other hand change the refraction index in refractive optics which also affects the focal distance. This variation of the effective focal distance changes the absolute value and spatial and spectral distribution of the irradiance in the cell. Therefore, the photocurrent produced by a CPV module is also highly dependent on the temperature of the primary optics (Hornung, Steiner, and Nitz 2012; Steve Askins et al. 2011). Silicone on glass (SoG) technology (Lorenzo and Sala 1979; Valery D. Rumyantsev 2010) is especially sensitive to this effect (Cvetkovic et al. 2011; Stephen Askins et al. 2012); however, the modules based on PMMA lenses, such as those from the plant under consideration, also slightly change its optical efficiency with temperature. The actual values depend on the final configuration, but the relative short-circuit current sensitivity to temperature of SoG can be up to ten times higher than that of PMMA (García, Victoria, and Antón 2016). Also, the presence of a secondary optic element (SOE) can reduce significantly such dependence with temperature. The improvement in angular tolerance and irradiance uniformity in the cell provided by the SOE leads to lower current variation (Victoria et al. 2009; Benítez et al. 2010; Jaus et al. 2011; Stephen Askins et al. 2012), so CPV systems including SOE exhibit lower current versus temperature dependence.

Considering the on/off nature of the *DNI*, the temperature of the primary optics of a CPV modules is strongly related to the ambient temperature (García, Victoria, and Antón 2016). To determine such dependence, both indoor (Peharz et al. 2011; Steve Askins et al. 2011; V. D. Rumyantsev et al. 2010; Hornung, Steiner, and Nitz 2012) or outdoor (Stephen Askins et al. 2012; César Domínguez and Besson 2014) characterization of the CPV technology, preferably at the module level, can be carried out. The great inconvenience is that a wide range of ambient temperature is needed together with a strong control of the spectral irradiance, which requires the means for changing the temperature of the primary optics indoors (Steve Askins et al. 2011) or outdoor characterization at different seasons (César Domínguez and Besson 2014).

Alternatively, it can be obtained by long term characterization of a CPV plant by filtering data. For the example case, Figure 5.11. shows the current dependence with temperature of the PMMA modules and a second-degree fit that accounts for losses when the operating temperature of the lens is not optimal.

Figure 5.11 DC current (I_{DC}) versus ambient temperature (T_{amb}) filtered under concentrator standard operation conditions (CSOC), where the ambient temperature variable is not fixed to CSOC conditions to show the correlation. At CSOC ($T_{amb}=20$ °C), the nominal I_{DC} is obtained. Initial soiling conditions are considered during the period of operation of the plant.

Again, as for the case of the power, the nominal current must be corrected with the initial soiling factor:

$$I_{CSOC(clean)} = \frac{I_{CSOC(initial)}}{F_{soiling(initial)}} = 136.5 \text{ A} \quad (5.8)$$

The equation of the fitting from Figure 5.11 adapted to current on clean conditions can be expressed as:

$$F_O(T_{amb}) = \frac{-2.04 \cdot 10^{-2} \cdot T_{amb}^2 + 0.667 \cdot T_{amb} + 130}{I_{CSOC(clean)}} \quad (5.9)$$

5.4.5 RELEVANT PARAMETERS OF THE EXAMPLE CASE

To sum up the characterization of the CPV plant of La Villa de Don Fadrique, the distinctive parameters at CSOC are listed in Table 5.4.

Table 5.4 List of characteristic parameters of La Villa de Don Fadrique plant at CSOC

Parameter	Value
$P_{CSOC(clean)}$	48.75 kW
V_{CSOC}	357.1 V
$I_{CSOC(clean)}$	136.5 A
β_{plant_DC}	-6.00 mV/°C (-0.25%) [per cell]
$R_{th\ m_a}$	0.069 °C/(W·m ⁻²)

5.5 A SIMPLE IMPLEMENTATION OF A FORECAST MODEL FOR CPV

As a reference, a simple forecast model based on the same CPV model, which is equation-based, is presented. With a full TMY, the energy estimation will be straightforward, as the integration of the estimated power can be seen in the previous section. Considering a more realistic scenario where the meteorological resources are limited, the inputs are not directly available but they are given as a reduced set of descriptive values for a given location:

- Geographical
 - Latitude
 - Longitude
 - Altitude
- Meteorological (twelve values per year)
 - $B_{d,m}$
 - T_{dM}, T_{dm}
 - $\eta_{spectral}$
 - T_{Linke} (if available)
- Corrections (or extrinsic factors)
 - $F_{shading}$ (trackers distribution)
 - $F_{tracking}$ (tracker reliability, wind)
 - $F_{convection}$ (wind)
 - $F_{soiling}$ (rain, soil)

5.5.1 CLEAR-SKY SIMPLE DNI MODEL

To model the *DNI* from monthly daily mean values, daily profiles should be generated with the peculiarity seen before; i.e., they should have representative *DNI* levels. In this case, this condition is implemented based on clear-sky days.

5.5.1.1 Definition of the clear-sky day

A simple proposal for a clear-sky day is to model the direct radiation profile with a trapezoidal distribution that maintains a simple shape resembling the typical clear-day profile of direct radiation, as shown in Figure 5.12. Other, more complicated models that better match the real profile are also possible, but they are not expected to notably improve the accuracy of the final forecast.

Figure 5.12 Typical Direct Normal Irradiance (DNI) daily profile measured with a pyrheliometer and the proposed DNI model that emulates the high levels of irradiance at central hours of the day using a simple definition.

The base of the trapezoid is equal to the length of the daylight in hours (from sunrise to sunset) and the top is the base minus the time assigned as slope, four hours (not valid for polar locations). These four hours account for the transient time that the sun takes to reach the sunrise and the sunset positions, and this time has been selected as a trade-off between fitting and simplicity.

The top level is constant during the day and its value is determined by the level of DNI of a typical day of a given month and place ($B_{Top}(m)$). An interesting possibility for determining this number can be by using the beam component proposed by the clear-sky ESRA model (Rigollier, Bauer, and Wald 2000), that accounts for the solar eccentricity (ε), and an atmospheric transmittance contribution (with Linke turbidity factor (T_{Linke}), integral Rayleigh optical thickness (Kasten 1996) (δ_R) and air mass (AM)).

$$B_{Top}(m) = B_0 \cdot \varepsilon \cdot \exp(-0.8662 \cdot T_{Linke} \cdot AM \cdot \delta_R) \quad (5.10)$$

All the variables are known except T_{Linke} , which can be obtained from an irradiation database as previously mentioned; m refers to month.

The integral of this trapezoidal typical day represents the daily total energy of a clear-sky day in that month ($B_{dm, clear-sky}$).

$$B_{dm, clear-sky} = \sum_{hour} B_{trapezoid}(m) \quad (5.11)$$

5.5.1.2 Number of clear-sky days

A representative month will be composed of clear-sky and cloudy days. The concrete proportion will be defined by the monthly daily energy expected according to the radiation databases ($B_{dm, db}$). Therefore, to match the energy that is expected each month with the model of the total energy of a month from the database, it should be divided by the energy of $B_{dm, clear-sky}$ to obtain the number of clear-sky days per month ($N_{sunny\ days}$). According to this approach, the rest of the days are considered to be fully cloudy.

5.5.2 EXTRINSIC FACTORS

In addition to the intrinsic parameters directly related to the optical and thermal properties of CPV modules or to the electrical behavior of photovoltaic cells, there are other factors that also affect the energy produced by a CPV system. These are parameters whose effect can be modeled only on a monthly or even annual basis.

5.5.2.1 Shading factor

Shadows projected by external objects should not be probable in plants, however mutual shadings are expected. This parameter depends on the distance that the arrays are placed apart from each other and is also affected by its shape, which is approximately rectangular. It is also influenced by the connection of the modules forming series/parallel branches.

Clearly, a very large separation between arrays can be used to avoid shadows; however, the actual design of a CPV plant shall be determined by the price of land and the price of interconnections (cable lengths, ditches, etc.).

Figure 5.13 Schema of the CPV plant detailing the situation of the trackers to help estimate the mutual shading.

Considering solar geometry, tracker dimensions and annual irradiance, losses due to mutual shading are calculated (Perpiñán 2012) and shown in Figure 5.14. Since CPV modules includes one by-pass diode per cell, the shading losses correspond directly to the geometrical shading factor. For the analyzed plant, the tracker number 2 is the one that suffers more shadows from its neighbors. As can be seen in Figure 5.13, this tracker receives shadows from numbers 3, 4 and 5. This effect has been computed and the influence from numbers 3 and 5 is similar.

Figure 5.14 Diagram of shading losses versus relative distance between trackers. The red dots show the effect on tracker number 2 of tracker 4 (left dot) and trackers 3 and 5 (right dot).

In the worst-case scenario, the total losses due to shading are 1.5%, bearing in mind that these are obtained by considering only the geometrical effect. The real impact will be a function of the electrical configuration of cells and modules and, in the case of CPV modules, that every single cell is protected with an individual bypass diode (P. Rodrigo et al. 2013). Thus the factor of shading will be set to 0.98, rounded up.

5.5.2.2 Tracking factor

This subsection refers to the losses due to the percentage of time that the array is not perfectly oriented towards the sun. This occurs when wind speed can bend tracker's arms if there is not enough rigidity and the mechanical deviation is higher than the array's angular acceptance. Apart from problems that are directly attributable to the reliability of the tracking system, the maximum wind speed that sets a threshold security will also limit the availability of the tracker, since it moves to stow position. Moreover, the trackers are equipped with an algorithm that controls when they come back to tracking mode (Luque-Heredia et al. 2007); in the trackers of the analyzed plant, this is as follows: go to stow

position after one minute during which wind speed is over the threshold and stay until the wind speed is under the limit for duration of three minutes.

Considering this algorithm, a wind speed limit of 10 m/s and the wind record of La Villa de Don Fadrique, 0.44% of the energy is lost due to tracking issues. Therefore, the tracking factor is 0.996.

5.5.2.3 Convection factor

Convection due to wind reduces the effective value of $R_{th\ m_a}$ (estimated at CSOC conditions), effectively increasing the DC voltage of the plant. Details about the wind effect on the thermal resistance are provided in the Appendix I, where a linear fit for moderate winds is provided:

$$R_{th\ m_a}(V_{wind}) = R_{th0\ m_a} \cdot (1 - a \cdot V_{wind}) \quad (5.12)$$

where the linear coefficient is $a=0.05\ (\text{m/s})^{-1}$ for this particular technology.

By using that dependence, the convection factor can be estimated instantaneously in combination with Eq. (5.6) and (5.7). Nevertheless, when it is known that its influence is low (e.g. a CPV plant installed in a not too windy location) it can be also estimated at a much lower resolution, considering only the annual mean wind speed of a particular location:

$$F_{conv}(V_{wind}) = 1 + k \cdot (V_{wind_avg} - V_{wind(CSOC)}) \quad (5.13)$$

$$k = a \cdot R_{th0\ m_a} \cdot DNI_{avg} \cdot \beta_{plant_DC} \quad (5.14)$$

being, for the example case, $a = 0.05\ (\frac{m}{s})^{-1}$, $R_{th\ m_a}=0.069\ ^\circ\text{C}/(\text{W}\cdot\text{m}^{-2})$, $\beta_{plant_DC}=0.25\%/^\circ\text{C}$.

The wind speed at CSOC is $V_{wind(CSOC)}=2\ \text{m/s}$ and for the studied plant, the annual average wind speed of the location is $3\ \text{m/s}$. $900\ \text{W}\cdot\text{m}^{-2}$ is considered as a representative annual value for the DNI for the location where the plant is sited (DNI_{avg}), which leads to $k=1\ \%/(\text{m/s})$ and an annual factor of approximately $F_{conv}=1.01$.

5.5.2.4 Soiling factor

Over the lifetime of the analyzed plant, natural rain was the only process that cleaned the CPV modules. Considering that, the plant does never reaches the fully clean condition so the soiling factor will be separated in two terms, one that accounts for the seasonal cleaning produced by rainfalls $F_{soiling(seasonal)}$ and a second that accounts that the modules

are never completely cleaned by the rain (fully clean condition achieved only when the modules left the factory) $F_{soiling(initial)}$:

$$F_{soiling} = F_{soiling(initial)} \cdot F_{soiling(seasonal)} \quad (5.15)$$

It has been determined that the "critical time" (number of days when the influence of soiling in the power has not a significant effect, i.e. it saturates) for the plant technology and place is five days, comparable to other values published in literature by ISFOC (Sánchez et al. 2012) in similar climates. Another characteristic parameter is the maximum decrease of power due to soiling after the critical time compared with the power just after the rainfall event, which is 5% in this case.

Considering that La Villa de Don Fadrique has, on average, 47 periods of five days without rain per year, which are mainly concentrated in the summer (when production is higher), and the previous characteristic values, a soiling seasonal factor of $F_{soiling(seasonal)}=0.96$ is expected. The $F_{soiling(initial)}$ was previously determined to be 0.91.

5.5.3 RELEVANT VARIABLES OF THE EXAMPLE CASE

As a summary, the list of variables presented above is shown in Table 5.5, grouped by their temporal resolution.

Table 5.5 List of variables order by temporal resolution according to its influence on the CPV forecast model.

Hourly	Monthly	Annually
$F_{IV(DNI)}$	$N_{sunny\ days}$	$F_{convection}$
$F_{V(Tamb)}$	$\eta_{spectral}$	$F_{shading}$
$F_{O(Tamb)}$		$F_{tracking}$
		$F_{soiling}$

All factors that are inputs of the forecast CPV model are given with a temporal resolution that depends on the concrete influence of the given factor on the final yield. Some factors that are given with annual resolution (a single value) could be expressed in monthly resolution if it is necessary. This could be the case of convection and tracking factors, if the location presents clear seasonal patterns of wind speed.

5.5.4 MODEL IMPLEMENTATION

Once all the input variables are known, the implementation of the forecast model is computationally simple. The input data are two main arrays of meteorological variables

that are expanded in hourly resolution (from DNI and T_{amb} models), forming matrices of 12x24 values, and an array of monthly values for the spectral efficiency. Every representative day is counted as many times as the number of sunny days of the month according to the irradiation model presented in Section 5.5.1.

The equations that characterize the plant (current and voltage versus irradiance and ambient temperature) use the values of the meteorological variables for the all months and hours plus the extrinsic factors as corrections. These steps are summarized in the following equation, where the intrinsic factors are computed with hourly resolution:

$$E_{year} = \sum_{month} \left[\sum_{hour} (P_{CSOC} \cdot F_{IV(DNI)} \cdot F_{V(T_{amb})} \cdot F_{O(T_{amb})}) \cdot N_{sunny\ days}(m) \cdot \eta_{spectral}(m) \right] \cdot F_{shades} \cdot F_{tracking} \cdot F_{convection} \cdot F_{soiling} \quad (5.16)$$

5.6 COMPARISON OF ENERGY YIELD ESTIMATIONS

The results of the instantaneous (power) and forecast models can be seen in Figure 5.15 in blue diamonds and green dots, respectively, with monthly resolution. To actually compare the produced DC energy (as given by the plant inverter, plotted in red circles) and the energy forecasted by the model, all the incidences in plant or instruments have been filtered out.

A SPICE model for this plant would need 36,000 pn unions at minute resolution for two years of data; consequently, this approach is not practical and requires huge amounts of computing time.⁹ However, to complete the benchmark, a simulation of nine selected clear days from different seasons at the same time resolution has been performed and the results are included with the other models in Table 5.6.

⁹ In the case of an office PC with NGSPICE, it takes about 50 seconds to simulate the circuit. Considering the filtered data used to validate the models (4,669 moments), this means that it would take about 162 full days of computing time.

Figure 5.15 Monthly DC energy evolution of the CPV plant, as recorded in the plant and as estimated by the forecast model presented in this chapter and the integration of the instantaneous values obtained directly from meteorological inputs. To estimate the energy production at low time-resolution (month, year), the forecast model shows annual deviation of 1.8%. Note: the data has been filtered according to the availability of the data of the measuring system and CPV plant.

5.6.1 EVALUATION OF MODELS

A comparison of energy produced by different models, including the forecast one, is given in Table 5.6. The figure of merit used to compare the accuracy of the models is the mean of the residuals with respect the measured energy (mean error, $\bar{\varepsilon}$).

$$\bar{\varepsilon} = \frac{\sum_{i=1}^n (\widehat{energy}_i - energy_i)}{n} \quad (5.17)$$

The figure of merit for comparing the precision of the models is the normalized root-mean-square error ($nRMSE$), which quantifies the amount of dispersion of the residuals between the measured and modeled values in relative terms, and is defined as:

$$nRMSE = \frac{RMSE}{range} = \frac{\sqrt{\frac{\sum_{i=1}^n (\widehat{energy}_i - energy_i)^2}{n}}}{energy_{max} - energy_{min}} \quad (5.18)$$

This procedure has also been applied to a tracker installed at IES-UPM facilities in Madrid (Nagai et al. 2014) for one year, an installation that uses similar technology than the plant presented earlier but with a higher concentration ratio. The main peculiarity of this installation from the point of view of modeling is that the wind speed is under 1.5 m/s more than 90% of the time, so the tracking and convection factors are practically negligible (these corrections are set to unity) and the operation cell temperature is higher (due to the higher concentration ratio) than that seen in the first plant.

Table 5.6 Model energy mean errors for the three models (power, forecast and SPICE) plus their associated nRMSE, except for the SPICE model since it uses a different time resolution and range of data.

	Power model energy	Forecast model energy	SPICE model energy [few representative days, minute resolution]
La Villa de Don Fadrique [5 trackers]	$\bar{\varepsilon} = -0.46 \%$ $nRMSE = 3.55 \%$	$\bar{\varepsilon} = 2.04 \%$ $nRMSE = 2.28 \%$	$\bar{\varepsilon} = 1.80 \%$
IES-UPM field test [1 tracker]	$\bar{\varepsilon} = 1.23 \%$ $nRMSE = 3.93 \%$	$\bar{\varepsilon} = 1.04 \%$ $nRMSE = 3.94 \%$	$\bar{\varepsilon} = 1.58 \%$

The main conclusion is that over the long term (at least one year), the two models present a similar accuracy expressed by the mean error of the model. A more realistic estimation of the mean error would require a larger number of plants and modeling periods to estimate the possible bias of the models. Concerning the precision, the dispersion obtained in the forecast and power models, measured in terms of $nRMSE$ at monthly resolution, is always below 4%, which is not far from the deviations of other CPV models with minute resolution based on the same data or reported in literature (Young 2010; Chan et al. 2013; Fernández et al. 2015; Steiner et al. 2015). The precision of the SPICE model is not comparable since it has a different time resolution and range of data than the other models.

A caveat about the goodness of modeling is necessary. The approach taken in this chapter can suffer overfitting due to the CPV plant has been characterized using data from the same the location where the model is validated, consequently the model will be slightly adapted to some specific features of the location and the CPV technology. A more realistic scenario for forecast modeling would imply a higher uncertainty because in that situation the CPV submodel should be estimated from generic datasheets from the manufacturer.

5.7 CONCLUSIONS

CPV modeling, while sharing input variables with PV, exhibits different sensitivities. Therefore, some valid assumptions for PV are not fully valid for CPV and the models based on these assumptions can present a lack of precision.

A review of the state of the art in the modeling of *DNI* and other meteorological variables, as well as CPV-specific features, has been presented. The main issue regarding *DNI* hourly

series expanded from monthly averages is that, in order to be realistic, they should be obtained from clear-sky models or obtained synthetically with an hourly resolution.

Regarding spectral effects, it has been shown that *AM* functions are very limited in their ability to express the variations of current due to spectral changes that are generated mainly by the variations of aerosols and precipitable water of the local atmosphere. Therefore, they can be used to estimate annual spectral losses but only if they are obtained from annual data and if they are used in locations where the atmosphere is very similar to the one used to obtain the *AM* function. An alternative based on spectral efficiency is proposed, and this gives a lower dispersion because it takes into account the atmospheric parameters.

Special attention should be given to the effect of the ambient temperature on the optics, which is translated to changes in current, and to the soiling due to the higher sensitivity of CPV modules with respect to PV and the expected accuracy of the tracker, which is also very sensitive to CPV systems.

All the submodels have been used together to estimate the power of an example CPV plant operating for two years and an individual tracker for one year. Additionally, a forecast energy model has been presented as an example and compared with energy production of the systems and the integrated power previously obtained. The model works with a few meteorological inputs with monthly resolution. Moreover, spectral influence that is especially relevant in MJ solar cells-based systems is also included, with a monthly series that can be measured in situ or estimated from atmospheric databases. Additional parameters based on external factors have been included to refine the estimation.

5.8 APPENDIX I - THERMAL CHARACTERIZATION OF A CPV MODULE

5.8.1 INTRODUCTION

The aim of this work is to describe a procedure for the characterization of the thermal resistances of a CPV module, with the final objective of determining the cell temperature and relating it to ambient operating conditions. A major difficulty in CPV technology is that cell temperature cannot be directly measured because of inherent characteristics of this technology such as concentrated high flux, small cell sizes and high thermal gradients, both in horizontal and vertical dimensions. The compactness of the receivers, which consist not only of the cell but also of the means for heat spreading, electrical insulation and connections, secondary optics,..., hinders the placement of sensors as close as necessary to the cell.

This difficulty has been solved by means of indirect methods which are based on the relationship between the cell temperature and other parameter. The open circuit voltage is strongly related to cell temperature and has been widely used to determine cell temperature variations. Nevertheless, while temperature variations can be easily related to V_{oc} changes through β parameter, obtaining the dependence between the absolute value of the cell temperature and V_{oc} is a very difficult task. Several methods (Matthew Muller et al. 2011; Matthew Muller et al. 2015; Menard, Meitl, and Burroughs 2012; M. Muller et al. 2013) have been proposed based on dark IV measurements, electroluminescence or simply direct characterization carried out on the cell level. But V_{oc} is also affected by other operating conditions such as non-uniformity light distribution, chromatic aberration, spectrum... which cannot be reproduced in none of these methods which leads to significant uncertainties in cell temperature.

5.8.2 EQUIVALENT THERMAL CIRCUIT

Heat flow is commonly modeled with an electrical circuit where thermal resistances are substituted by resistors and thermal capacitances by capacitors. In CPV, since the input of power to a CPV module is DNI , whose dimensions are W/m^2 , it is more practical to define its thermal resistances per unit of area ($^{\circ}C/(W/m^2)$) instead of the absolute value ($^{\circ}C/W$). In this way, it is simple and direct to compare different CPV technologies according to their thermal properties.

In CPV, heat exchange is deeply dominated by thermal conduction between the cell and the heat-sink of the module, which in many cases is simply a flat metal or glass sheet which constitutes the rear side of the housing, and by convection and radiation between such heat-sink and the ambient. Consequently, a simple thermal circuit of a CPV module

or systems consists of only on two thermal resistances in steady state condition. This approach is accurate enough to relate the cell temperature to ambient conditions.

Besides cell and ambient temperature, an intermediate temperature called module or heat-sink temperature is commonly defined as the temperature at the rear plate or heat-sink of the module. Unlike cell temperature, module temperature can be directly measured. In the rear plate or heat-sink temperatures are highly non-uniform, so the sensor must be placed in the plate or heat-sink core just behind a cell position, in such a way that the $T_{cell} - T_{module}$ difference is caused only by the vertical temperature drop through the stack of different. Besides, there can be significant differences in the module temperature throughout the cells (Wiesenfarth et al. 2013), so it is convenient to measure in more than one cell and average them.

The two thermal resistances relate these three temperatures: $R_{th\ c_m}$ between cell and module and $R_{th\ m_a}$ between module and ambient, this last being highly dependent on wind (see Figure 5.16).

Figure 5.16 Equivalent thermal circuit of a CPV module or systems at steady state condition.

Summarizing, module temperature provides an intermediate point between cell temperature and ambient, it being strongly related to cell temperature by heat conduction.

Heat power (P_{hea}) to be dissipated is related to DNI . Nevertheless part of the incident irradiance is not transmitted by the lens (see Figure 5.17), accounted by the optical efficiency (η_{opt}) and another part is converted by the cell in electricity (η_{cell}). Consequently heat power is defined as:

$$P_{hea} = DNI \cdot \eta_{opt} \cdot (1 - \eta_{cell}) = DNI \cdot (\eta_{opt} - \eta_{DC}) \quad (5.19)$$

where $\eta_{DC} = \eta_{opt} \cdot \eta_{cell}$ is the DC efficiency of the CPV module and DNI is the incoming irradiance.

Figure 5.17 Power balance in a CPV module; heat power depends on incoming irradiance (DNI), optical efficiency (η_{opt}) and electrical efficiency of the module (η_{DC}) defined as the product of η_{opt} and the cell efficiency (η_{cell}).

The thermal resistances of the CPV thermal model are obtained by dividing the temperature (ΔT) drop by the heat power (P_{hea}) dissipated by the cell.

$$R_{th} = \frac{\Delta T}{DNI \cdot (\eta_{opt} - \eta_{DC})} \quad (5.20)$$

5.8.2.1 Temperature sensors

To measure module temperature, a sensor must be placed preferably without module modification. A few points are advisable to reduce at minimum the influence of the sensor:

- Placed at rear panel or heat-sink core, just behind and as close as possible to the cell.
- More than one sensor is recommended, to obtain a more representative value from the entire module.
- Sensor should be smaller than the cell size (thermocouple, PT100...)
- It should have the minim additional thermal resistance due to the sensor itself, so it is recommended that it is flat side (i.e., lentil shape), attached with thermal glue/paste and fixed with adhesive tape

5.8.3 R_{TH} MODULE-AMBIENT

The thermal resistance between module and ambient ($R_{th\ m_a}$) can be directly obtained through the expression:

$$T_{module} = T_{amb} + P_{hea} \cdot R_{th\ m_a} \quad (5.21)$$

which requires data acquisition of DNI , T_{module} and T_{amb} for a long time, commonly covering several periods at different ambient temperatures and wind speeds. Appropriate data filtering must be applied to reject any thermal transient caused by clouds, rejecting periods of at least 20 minutes subsequent to any DNI deep change.

5.8.3.1 Concentration Nominal Operation Module Temperature (CNOMT)

The Concentrator Nominal Operating Module Temperature is defined as the module temperature at Concentrator Standard Operating Conditions (CSOC, $DNI=900$ W/m², ambient temperature=20 °C, wind speed=2 m/s, spectrum: direct normal AM1.5) as defined in (IEC committee 2013).

If CNOMT is known, module temperature can be obtained from operating ambient conditions by means of the following expression:

$$T_{module} = T_{amb} + \frac{CNOMT - 20}{900} \cdot DNI \quad (5.22)$$

Both expressions (14) and (15) are then equivalent for a given wind condition, in this case 2 m/s, and are related by the formula:

$$\frac{CNOMT - 20}{900} = R_{th_ma} \cdot (\eta_{opt} - \eta_{DC}) \quad (5.23)$$

It is noticeable that the term $(\eta_{op} - \eta_{DC})$ appears in the denominator for the calculus of $R_{th_m_a}$ in Eq. (5.20), so it is cancelled in Eq. (5.23) and does not influence in $CNOMT$. Figure 5.18 shows an example case of a CPV module characterization where regression lines are obtained fixing the slope to 1 and the values of $R_{th_m_a}$ and $CNOMT$ are obtained by Eq. (5.21) or (5.22).

Figure 5.18 Module temperature (Type A – Table 5.7) as a function of ambient temperature and *DNI* as parameter in intervals of $100 \text{ W}\cdot\text{m}^{-2}$ (i.e. $700 \text{ W}\cdot\text{m}^{-2}$ stands for $650\text{--}750 \text{ W}\cdot\text{m}^{-2}$); wind filter: $< 2 \text{ m/s}$; *CNOMT* is obtained for CSOC conditions.

A comparison of the *CNOMT* obtained for three HCPV modules (details in Table 5.7) is shown in Figure 5.19. Tight data filtering has been applied to fulfill CSOC conditions.

SMR_{mid}^{top} has been used to filter the spectrum (Núñez et al. 2016).

Table 5.7 CPV technologies measured and compared.

Type	Concentration	Heat-sink	NOMT
A	820 X	2 mm rear flat plate	55.8 °C
B	820 X	4 mm rear flat plate	50.1 °C
C	1300 X	Aluminum heat-sink	58.2 °C

Figure 5.19 Module versus ambient temperature of three different technologies. (Data filtering: $DNI = 900 \pm 50 \text{ W}\cdot\text{m}^{-2}$, wind $< 2 \text{ m/s}$, $SMR_{mid}^{top} = 1 \pm 0.05$).

5.8.3.2 Wind effect on R_{th} module-ambient

By applying several filters, influence of wind on $R_{th\ m_a}$ can be determined. Wind effect depends not only on speed but also on relative direction to the module normal (Castro et al. 2013) which can increase data dispersion and uncertainty. Nevertheless, with long term characterization it is possible to obtain high correlation between ambient and module temperature as a function of wind speed. Figure 5.20 shows the result for type A technology and Figure 5.21 the evolution of the thermal resistances for the three technologies.

Figure 5.20 Module versus ambient temperature of Type A technology for three wind speeds (data filtering: $DNI = 900 \pm 50 \text{ W} \cdot \text{m}^{-2}$, $SMR_{mid}^{top} = 1 \pm 0.05$). $R_{th\ c,m}$ dependence on wind can be obtained with regression lines and Eq. (5.21).

A simple linear fit can be obtained for low wind speeds ($< 6 \text{ m/s}$):

$$R_{th} = R_{th0} \cdot (1 - a \cdot V_{wind}) \quad (5.24)$$

Figure 5.21 Dependence of the $R_{th\ m_a}$ with wind for three CPV module technologies.

It can be observed that Type A and B technologies, identical except for the thickness of the backplane (2 and 4 mm respectively), have the same wind dependence, while Type C, based on an aluminum heat-sink has a higher slope and thermal improvement with higher wind speeds.

5.8.4 R_{TH} CELL-MODULE

In this section two procedures to obtain the thermal resistance between the cell and the module temperature defined in previous section.

5.8.4.1 Indoors-outdoors V_{oc} comparison

The procedure consists of the comparison of the V_{oc} of a CPV module measured indoors with a solar simulator (as the Helios 3198 (C. Domínguez, Anton, and Sala 2008)) and outdoors at similar incoming irradiances. On the one hand, indoor measurement is done at a known cell temperature $T_{cell(in)}$ since the flash light lasts just few milliseconds and does not heat up the cell. On the other hand, outdoor cell temperature $T_{cell(out)}$ can be determined if β is known (Matthew Muller et al. 2015) by means of the expression:

$$T_{cell(out)} = T_{cell(in)} + \frac{\frac{\Delta V_{oc}}{N_s} + n \cdot V_t \cdot \ln \frac{I_{out}}{I_{in}}}{\beta} \quad (5.25)$$

where ΔV_{oc} stands for the V_{oc} difference between indoors and outdoors measurements, n is the ideality factor, V_t is the thermal voltage, N_s is the number of cells connected in series, β is dV_{oc}/dT , and I_{out} and I_{in} are the respective short circuit currents.

Once outdoors cell temperature is determined, outdoor module temperature $T_{module(out)}$ is also needed to obtain $R_{th\ c_m}$ by means of Eq. (5.20), where $\Delta T = T_{module(out)} - T_{cell(out)}$.

Even though both measurements were carried out at exactly the same irradiance DNI and similar spectral condition (fixed by SMR_{mid}^{top}), most probably short circuit currents will not be equal because of its strong dependence on lens temperature (Steve Askins et al. 2011; Victoria et al. 2013; García, Victoria, and Antón 2016) so the current correction included in Eq. (5.25) would be needed. This lens temperature variation leads to differences in color distribution which can also affect V_{oc} and increase uncertainty.

5.8.4.2 Mesh grid procedure

Using similar translating relationship, the value of the $R_{th\ c_m}$ can be estimated using two identical modules outdoors at V_{oc} condition in a side-by-side comparison. The two modules should be placed in the same tracker, being then under the same ambient conditions, one of them covered by a mesh neutral filter that reduces the irradiance.

Module temperatures and V_{oc} of both modules must be recorded after the initial thermal transient period of 15-20 min caused by the module thermal capacitances and the thermal resistance can be obtained according to:

$$R_{th\ cell_mod} = \frac{\frac{\frac{\Delta V_{oc}}{N_s} + n \cdot V_t \cdot \ln T_{filter}}{\beta} - \Delta T_{module}}{\Delta P} \quad (5.26)$$

where ΔV_{oc} and ΔT_{module} stands for the V_{oc} and module temperature difference respectively between both modules, T_{filter} is the transmission of the mesh filter (50-70% values are recommended) and ΔP is the heat power variation between both modules, i.e., $\Delta P = DNI \cdot (1 - T_{filter}) \cdot \eta_{opt}$ where DNI stands for the incoming irradiance.

5.8.4.3 Concentrator Nominal Operating Cell Temperature (CNOCT)

Similarly to CNOMT, it can be defined the Concentrator Nominal Operating Module Cell (CNOCT), as the cell temperature at CSOC.

The value of CNOCT is related to CNOMT by the $R_{th\ c_m}$, as:

$$CNOCT = CNOMT + 900 \cdot R_{th\ c_m} \cdot (\eta_{opt} - \eta_{DC}) \quad (5.27)$$

5.8.4.4 Results

Both procedures have been applied to Type A modules to determine the thermal resistance between cell and module leading to $0.054\ ^\circ\text{C}\cdot\text{m}^2/\text{W}$ for the indoor-outdoor V_{oc} comparison and $0.051\ ^\circ\text{C}\cdot\text{m}^2/\text{W}$ for the mesh grid procedure. It is remarkable the good agreement between both despite the uncertainty associated to the indoor-outdoor V_{oc} comparison caused by the strong lens temperature variation.

For the same CPV technology, the $CNOCT$ has been obtained using Eq. (5.27), $CNOCT \approx 77\ ^\circ\text{C}$.

5.9 APPENDIX II - CPV MODULE SPICE MODEL VALIDATION

Before any CPV system SPICE modeling, a model of a CPV module should be validated against a real IV curve.¹⁰ Figure 5.22 illustrates the IV curve of a 550X refractive with a secondary CPV module and 25 solar cells in series with the particularity of a non-working solar cell, measured with the CPV module simulator Helios 3198 (C. Domínguez, Anton, and Sala 2008). The exact fitting includes a particular value of series resistance ($0.01\ \Omega$), the I_{sc} of a MJ solar cell (3.7 A) and a value of dispersion in current among the solar cells (3%) responsible for a reduction in module current. Ambient temperature at measurement time was 29.9°C , used as the junction temperature in SPICE and representative of the cell temperature. This is especially important to take into account when simulating real operating conditions.

Figure 5.22 An IV curve of a CPV module of the same technology that has been installed in the plant being studied in this research. It has been measured with a CPV simulator (Helios). Superimposed is the IV curve modeled using SPICE. Note: the module has a cell that is short-circuited, which has also been modeled with SPICE.

The specific details of both IV curves can be found in Table 5.8.

¹⁰ The considered case has been implemented with the software SolCore (Führer, Farrell, and Ekins-Daukes 2013) (based on Syracuse (Ekins-Daukes et al. 2005)) developed at Quantum Photovoltaics group at Imperial College of London. SolCore is a Python-based software for photovoltaics modeling with a SPICE module.

Table 5.8 Electrical parameters of a CPV module of the same technology that has been installed in the plant under study in this research, measured with a CPV simulator and modeled with SPICE-based software.

	V_{oc} [V]	I_{sc} [A]	V_{MP} [V]	I_{MP} [A]	FF [%]	P_{MP} [W]
Measured	77.45	3.73	3.46	66.90	80.12%	231.58
Modeled [SPICE]	77.14	3.76	3.51	65.80	79.63%	231.16

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CHAPTER 6 – STUDY OF A HYBRID CPV MIXED WITH LIGHTING

CONCEPT AND DEVELOPMENT OF A PROOF-OF-CONCEPT

6.1 INTRODUCTION

6.1.1 SOLAR ENERGY IN BUILDINGS

Building (residential and commercial) sector represents about 40% of the global energy consumption, and the electricity demand in this segment is growing more than the rest of the energy-consuming segments (EIA 2015; International Energy Agency. and Organisation for Economic Co-operation and Development. 2013). An important part of this account comes from lighting; moreover, global electrical-based lighting consumed 19% of the total electricity production at 2006 (Waide and Tanishima 2006), and by 2030 is expected that the demand of artificial light will be almost doubled (International Energy Agency. and Organisation for Economic Co-operation and Development. 2013).

It seems necessary a reduction of the energetic impact from buildings as zero-energy building concept claims and already administrations starts to demand (European Union 2010, sec. 153). Solar energy as a resource widely available appears as a great help to achieve the necessary reductions, in forms of electricity (photovoltaics, PV) or light, especially interesting for offices and industry that develop their activity in daylight time.

Some benefits come also with the solar energy. As renewable energy it contributes to reduce the impact of buildings to global warming. Apart from that, it is also relevant to point out the benefits of sunlighting on human beings, starting from its role to synchronize the circadian rhythms (Berson, Dunn, and Takao 2002; Rea et al. 2005) and a generic effect on mood (Veitch et al. 2003) even on surgery recovery (Walch 2005). It has been also

observed improvement in office (Edwards and Torcellini L. 2002) and school (Heschong 2003b) productivity. Even retail sales in shops illuminated with natural light show better performance than with artificial (Heschong 2003a).

Building integration photovoltaics (BIPV) is already a mature PV methodology that is actively generating electricity in buildings where different PV materials and approaches are possible. Concentrator PV (CPV) integrated into buildings (BICPV) is intended to achieve the highest efficiency producing electricity in a building and some examples have been already presented (Baig, Sellami, and Mallick 2015; Baig et al. 2014; Chemisana 2011; Muhammad-Sukki et al. 2014; Mallick et al. 2004). Nevertheless, the inherent requirement of sun tracking of CPV systems at medium and high concentration ratios makes this integration more difficult. In this chapter we will analyze the use of concentrating optics not only for PV generation, but also for lighting in buildings, combining both in a unique system that provides electricity and lighting at the same time.

6.1.2 SUNLIGHT IN BUILDINGS

Sunlighting in wide offices, commercial areas or generically spaces without (or far from) windows requires light transportation. Solar light inside buildings can be achieved by using devices that redirect solar light to all parts of the building during daylight hours with other architectural elements as windows. Light pipes (Al-Marwaei and Carter 2006) transport sunlight by reflection on the walls of a rigid tube so it is practically impossible to conduct the light horizontally without appreciable losses. Light tubes operate at less than or equal to one sun intensity, so the luminous flux per volume of light guide is low, a potential inconvenient especially for building integration.

From the point of view of the simplicity and flexibility, the distribution of solar light inside buildings requires optical guides (where light confinement is achieved by total internal reflection) made of low cost materials to be used with the same simplicity as electrical wires. Actually, the use of optical guides for sunlighting of buildings is already a commercial technology (Himawari 2009; Parans 2011), and different prototypes based on this technology have been proposed (Feuermann, Gordon, and Huleihil 2002b; Sansoni et al. 2008; Tekelioglu and Wood 2009; Liang et al. 1998; Wong and Yang 2012; Ullah and Shin 2014; Sapia 2013; Fraas, Pyle, and Ryason 1983). This involves coupling concentrated sunlight into fibers or other guides made of plastic or glass. However, a long payback time would be required to produce light for indoor illumination because a concentrating and tracking infrastructures are necessary to inject light into optical fibers.

6.1.3 CPV-LIGHTING HYBRID

Hybrid thermal CPV (Segal, Epstein, and Yogev 2004; Rosell et al. 2005; Coventry 2005; Helmers et al. 2011) have been regularly proposed as an interesting way of mixing low-temperature residential heating with cell cooling. However, no suggested approach has actually reached commercial use. This is partially because of the low quality of heat at low temperatures and the extra cost.

The concept presented in this chapter started with the idea that a CPV module designed for electricity production can provide the basic "infrastructure" for injecting concentrated sunlight into the optical guides with small additional cost and with a positive energy conversion balance. This means that both solar cells and optical fibers can receive concentrated sunlight and share the necessary tracker. If an appreciable concentration ratio is achieved, the collection area and the volume for transportation are reduced by almost the same ratio, reducing also the amount of material needed for sunlight transport. This reduction also contributes to ease the integration of the sunlight system in buildings.

6.2 BASIC CONCEPT AND ADVANTAGES

A simple model for a hybrid lighting-CPV module is shown in Figure 6.1. It consists of a bifocal Fresnel lens parquet where part of the overall collector area is used for directing sunlight towards the optical guide, while the remaining area focuses the incoming light onto a solar cell for electrical energy conversion, as in a conventional CPV system. The corners of the CPV Fresnel lens are the least efficient areas of the lens because they need to redirect incoming light over larger angles and have a lower acceptance angle. These edge areas can be better devoted to the illumination system by shaping a new lens that focuses the sunlight on the fiber and constitutes the primary optical stage of the lighting system.

Figure 6.1 Artist's impression of the use of optical fibers in a CPV bi-concentration parquet of lenses.

In Figure 6.2, an ideal quantitative case example is presented, showing the predictable advantage of using the hybrid lighting-CPV system. On the left-hand side, 100 W of solar energy is needed to obtain 2100 lm for illumination, if a 30% efficient multi-junction CPV system for PV electrical generation and a LED lamp are used (assuming a luminous efficacy of 70 lm/W). On the right, we predict that the same 2100 lm can be achieved if we inject only 35% of the direct sunlight (solar efficacy at noon is about 100 lm/W (Littlefair 1985)) into fibers that we assume are 75% efficient, leaving 65 W of solar power that can be converted into 19.5 W for other electrical applications.

Figure 6.2 Comparative schema: classic CPV and Hybrid Lighting-CPV.

Assuming a small additional cost for the Hybrid Lighting-CPV system, we can see that the hybrid concept could obtain an obvious advantage in terms of efficiency conversion over the conventional CPV electricity used for lighting.

6.3 DESIGN OF A PROOF-OF-CONCEPT

To prove the viability of the idea, a proof-of-concept has been developed under the umbrella of a Spanish national project ("*Concentrador Híbrido para Generación Eléctrica Fotovoltaica e Iluminación de Edificios*" (LUZ-CPV-ENE2010-18878). All the experimental actions and prototypes are based in the most accessible materials that can be found in the market and in current designs of commercial CPV modules. The aim is to validate the concept, so the actual selection of optimal materials that make the concept viable at realistic lengths is studied at the end of the chapter. Based on the proof-of-concept, a study of the constraints of design and some parameters of merit will be carried out.

6.3.1 OPTICAL GUIDE MATERIALS

Polymer optical fiber (POF) has been chosen as optical guide of the Lighting-CPV Hybrid proof-of-concept, as an affordable alternative for classical silica fiber optics.¹¹ POF can be obtained by simple extrusion of plastic material, so its cost is relatively low (the ratio of prices between similar silica and POF optical fibers is in the order of 100:1) and presents an alternative for silica optical fiber mainly focused on data transmission by using some specific spectral windows. While the typical values of transmission losses in the visible region for silica fibers are as low as 10 dB/km (99.8%/m expressed as transmittance¹²), POF presents 200 dB/km (95.5%/m). Maximum silica fiber diameters are below one millimeter while POF fibers for lighting are up to 12.6 mm (Cates et al. 2003), especially interesting to minimize light rebounds inside long fibers. POF handling is much simpler and its robustness under bending and stretching is an appreciated advantage in lighting applications.

Among the POF materials some stand out. Polymethyl methacrylate (PMMA, also known as acrylic) is by far the most used polymer in fiber optics (Ziemann et al. 2008). Its refractive index is 1.49 (at 589 nm) and the glass transition temperature is around 100 °C (Bäumer 2005). It is a material easy to polish, and although it presents worse UV¹³ transmission than polycarbonate, it is more transparent in the overall visible range (Ziemann et al. 2008). PMMA transmittance is only slightly better for thin samples, however when long (several meters) optical fibers are considered, the exponential nature of light absorption makes the differences much more evident.

¹¹ When silica (SiO₂) is doped or manipulated can present different properties and then is called glass or quartz.

¹² dB/km is a typical unit in fiber optics of telecommunications. It can be easily converted to transmittance per meter: $\%/m = 10^{\frac{-db/km}{10000}}$

¹³ Nowadays there are modified PMMA and PC optical fibers that make this feature indistinguishable.

Figure 6.3 Spectral transmission of two POF materials: PC and PMMA (thickness: 1.5 mm). Note: measurement includes Fresnel reflection losses.

The best advantage of polycarbonate with respect PMMA is its higher glass transition temperature, around 130 °C and that is a less rigid material (Bäumer 2005). Other materials with minimal market penetration are some elastomers and polyoleofins that can stand up to 200 °C (Ziemann et al. 2008). In POF industry, PMMA is ubiquitous, only few examples of PC can rarely be found and their diameters are usually beyond one millimeter (ESKA 2007).

Also there are some advances on modified polymeric fibers that replace hydrogen atoms present in C-H bonds responsible of attenuation in some spectral bands with deuterium or fluorine (Ziemann et al. 2008). These materials are typically used as cladding¹⁴ because they have a relative low refractive index.

Numerical aperture (*NA*) is a figure of merit for fiber optics or most optical devices and it describes the cone of acceptance angles of the fiber. The value can be derived from the Snell's law and is a direct relationship of core and cladding refractive indexes.

$$NA = \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2} \quad (6.1)$$

NA values in POF are usually larger than in silica fibers, mainly due to the use of modified polymers as cladding, whose low refractive index (1.39) are lower enough to allow a NA up to 0.55 when combined with PMMA cores.

¹⁴ An optical fiber does not require having cladding as an additional material since air, whose refractive index is one, will always allow wide critical angles. However air's density does not protect the core and any other material that touches can provoke light leaking.

6.3.2 BOUNDARIES OF THE HYBRID APPROACH

First, we will focus on the practical design limits of the illumination system. The optical limitations of lenses and fibers, as well as the thermal and transmission properties of materials involved will impose limits on the hybrid operation.

6.3.2.1 Maximum optical concentration

The optical design of the illumination system has an additional constraint compared to CPV optical systems: the limited numerical aperture imposed by the fibers (Antón et al. 2007). The higher the concentration ratio desired, the wider the cone of rays entering the fiber. However, the fiber will only transmit the rays within its NA , which can be also defined as:

$$NA = n \cdot \sin \theta_{inc,max} \quad (6.2)$$

where n is the index of refraction, in this case $n=1$ for air, and $\theta_{inc,max}$ is the maximum incidence angle for which a ray is transmitted to the fiber exit.

The concentration ratio is defined as the ratio between the entrance aperture area of the primary lens and the entrance area of the fiber. The limited NA imposed by the fiber leads to a maximum concentration ratio. Matching the NA of the fibers (determined by $\theta_{inc,max}$) to the NA of the concentrated beam (determined by the angle setting the exit cone from the concentrator θ_{lens}), the above-mentioned concentration limit can be deduced:

$$C_{max} = \left(\frac{n \cdot \sin \theta_{inc,max}}{\sin \theta_{sun}} \right)^2 = \frac{NA^2}{\sin^2 \theta_{sun}} \quad (6.3)$$

where θ_{sun} does not stand for the sun disk ($\pm 0.275^\circ$) but for an extended source (greater than the real sun disk, i.e., $\pm 1^\circ$) to provide some angular tolerance in the system.

Considering a typical value of $NA=0.55$ for PMMA fibers, Eq. (6.3) yields a C_{max} of 993X. However, this figure must be reduced for practical concentrators owing to the effects described below.

6.3.2.2 Limitations due to fiber transmission losses and concentrating optics

Here, we only consider multimode fibers that have sufficient thickness to be analyzed by geometric optics (Zubia and Arrue 2001). Although the NA of the fiber defines the maximum incidence angle, the bulk absorption at the core and light leakages caused by the absorption at the cladding at every total internal reflection (TIR) (Feuermann, Gordon, and

Huleihil 2002a) reduce considerably the practical value of the NA for limiting the power losses. In order to minimize the impact of these two sources of losses, absorption and TIR, only a small portion of the NA of the fibers must be used.

Figure 6.4 shows the angular transmission function of a particular PMMA fiber with $NA=0.55$. The theoretical basis and concrete details used to obtain the transmission function vs. incidence angle can be reviewed in the Appendix I. This example case shows that while the angle of incidence is kept below 15° (equivalent to $NA=0.26$), the transmission function is very flat and close to the maximum, but beyond that angle, the power losses become very significant. This means that although the NA of the fiber is 0.55, the NA of the concentrated beam should be limited to 0.26 for a good power transmission.

Figure 6.4 Angular transmission function for a fiber 2 m long and 3 mm in diameter ($\alpha_{core}=3.5 \times 10^{-5} \text{ m}^{-1}$ and $k_{cladding} = 1 \times 10^{-5}$).

The angular transmission function represents the power loss in the fiber for a single ray, and must be integrated to compute the total losses for all of the rays in a light cone produced by a lens with a given f -number ($f\#$). Since the rays entering the lens are nearly perpendicular, we can assume that the rays inside the cone generated by the lens are all meridian rays. The fiber transmission as a function of the f -number ($T_{\text{fiber_cone}}$) of the primary lens is given then by Eq. (6.5), where the f -number corresponds to a particular incidence angle of the light cone (Eq. (6.4)):

$$f\# = \frac{1}{2 \cdot \tan \theta_{inc,max}} \quad (6.4)$$

$$T_{\text{fiber,cone}}(f\#) = \int_0^{f\#} T_{\text{fiber}}(\theta_{inc}) d\theta_{inc} \quad (6.5)$$

The resulting fiber transmittance versus f -number is shown in Figure 6.5 for the fiber with $NA = 0.55$. Before any further analysis, we can conclude that the higher the f -number is, the lower the power transmission losses are in the fiber.

Figure 6.5 Transmission function vs. f -number for a fiber 2 m long and 3 mm in diameter of $NA = 0.5$ ($\alpha_{core} = 3.5 \times 10^{-5} \text{ m}^{-1}$ and $k_{cladding} = 1 \times 10^{-5}$).

On the other hand, another source of losses to be considered is chromatic aberration caused by the primary lens. The larger the focal distance is, the higher the spatial effect of chromatic aberration at the focus is, which reduces the effective concentration and acceptance angle as detailed below. Since both optical systems are sharing the same structure (at most they can have the same focal length) the f -number of the lighting part ($f\#_{lighting}$) is related to the f -number of the CPV part ($f\#_{CPV}$):

$$f\#_{lighting} = \sqrt{\frac{1 - \frac{\%_{fiber}}{100}}{\frac{\%_{fiber}}{100}}} \cdot f\#_{CPV} \quad (6.6)$$

where $\%_{fiber}$ represents the percentage of the collector area dedicated to the illumination system based on optical fibers.

Consequently, if the lighting entrance area is lower than the entrance CPV area, the f -number of the lighting system can be larger than the f -number of the CPV primary optics. That means that considering typical CPV f -numbers in the range 1.3–2 and a collecting area percentage of 35% for the illumination part, a maximum f -number ranging between 1.8 and 2.7 is obtained for the lens of the illumination system.

6.3.2.3 Combined optical efficiency of the lighting concentrator system

Because of the chromatic aberration associated to the lens, an increase in the f -number leads to an enlargement of the spot size and consequently to a decrease of the effective

concentration ratio and acceptance angle. For a given concentration ratio, this effect leads to a decrease of the optical efficiency of the lighting lens for longer focal distance because some rays do not enter the fiber.

Assuming an optical design with an acceptance angle of 1° , and taking into account the refractive index variation between 400 nm and 750 nm (visible spectrum) of the primary PMMA lenses, we have analyzed the optical efficiency as a function of the f -number, calculated with a ray-tracing simulation using a Monte Carlo approach. The results of this simulation are shown in Figure 6.6 with the curve labeled “Lens efficiency.”

If we combine these effects on the total optical efficiency of the system due to the fibers and the lenses we can obtain the global performance of the lighting concentrator part as a function of the f -number. This is shown as the red curve in Figure 6.6.

Figure 6.6 Global transmission efficiency, obtained as a product of the fiber and optical efficiencies, versus f -number for a fiber of $NA = 0.55$ (PMMA fiber of length 2 m and diameter 3 mm, $\alpha_{core} = 3.5 \times 10^{-5} \text{ m}^{-1}$, and $k_{cladding} = 1 \times 10^{-5}$).

Therefore, for the example case of fibers of $NA = 0.55$ and PMMA lenses, the optimum f -number, for lengths between 2 and 15 meters, ranges between 2 and 4. These values are practicable for adapting the lighting optics in a CPV module.

6.3.2.4 Limits of concentration level imposed by the fiber and primary lens material

Lens transmittance is relevant not only in the visible range, which affects the luminous flux of the illumination system, but also in the ultraviolet and infrared regions because these ranges are significantly absorbed by the PMMA fiber, contributing to temperature increases. Therefore, the maximum concentration achievable is also limited by the amount

of non-lighting radiation entering the fiber. Additionally, UV affects the reliability of the fiber, especially that of the cladding (Appajaiah, Kretzschmar, and Daum 2007).

Another point to be considered is that PMMA primary lenses can potentially filter more UV and IR than a silicon on glass (SoG) parafocal lenses. However, a reduction of UV and IR radiation decreases the efficiency of the CPV part, and this effect is even greater if multijunction (MJ) cells are used. For that reason, an ideal hybrid system should filter the UV and IR only on the part of the parafocal that focuses into the optical fiber.

In the next section the maximum achievable concentration ratios will be experimentally determined.

6.4 EXPERIMENTAL CHARACTERIZATION OF PMMA FIBERS

This section describes the experiments carried out to determine the operating limits and transmission efficiency of plastic fibers. In accordance with the theoretical studies and simulations described above, the experiments have been conducted with several PMMA fibers of 2 and 3 mm diameter and high NA . The main characteristics of the measured fibers are $n_{\text{core}}=1.49$ and $n_{\text{cladding}}=1.39$, so NA is 0.575.

In order to characterize the fiber absorption, it is necessary to measure the core and cladding absorption parameters. All the measurements have been completed with collimated light coming from the Helios CPV simulator (Domínguez, Anton, and Sala 2008) and a photopic sensor that provides a response equivalent to that of the human eye to the light coming from the optical fiber to be measured. The sensor consists of a solar cell with a photopic filter that integrates the luminous efficacy function (see Figure 6.7).

Figure 6.7 Sensor based on a solar cell to measure light transmission of optical fibers, including a photopic filter.

To determine the absorption of the core, the spectral transmittance has been measured for fibers of two different lengths and of the same diameter. By using differential measurements, both spectral and absolute transmission values can be determined. The fiber shows an almost constant transmission value in the visible region of 96% per meter.

Then the core absorption coefficient is deduced to be $\alpha_{\text{core}} = -\ln(0.96) = 0.0408 \text{ m}^{-1}$. Some other measured PMMA fibers with less luminosity have shown lower transmission (80%/m).

To characterize the fiber behavior to rebounds of light inside, the fiber's tip is placed in a goniometer, as shown in Figure 6.8. As a result, we can infer the cladding's extinction coefficient (k_{cladding}).

Figure 6.8 Experimental setup used to characterize the cladding's extinction coefficient of an optical fiber.

The angular transmission function of the fiber compared to the theoretical one is shown in Figure 6.9. From these results, the cladding losses and consequently the effective extinction coefficient of the cladding can be deduced by fitting experimental measurements with the theoretical curve. The values of k_{cladding} obtained from the measured optical fibers are around 1×10^{-4} ; the best value is 0.9×10^{-4} , and the worst is 3×10^{-4} .

Figure 6.9 Angular transmission function experimentally obtained for a plastic fiber of $NA = 0.55$ ($\alpha_{core} = 3 \times 10^{-2} \text{ m}^{-1}$ and $k_{cladding} = 1 \times 10^{-4}$).

6.4.1 TRANSMISSION LOSSES VS. F-NUMBER

Using the solar-cell-based sensor, we measured the overall power transmission of the lighting system (including both the optics and the fiber) in real sunlight, with several lenses of the same diameter but different f -numbers.

The results of this experiment are shown in Figure 6.10. The measured values show good agreement with the shape of the theoretical curve. As discussed earlier, for low f -numbers, the efficiency losses are caused by both the fiber losses and Fresnel losses in the lens, while for high f -numbers, the decrease is caused by the optical characteristics of the lens, specifically, because the chromatic aberration enlarges the spot size and reduces the interception factor.

Figure 6.10 Theoretical and measured efficiency of the lighting subsystem (PMMA fiber of length 2 m and diameter 3 mm)

Longer fibers will slightly shift the maximum peak to higher f -numbers due to the longer optical path of light inside the fiber and the higher number of reflections (see the Appendix I for details of the transmission of a light ray inside an optical fiber).

6.4.2 MAXIMUM CONCENTRATION VS. FIBER TEMPERATURE

The temperature reached by the fiber is affected by the absorption of concentrated light by the core and cladding. Since PMMA softens around 85 °C, in order to be conservative, we impose a maximum operational temperature of 65 °C in exceptionally high ambient temperature and solar irradiation conditions.

The temperature increase at the entrance of the fiber, which is the hottest and most critical point, has been experimentally measured as a function of the concentration level by means of a SoG Fresnel lens capable of concentrating up to 200 suns at the entrance of the fiber and a diaphragm to vary the aperture area of the lens. A thermographic camera, whose emissivity was previously experimentally trimmed, was used to determine the temperature at the entrance of the fiber. Figure 6.11 shows the results of this experiment.

Figure 6.11 Measured fiber temperature as a function of the concentration ratio.

With the temperature limit of 65 °C, the maximum concentration attainable on the fiber without any spectral filtering is 100X. Filtering the IR with a hot mirror, the maximum value increases to 150X, which is still attainable without any secondary optical element for the lighting system. It should be noted that, in the hybrid system, the concentration ratio of the electricity-generating part of the system would be much higher.

6.5 LIGHT TRANSMISSION THROUGH OPTICAL FIBERS

6.5.1 LIGHT ATTENUATION IN OPTICAL FIBERS

Light transport using optical fibers is mainly constrained by the optical path that sunlight has to pass while goes trough. This is influenced by the material and dimensions of the

optical fibers and by the angle of the cone of light imposed by the lenses (Núñez, Antón, and Sala 2013).

The effect on transmittance of the diameter and the length of optical fibers and the f-number that characterizes the lenses considering the model proposed in Appendix I can be seen in Figure 6.12, considering PMMA as the material of optical fibers. We can see that the sensitivity to diameter is relatively low especially at short distances while increasing the length reduces notably the fiber transmittance. This means that light transmission is going to be mainly influenced by the length of the fibers, which should be kept as short as possible. Nevertheless, fiber lengths below 10 meter are difficult to meet in a building, even though light transport should be conducted mostly vertically.

Figure 6.12 Simulation of the fiber transmittance versus the f-number of the lens that injects solar light onto the optical fiber. (left) Changing the diameter of the optical fiber and (right) changing the length of the optical fiber.

6.5.2 SPECTRAL ISSUES - QUALITY OF LIGHT

Another important question to consider is the variation of the spectrum of the transmitted light by the lighting subpart.

On the one hand solar spectrum varies mainly due to solar altitude changing along the day; consequently the tone of sunlight also changes. On the other hand, PMMA transmittance is not completely flat in the visible range (see Figure 6.13), so an extra spectral shift due to the optical fiber transmittance is expected.

Figure 6.13 Fiber transmittance versus light wavelength at different lengths. The photopic response of human eye is also presented to stress the weight of different colors in human vision.

While the absorption peak at 623 nm due to a C-H bond is not a considerable issue at short distances, when considering practical length of fibers starts to be noticeable. For example, if we consider the spectral transmittance of 10 m (Figure 6.13) a significant reduction of the transmitted luminous flux is not expected (the maximum of photopic curve is in 555 nm while at 623 nm the photopic response is low) but it could appear a color rendering issue, concretely at orange colors.

6.6 PROTOTYPE DESCRIPTION

In order to prove the hybrid lighting-CPV idea, a prototype based on a commercial CPV module has been developed. This module is composed of a two stage optical system working at 476X, consisting of a based in SoG primary lens, and an dielectric totally internal reflecting concentrator made of glass as secondary optics, which focuses light on three junctions (3J) lattice matched (LM) GaInP – InGaAs – Ge solar cells.

Two main adaptations were necessary to convert the CPV module into a hybrid one. The main change is the parquet of lenses that needs to be bifocal, so sunlight can be focused into solar cells and optical fibers. The other variation is to adapt the host module to allow the entrance and positioning of the fibers.

Optical fibers were made of PMMA at core and a fluorinated polymer at cladding with a 3 mm diameter and 17 m long to cover the distance from a solar tracker installed in the rooftop of the IES building to one of the laboratories of the second floor. Both ends have been treated with sandpaper and polishing spray to allow the best optical coupling.

6.6.1 PARQUET OF LENSES

The hybrid parquet has been manufactured with SoG lenses, including the lighting optics properly designed to the constraints imposed by the optical fibers.

The new parquet of lenses keeps the main structure of the original one but using part of the area to host another set of lenses that inject sunlight on the optical fibers. The CPV individual lenses have just been reduced on the corners, keeping the original design, 120x120 mm² (except 5.3% given to lighting) and 200 mm of focal length.

Figure 6.14 Bifocal parquet of lenses. Similar to classical CPV parquets (where CPV lenses are emphasized in green), includes another set of lenses in the lenses corners to inject light to optical fibers (highlighted in red).

The lighting lenses have an area of 35x35 mm² and a focal length of 115 mm, injecting the maximum power that allows the material of the optical fibers (PMMA). The final design is a trade-off between spot size and a reduced cone of light, to avoid the minimum absorption inside the fiber due to reflections (Núñez, Antón, and Sala 2013); the Fresnel lens has been optimized following a nonimaging design (Leutz and Suzuki 2001). Figure 6.14 shows a picture of the hybrid parquet, highlighting both kinds of lenses.

It should be noticed that the original CPV design and the material of optical fibers act as constraints to have a higher percentage of area of parquet dedicated to lighting as is proposed in the description of the concept. Nevertheless, the proposed prototype is a full suitable one, and validates the concept.

6.6.2 OPTICAL FIBERS PLACEMENT

Since CPV and lighting lenses have different focal lengths a metallic grid has been placed in the middle of the module in order to place the optical fibers in the proper position (Figure 6.15).

Figure 6.15 Optical fiber holder sited inside the Hybrid module to place fibers in the proper position and focal length.

The rear plate of the module has been adapted and pipe glands were placed to pass the fibers through corrugated tubes, as shown in Figure 6.16.

Figure 6.16 Rear view of the Hybrid module, showing the exit of optical fibers from the CPV receiver.

6.6.3 BACK-UP LAMP

To balance the inherent discontinuity of solar energy, an additional back-up LED lamp can be installed with a light sensor that works in a feedback loop, so when clouds cover sunlight, the electrical lamp keeps lighting. Moreover, the lighting part of the hybrid system can be considered as a saving on an electrical lamp that works every time sunlight is available.

6.6.4 PROTOTYPE RESULTS

6.6.4.1 Electrical results

The original CPV module is composed of 24 cells in series. The short-circuit current (I_{sc}) is 1.5 A and the open-circuit-voltage (V_{oc}) 70.4 V, having therefore a maximum power point (P_{MP}) of 84.5 W at Concentrator Standard Operation Conditions (CSOC, $DNI=900 \text{ W}\cdot\text{m}^{-2}$, $T_{amb}=20 \text{ }^{\circ}\text{C}$ and spectrum similar to AM1.5D-G173-03 (IEC committee 2013)). Considering the active area useful for CPV and the power at CSOC, the hybrid module achieves an efficiency of 28.7%.

As it was previously commented, a fraction of the total area of the parquet of lenses is used to concentrate light onto the fibers. The CPV lenses area reduction will be reflected in less solar power received by the solar cells, mainly a reduction on the module photocurrent. It should be noticed again that the lighting lenses are placed at the corners of the CPV lenses, the least efficient areas of the lenses. While lighting lenses suppose a reduction of 5.3% of the module active area, the current compared to an original module is 4.8% inferior.

6.6.4.2 Lighting results

At the end of fibers we get 467 lumens, normalized to the same conditions of electrical part (CSOC) for this specific configuration. The angle of the light emitted by the optical fibers is $\pm 14^{\circ}$, fixed by the *f-number* of the optical fiber lens if the angle at the end of the fiber is assumed to be the same than the entrance. On the other hand, due to the small diameter of the fibers and the high throughput, the luminance is about 10^8 cd/m^2 , causing glare. Therefore, a diffuser covering the optical fibers is necessary.

The color mix of the light is influenced by the solar spectrum, which basically depends on the sun position (time and date), and on the length of the fiber. This can be seen in a chromaticity diagram (as in Figure 6.17, more explanation can be found in Appendix II), where the different colors are easily plotted. In addition to the simulated spectra at different lengths of optical fibers and hours of the day, some standard illuminants have been added for comparison: D65 (represents average daylight), A (represents incandescent bulb), F2 (represents standard cool white fluorescent lamp) and F11 (represents narrow tri-band fluorescent lamp).

Correlated Color Temperature (*CCT*) is the appropriate parameter to quantify the different white hue. This parameter measures the equivalent temperature of a black-body radiator of a light source of comparable hue. The *CCT* of sunlight at noon is about 6000 K (reduced when considering only direct solar irradiance, as seen by a concentrator), while at sunrise or sunset this value is reduced quickly, meaning a more reddish white light. PMMA optical

fiber with non-homogenous light transmittance shifts gradually the *CCT* to higher values due to its absorption peak at 623 nm as can be seen in Table 6.1 and Figure 6.17. The *CCT* of the prototype for midday in a summer day is 6832 K.

A similar conclusion can be obtained for Color Rendering Index (*CRI*) that gives an idea about how well a light source renders colors. In Table 6.1 it can be seen a reduction of *CRI* related to the length of the optical fibers, however up to 15-20 meters, *CRI* is comparable to F2 lamps that render 81%. The *CRI* of the prototype for midday in a summer day is 79.5%.

Table 6.1 Correlated Color Temperature (*CCT*) and Color Rendering Index (*CRI*) for sunlight after being transported by PMMA optical fibers of different lengths according to model of Appendix I.

Time	0 meters		10 meters		20 meters	
	<i>CCT</i>	<i>CRI</i>	<i>CCT</i>	<i>CRI</i>	<i>CCT</i>	<i>CRI</i>
07 h (Sunrise+2h)	5052 K	97.8%	6060 K	85.6%	6726 K	75.8%
12 h (Midday)	5639 K	97.8%	6759 K	84.9%	7497 K	74.9%
17 h (Sunset-2h)	5236 K	97.9%	6278 K	85.3%	6966 K	75.5%

Figure 6.17 CIE 1931 color space Chromaticity diagram. Several standard illuminants are represented. Additionally simulated solar spectra of a summer day in Madrid are also plotted from sunrise to sunset together with the spectra after 1 to 20 meters of PMMA optical fiber at every hour. Office hours (solar time, 07h-17h) are zoomed, showing that color shift of direct sunlight and after passing through optical fibers is comparable to other illuminants.

6.7 FEASIBILITY OF HYBRID SYSTEMS BASED ON OPTICAL GUIDE MATERIALS

We have seen several constraints that are imposed by design and by the material used as light guide. In any case, the most critical factor to analyze in a hybrid system based in

optical fibers for lighting is the maximum length of fibers that would provide the same amount of lumens that the equivalent CPV system plus electrical luminary (LED), i.e. the example shown in Figure 6.2 but considering a only-lighting system ($\%_{fiber}=100\%$). Under this assumption the optical guide should be at least 26% efficient transporting lumens, as it is shown in Figure 6.18. Consequently considering as light guide the PMMA fiber show in the Section 6.2, the 2100 lm would be reached around 20 meters. Other plastic materials that could be envisioned (although with very limited availability in the market) that can stand higher temperatures as seen in Section 6.3.1 could double the final concentration but not the length since their optical transmittance are similar at best.

Figure 6.18 Comparative schema: classic CPV and only lighting fiber optics based. This case represents $\%_{fiber}=100\%$ and it represents the minimum amount of transmission losses that compares to CPV plus LED lamp.

Consequently 20 meters actually limit the scope of the PMMA-based (or plastic) hybrid system, a length that the increasing efficiency of both CPV system and LEDs are predating more and more , reducing the feasibility of plastic-based solutions.

If silica fibers are consider (ignoring technological limitations as tiny diameters, manipulability and cost) much longer lengths are expected. Around 100 m can be achieved considering a typical silica optical fiber with large diameter (0.5 mm), transmission losses of 10 dB/km and a cladding made of silica (plastic claddings will also limit the maximum concentration as in all-plastic fibers).

Also silica higher transition temperatures (above 1000 °C) allow increasing notably the throughput of lumens per fiber by increasing the concentration ratio. Consequently the cost of the delivered lumen is proportionally reduced, although a higher concentration will decrease the effective f-number and therefore the total transmissivity.

Regarding the quality of the white light, if we consider 100 m of silica optical fiber and the same summer day seen before, a very high level of *CRI* (97%) is still maintained and a *CCT* of 4926 K, a value very close to natural sunlight. This is due to the flat transmittance of silica in the visible range.

6.8 CONCLUSIONS

We have proposed a hybrid CPV module that simultaneously produces electricity and injects concentrated light into optical guides for lighting and as an active building integration solution that generates electricity and transports sunlight. It has been verified that the CPV module and the fiber optics for collection and distribution of visible light are compatible. The main advantage of this proposal is that both concepts (CPV and lighting) need an infrastructure to concentrate light and to aim to the sun. Sharing these needs, they both benefit when they are integrated in the same module, reducing costs.

The transmission efficiency versus the incidence angle has been studied as a function of the absorption coefficient of the core and the extinction coefficient of the cladding in order to understand the losses in fibers for concentrated light. It can be concluded that the higher the *f-number* of the light cone feeding the fiber is, the lower the losses are. However, this value is also limited by the optical efficiency of the lens versus the *f-number* and the compactness of the receptor. The optimal *f-number* ranges between 2 and 4.

PMMA optical fibers have been chosen for the proof-of-concept, which have been characterized experimentally. It has been concluded that the maximum concentration level is limited by the PMMA softening temperature to 100X, although higher concentrations are possible with UV and IR filtering. Based on these fibers, a full hybrid system has been completed.

Nevertheless the transmissivity of PMMA clearly limits the feasibility of a hybrid system based in plastic materials to less than 20 m and only silica optical fibers based systems can compete with a CPV+LED solution, achieving lengths around a hundred meters.

The main conclusion about quality of light for optical fibers is that they shift sunlight to bluish white tones; for example, PMMA fibers from 0 to 20 meters the *CCT* increases about 1500 K, while silica fibers reduces the *CCT*. Another relevant conclusion is that the *CRI* for the PMMA example reduces about 20 percentage points, however it is still comparable to a typical fluorescent lamp used in offices (*CRI*=80%) and the silica can preserve up to 87% of *CRI* after 100 m.

6.9 APPENDIX I - TRANSMITTANCE OF LIGHT IN AN OPTICAL FIBER

The light entering into a fiber is refracted according to Snell's law. The angle of incidence (θ_{inc}) of the most tilted ray of light that can enter an optical fiber is limited by the NA according to Eq. (6.2); therefore, the angle of the ray of light inside the core of the fiber (θ_{core}) is given by:

$$\theta_{core} = \sin^{-1} \left(\frac{n_{air}}{n_{core}} \sin \theta_{inc} \right) \quad (6.7)$$

For a fiber of length (L) and core diameter (d), as described in Figure 6.9, the number of reflections (N_{ref}) depends on the angle of the light ray in the core as shown in Eq. (6.8):

$$N_{ref}(\theta_{core}) = \frac{L}{d} \tan \theta_{core} \quad (6.8)$$

The total path (L_{opt}) covered by this ray is given by Eq. (6.9):

$$L_{opt}(\theta_{core}) = \frac{L}{\cos \theta_{core}} \quad (6.9)$$

Figure 6.19 Schematic showing the parameters of an optical fiber and a lens injecting light on it.

The losses at the core-cladding interface can be calculated by applying the Fresnel equations and using the complex refractive index of the cladding ($\tilde{n}_{cladding} = n + jk$), the imaginary part of which accounts for absorption losses. The extinction coefficient (k) represents the damping factor of the electromagnetic wave, so it is related to the absorption coefficient of the cladding ($\alpha_{cladding}$) as shown in Eq. (6.10).

$$k_{cladding} = \alpha_{cladding} \cdot \frac{\lambda}{4\pi} \quad (6.10)$$

η_{TIR} is defined as the effective reflectivity of the total internal reflection (TIR) at the core-cladding interface (Tekelioglu and Wood 2005) for each ray angle inside the fiber. For n and

k , we are assuming a constant value in the visible range, which is realistic for this approach.

$$R_{\perp} = \left[\frac{\cos \theta_{reb} - \sqrt{n_{rel}^2 - \sin^2 \theta_{reb}}}{\cos \theta_{reb} + \sqrt{n_{rel}^2 - \sin^2 \theta_{reb}}} \right]^2 \quad (6.11)$$

$$R_{\parallel} = \left[\frac{-n_{rel}^2 \cos \theta_{reb} + \sqrt{n_{rel}^2 - \sin^2 \theta_{reb}}}{n_{rel}^2 \cos \theta_{reb} + \sqrt{n_{rel}^2 - \sin^2 \theta_{reb}}} \right]^2 \quad (6.12)$$

$$\eta_{TIR}(\theta_{reb}) = \frac{|R_{\perp}| + |R_{\parallel}|}{2} \quad (6.13)$$

where $n_{rel} = \frac{\tilde{n}_{cladding}}{n_{core}}$; $\theta_{reb} = 90^\circ - \theta_{core}$.

So, finally, the transmittance for a given incidence angle of a ray entering the fiber is expressed as:

$$\mathcal{T}_{fiber}(\theta_{core}) = e^{-\alpha_{core} \cdot L_{opt}} \cdot \eta_{TIR}^{N_{ref}} \quad (6.14)$$

where α_{core} is the absorption coefficient of the core per unit of fiber length (it can be considered constant in the visible range with an error less than 2% for PMMA fibers with lengths up to 10 meters). We note that there are two clear components of the transmission expression: the first accounts for the losses in the core, and the second accounts for the losses in the cladding.

6.10 APPENDIX II - COLORIMETRY TERMS

Colorimetry knowledge and terminology is wide and complex. Below there is a concise collection of concepts and algorithms used to describe and to obtain useful figures of merit. For further detail, some specialized references (Commission Internationale de L'Eclairage 2011) are a good starting point.

6.10.1 CIE XY CHROMATICITY DIAGRAM

The standard from the *Commission internationale de l'éclairage* (CIE) colorimetric observer represents an average human's chromatic response and they are numerically represented by its color matching functions. They can be understood as the spectral response of human eyes' photoreceptors. In concrete they were chosen as a more practical adaptation of the responsivities of the three types of cone cells in eyes: long, medium and short. In this case we are representing the CIE 1931 2° Standard Observer, the most widely used and base for newer standards.

Figure 6.20 CIE 1931 2° Standard Observer color matching functions.

The spectral power distribution of a light source ($SPD_{ls}(\lambda)$) can be transformed into chromaticity coordinates (X, Y, Z) associated to a standard observer (the standard for human vision).

$$X = \int_{380}^{780} SPD_{ls}(\lambda) \cdot \bar{x}(\lambda) d\lambda \quad (6.15)$$

$$Y = \int_{380}^{780} SPD_{ls}(\lambda) \cdot \bar{y}(\lambda) d\lambda \quad (6.16)$$

$$Z = \int_{380}^{780} SPD_{ls}(\lambda) \cdot \bar{z}(\lambda) d\lambda \quad (6.17)$$

Therefore we can obtain a tuple (x, y) that represent its chromaticity (with normalized luminance).

$$x = \frac{X}{X + Y + Z} \quad y = \frac{Y}{X + Y + Z} \quad (6.18)$$

These pair of values define the CIE xyY color space and its graphical representation can be seen in a chromaticity diagram, as in Figure 6.21. In this representation we can see only the chromaticity of the visual stimulus and to ignore its brightness (luminance).

Figure 6.21 CIE 1931 xyY color space chromaticity diagram.

6.10.2 CIE 1960 COLOR SPACE

Also known as the (u, v) chromaticity space, it presents a more uniform color space than CIE xy . It can be derived as a direct translation from xy coordinates (Macadam 1937):

$$u = \frac{4x}{12y - 2x + 3} \quad v = \frac{6y}{12y - 2x + 3} \quad (6.19)$$

6.10.3 ESTIMATION OF CCT

The correlated color temperature (CCT) is the temperature of the Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution on u, v coordinates. It therefore gives an idea about the hue of the light source meaning that higher values represent bluish lights and lower ones represent reddish lights.

An approach to obtain the CCT is given in (Robertson 1968).

6.10.4 ESTIMATION OF CRI

The color rendering index is a “measure of the degree to which the psychophysical color of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation” (Commission Internationale de L’Eclairage 2011). A perfect score will be when all the colors are perfectly rendered and that would be the case of a pure white-light source.

An implementation of the algorithm used in this thesis is presented in (Geisler-Moroder and Dür 2009).

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CHAPTER 7 – CONCLUSIONS

7.1 SUMMARY OF CONCLUSIONS

SMR indexes for identification of spectral prevailing conditions

A set of component cells has been presented as a simple and effective instrument to quantify the spectral variation of the DNI and its influence on MJ solar cells and CPV systems. They can be used together with collimating tubes to compose an instrument (spectroheliometer) that provides experimental data to obtain the spectral matching ratios (SMRs), a set of spectral indexes that quantifies any particular spectra by comparing it to a reference spectrum.

The main use of these SMR indexes is filtering of operating conditions, providing a simple way to determine prevailing spectral conditions by keeping SMR values around one. This approach has proved a significant reduction in the dispersion of the rated current of CPV cells, modules and systems based on MJ cells. The study of the site of Madrid has revealed the probability of the occurrence of the prevailing spectral conditions according the range of the SMR filters for several MJ solar cell technologies, which is one of the open questions in the CPV community.

Biases during spectral calibration

A detailed study about spectral calibration of MJ solar cells has shown several sources of bias: the use of a SMR=1 tolerance not narrow enough; the non-symmetry of the data and the spectral mismatch between the cell and the component cells. Nevertheless it has been shown that the real impact on the calibration value is dependent on the spectral sensitivity of the MJ solar cell under calibration.

Spectral calibration of CPV systems

In the case of CPV systems, ranges of $\pm 1\%$ for the SMR filters showed dispersion values of the rated current at the maximum power point as low as $\pm 0.2\%$ for a 15 kWp CPV array during a rating period of two clear-sky days, while simple clear sky condition of DNI higher than $700 \text{ W}\cdot\text{m}^{-2}$ led to dispersion values as high as $\pm 7\%$. Higher ranges of SMRs $\pm 2.5\%$ showed also very good results ($\pm 0.6\%$), with the clear advantage of a much higher probability of occurrence, but it should be accompanied of further conditions to avoid possible bias errors during the spectral calibration.

Worldwide spectral classification based on SMRs

SMR indexes have been used to characterize the solar resource at a specific site through their annual DNI-weighted average values related to a MJ solar cell technology. This provides the spectral information that gives most of the necessary information for optimizing the spectral response of a CPV module (whose response at a reference site is known) for a new location. This may be carried out by tuning the current ratio of the receiver multi-junction cells by a factor corresponding to the difference in SMR between the known site and the new site or considering external factors as optics. In addition, the estimation of the spectral losses due to current mismatch is obtained through the integrated value of the spectral efficiency in a year. As a general remark, the further are the SMR coordinates from reference spectrum, the larger are the spectral losses.

Relationships between SMR indexes and atmospheric parameters

Later the relationships between SMR indexes and atmosphere parameters, mainly AM, AOD, and PW have been determined not only for instantaneous values, but also for annual DNI-weighted averages, which allows the prediction of the SMR indexes if some geographic and atmosphere parameters of a site are known. The capability of the AERONET network to provide such needed parameters has been exploited in this study, selecting 34 worldwide sites with the best data quality and covering many different climate conditions.

Spectral classification based on several MJ technologies

Finally, the site characterization by means of SMR indexes has been extended to several triple-junction technologies, covering lattice-matched cells based on germanium and dilute nitrides and both inverted and upright metamorphic cells. The comparative analysis shows large differences in the performance of the devices between the selected locations, while the differences among the technologies were much less significant. Impact of solar cells temperature has been shown to be negligible in this analysis.

Spectral uniqueness of solar spectra

A PC analysis about solar spectrum uniqueness has shown that with just three independent parameters more than 99% of the variability is explained. In terms of goodness of fitting, the main three PC eigenvectors can recover spectra with a $\overline{nRMSE}$ lower than 1.7% for most of the annual datasets representative of several locations with very different spectral conditions.

It is concluded that a single spectral index is clearly insufficient to establish spectral uniqueness and that three independent indexes are close to the biunivocal spectral identification. Following the pervious result, a possibility for SMRs as spectral indexes is deepened and based on this idea the use of SMR to establish correlations among different MJ cell technologies and other devices is suggested.

SMRs as spectral indexes valid for spectral uniqueness

SMR values of a technology were simulated by a reference set of component cells with a substantial reduction of the CV_RMSE compared with the direct use of the SMR values of the reference technology for annual spectral datasets. The reduction is especially notable for technologies whose QEs are more different with respect the reference, with cases with a reduction from 3.22% to 0.5% in terms of CV_RMSE. In some cases the conclusions are confirmed by direct outdoors side-by-side comparison of two sets of component cells.

CPV modeling issues

CPV modeling, while sharing input variables with PV, has different sensitivities. Therefore some valid assumptions for PV are not fully valid and the models based on them can present a lack of precision.

A review of the state of the art in DNI and other meteorological variables modeling and CPV specific features has been presented. The main issue regarding DNI hourly series expanded from monthly averages is that in order to be realistic they should be obtained from clear-sky models or synthetically at hourly resolution.

Modeling of spectral effects

Regarding spectral effects, it has been shown that AM functions are very limited to express the variations of current due to spectral changes generated mainly by the variations of aerosols and precipitable water of the local atmosphere. Therefore they can be used to estimate annual spectral losses but only if they are obtained from annual data and they are used in locations whose atmosphere is very similar to the one used to obtain the AM function. An alternative based on spectral efficiency is proposed that gives a lower dispersion because takes into account the atmospheric parameters.

Special attention should be paid to the effect of the ambient temperature on the optics that is translated to changes in current, to the soiling due to the higher sensitivity of CPV modules with respect PV and the expected accuracy of tracker, also very sensitivity in the case of CPV systems.

Validation with two years of data of an experimental CPV plant

All the submodels has been used together to estimate the power of an example CPV plant operating for two years and an individual tracker for one year. Additionally a forecast energy model has been presented as example and compared with energy production of the systems and the integrated power previously obtained. The model works with a few meteorological inputs with monthly. Moreover, spectral influence that is especially relevant in MJ solar cells based systems is also included with a monthly series that can be measured in situ or estimated from atmospheric databases. Additional parameters based on external factors have been included to refine the estimation.

Development of hybrid CPV-lighting concept

A hybrid CPV module has been proposed that simultaneously produces electricity and injects concentrated light into optical guides for lighting and as an active building integration solution that generates electricity and transports sunlight. It has been verified that the CPV module and the fiber optics for collection and distribution of visible light are compatible. The main advantage of this proposal is that both concepts (CPV and lighting) need an infrastructure to concentrate light and to aim to the sun. Sharing these needs, they both benefit when they are integrated in the same module, reducing costs.

Study of design constraints

The transmission efficiency versus the incidence angle has been studied as a function of the absorption coefficient of the core and the extinction coefficient of the cladding in order to understand the losses in fibers for concentrated light. It can be concluded that the higher the *f-number* of the light cone feeding the fiber is, the lower the losses are. However, this value is also limited by the optical efficiency of the lens versus the *f-number* and the compactness of the receptor. The optimal *f-number* ranges between 2 and 4.

Development of a proof-of-concept based on PMMA optical fibers

PMMA optical fibers have been chosen for the proof-of-concept, which have been characterized experimentally. It has been concluded that the maximum concentration level is limited by the PMMA softening temperature to 100x, although higher concentrations are possible with UV and IR filtering. Based on these fibers, a full hybrid system has been completed.

Nevertheless the transmissivity of PMMA clearly limits the feasibility of a hybrid system based in plastic materials to less than 20 m and only silica optical fibers based systems can compete with a CPV+LED solution, achieving lengths around a hundred meters.

Characterization of light coming from optical fibers

The main conclusion about quality of light for optical fibers is that they shift sunlight to bluish white tones; for example, PMMA fibers from 0 to 20 meters the CCT increases about 1500 K, while silica fibers reduces the CCT. Another relevant conclusion is that the CRI for the PMMA example reduces about 20 percentage points, however it is still comparable to a typical fluorescent lamp used in offices (CRI=80%) and the silica can preserve up to 87% of CRI after 100 m.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Below, some suggestions for several open issues that require further investigation are listed:

- MJ solar cells based on four subcells are a reality for CPV. A third SMR arises as an additional index. It will limit the spectral prevailing conditions valid for such solar cells and therefore it will improve the accuracy of the uniqueness of SMRs as spectral indexes. In any case, the presented procedures will be still valid.
- While CPV plants are entering in bankability, the reduction of the CPV modeling uncertainty is getting more and more critical. A more concrete estimation of CPV power rating and resources is especially necessary, so among others, a spectral model considering optics that represents better a CPV module is then mandatory.
- It can be interesting to proceed a spectral uniqueness analysis to a dataset representative of xenon-lamp spectra typical of solar simulators. This could allow to determine spectral sensitivities of different MJ solar cells technologies under xenon spectra and to validate the use of component cells of a technology with a device that has cells of another technology.
- Considering more realistic cell operation conditions. On one hand, temperature when acquiring or simulating SMR values can be interesting for high precision estimation of spectral prevailing conditions. On the other hand, photocoupling effects that are more evident in component cells than in the corresponding MJ solar cells, as in the case of the bottom subcell of lattice-matched based on germanium, generate mismatches that lead to some bias.
- Spectral characterization of locations considering specific CPV setup, mainly optics, to extend conclusions about spectral classification of locations to system level.

- Implementation of a hybrid CPV-lighting prototype based on silica optical fibers to confirm expected results.
- A different approach to distribute the solar energy of a hybrid CPV-lighting concept: a spectral-splitting-based approach. Humans only need spectral range from 380 to 780 nm, and the rest (mainly UV and IR) can be used by a CPV system tuned to non-visible light.

7.3 CONTRIBUTIONS

INTERNATIONAL JOURNAL ARTICLES

1. **Núñez, Rubén**, Ignacio Antón, and Gabriel Sala. 2013. "Hybrid Lighting-CPV, a New Efficient Concept Mixing Illumination with CPV." *Optics Express* 21 (4): 4864–74. doi:10.1364/OE.21.004864.
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3. **Núñez, Rubén**, César Domínguez, Stephen Askins, Marta Victoria, Rebeca Herrero, Ignacio Antón, and Gabriel Sala. 2016. "Determination of Spectral Variations by Means of Component Cells Useful for CPV Rating and Design." *Progress in Photovoltaics: Research and Applications* 24 (5): 663–79. doi:10.1002/pip.2715.
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