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TESIS DOCTORAL

NEW TRENDS IN PHOTOVOLTAIC ECONOMY AND DEVELOPMENT OF A DIFFERENT TECHNOLOGICAL SPECTRAL APPROACH IN CONCENTRATOR PHOTOVOLTAICS

PRESENTADA POR:
EMILIO MUÑOZ CERÓN

DIRIGIDA POR:
DR. D. GABINO ALMONACID PUCHE
DR. D. JUAN CARLOS MIÑANO DOMÍNGUEZ

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Nuevas tendencias en Economía Fotovoltaica y desarrollo de un enfoque técnico-espectral diferente en Concentración Fotovoltaica

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Emilio Muñoz Cerón

Departamento de Ingeniería Electrónica y Automática

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Emilio Muñoz Cerón

Electronics and Automation Engineering Department
University of Jaén

Directed by:

Dr. Gabino Almonacid Puche

(Universidad de Jaén)

Dr. Juan Carlos Miñano Domínguez

(Universidad Politécnica de Madrid)

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AUTOR: Emilio Muñoz Cerón

DIRECTORES:

Dr. Gabino Almonacid Puche
Dr. Juan Carlos Miñano Domínguez

TRIBUNAL

PRESIDENTE:

Dr. Pablo Benítez Giménez
Universidad Politécnica de Madrid

VOCAL:

Dr. Gerald Siefer
Fraunhofer Institute for Solar Energy Systems ISE

SECRETARIO:

Dr. Jorge Aguilera Tejero
Universidad de Jaén

SUPLENTES:

Dr. Damien Picault
Grenoble Electrical Engineering Laboratory. Grenoble INP.

Dr. Gustavo E. Nofuentes Garrido
Universidad de Jaén

Realizado el acto de lectura y defensa de la tesis en la Universidad de Jaén, en fecha:

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EL PRESIDENTE EL VOCAL EL SECRETARIO

A mis padres

La vida siempre te da dos opciones:
La cómoda y la difícil.
Cuando dudes, elige siempre la difícil, porque
así siempre estarás seguro de que no ha sido la
comodidad la que ha elegido por ti.

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Este adiós no maquilla un hasta luego,
este nunca no esconde un ojalá,
estas cenizas no juegan con fuego,
este ciego no mira para atrás.
Este notario firma lo que escribo,
esta letra no la protestaré,
ahórrate el acuse de recibo,
estas vísperas son las de después.
....
Para decir *con Dios*
a los dos nos sobran los motivos

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Abstract

The photovoltaic solar energy (PV) based on crystalline Silicon cells has a great technological maturity as a result of a long research period and a host of years of experience. It has also been favored from several expansion plans, policies and support mechanisms promoted by many countries. For all of these reasons, we assisted to an exponential growth of PV power installed in Spain and within several European countries in the last decade.

Nowadays there is an inflection point regarding the continuity of its development, which it is mainly related to the fact that energy conversion efficiency levels close to its maximum theoretic value are being achieved. This limitation, together with the low special density of the solar energy, do not allow to forecast large price reductions of the energy generated by the photovoltaic technology beyond the ones related to the optimization of the manufacturing process. Additionally, several bureaucratic and economic barriers are being induced, which in a certain way may handicap this PV growth as well as influencing the purchase and generation prices.

Therefore, the search of new approaches, applications and/or procedures based on the exiting technology is necessary, combined with the investment and contribution to other alternatives based on technological concepts different to the traditionally used on the PV modules made of Silicon, which may consist on the increase in the efficiency through a better exploitation of the solar resource.

Regarding these new approaches based on flat-PV modules, the opportunities analyzed and the contributions made in this manuscript are

focused on the increasingly introduced self-consumption concept, where the end user turns into his own electrical energy producer. Although the grid-parity is a consolidated reality in Spain, a new economic calculus methodology is proposed, based on the consumption profiles and the retail electricity tariffs that the user is subscribed to. It will be detected some specific cases where the profitability of this grid-parity is questionable.

By contrast, regarding the PV technological alternatives, the High Concentrated Photovoltaic (HCPV) systems are studied. These systems are composed by high efficiency solar cells (multijunction) based on a higher sensitivity of the incident solar spectrum and optical elements which concentrate the light on the cell's surface. This combination has achieved laboratory efficiencies greater than 40%. Although the solar concentration has been widely used in the PV history and since the 80's it was used to decrease generation costs, in fact, it was during the last decade when it experimented an exponential growth. Nevertheless, the needs of deeper research lines and its uncontrolled growth have produced a deceleration in its deployment in the recent years.

One of these research lines falls on the further study of the sensitivity of these MJ cells regarding the solar spectrum, which constantly changes depending on the moment of the day, the meteorological characteristics of the surroundings, the optical mechanism used for the concentration and the sun tracking system. The immediate effect on the operational behavior of the MJ cells is the current limitation in any of its junctions, reducing the total current at the output of the cell, thus, the amount of energy generated by a cell is strongly dependent on the spectrum's characteristics. Therefore, the adaptation of the cell's design to the spectrum is crucial to achieve greater efficiencies.

The technological contribution expected in this thesis is directed to the development of an experimental setup, denominated Limiting Current Ammeter (LCA), capable of directly measuring the relation between the photocurrents of the top and middle subcells in a MJ device, because nowadays there is no sensor that measures directly this parameter in outdoor conditions. Thereby, it is intended to establish the relationship between the incident solar spectrum and the electrical current generated by means of a procedure which is reliable and simple at the same time.

Resumen

La energía solar fotovoltaica (FV) basada en la célula de Si cristalino posee una gran madurez tecnológica fruto de un largo periodo de investigación y un cúmulo de años de experiencia; favorecida a su vez por las diferentes modalidades de planes de expansión y apoyo promovidos por numerosos países. Por todo ello, en la última década hemos asistido a un crecimiento exponencial de la potencia fotovoltaica instalada en España y algunos países Europeos.

En la actualidad existe un punto de inflexión en la continuidad de su desarrollo, principalmente relativo a que se está llegando a cotas de eficiencia de conversión energética muy próximas a su límite máximo teórico. Esta limitación junto con la relativamente baja densidad espacial de la energía solar no permite predecir grandes reducciones del precio de la energía generada con fotovoltaica más allá de los relacionados con la optimización de los procesos de fabricación. Adicionalmente, se está induciendo algún pormenor burocrático y económico que en cierta medida también lastran este crecimiento e influyen en los precios de adquisición y generación eléctrica.

Por todo ello, se estima necesaria, por un lado, la búsqueda de nuevos enfoques, aplicaciones y/o procedimientos basados en la tecnología existente, así como la inversión e innovación en alternativas tecnológicas a partir de otros conceptos distintos a los tradicionalmente empleados en los módulos FV basados en Silicio, consistentes en el aumento de la eficiencia mediante el mejor aprovechamiento del recurso solar.

En cuanto a los nuevos enfoques de los sistemas FV panel plano, las oportunidades analizadas y los aportes realizados en este manuscrito van en la dirección del cada vez más implantado concepto de autoconsumo, donde el usuario final se convierte en productor de su propia energía eléctrica. A pesar

de que la paridad de red es una realidad en España, se propone un nuevo modelo de cálculo económico adaptado a los perfiles de consumo y a las tarifas a las que un usuario esté sujeto, y en donde se apreciará que la rentabilidad de dicha paridad podrá ser cuestionada.

Por otro lado, en cuanto a las alternativas tecnológicas, se encuentran los sistemas de Alta Concentración Solar Fotovoltaica (HCPV), compuestos por células de alta eficiencia (multiunión, MJ) basadas en un mejor aprovechamiento del espectro solar incidente que, combinadas con elementos ópticos que concentran la luz, han alcanzado ya, en laboratorio, eficiencias superiores al 40%. Si bien la concentración solar se ha utilizado ampliamente a lo largo de la historia y ya en los años 80 se comenzó a aplicar en los sistemas FV con la finalidad de reducir costes, ha sido en la última década cuando ha experimentado un auge exponencial, aunque las necesidades de investigación y un crecimiento no controlado han hecho que se produzca una ralentización en su desarrollo en los últimos años.

Una de las líneas de investigación en esta alternativa FV recae en profundizar en el estudio de la sensibilidad de estas células MJ al espectro solar incidente, el cual varía dependiendo del tiempo, de las características ambientales del entorno, de la óptica del concentrador, así como de la precisión del seguimiento solar. El efecto más inmediato de la variación del espectro solar en el comportamiento de la célula MJ es la limitación en intensidad en alguna de sus uniones que reduce la corriente total de la misma, por lo que la cantidad de energía entregada por una célula esté fuertemente condicionada a las características del espectro. La adaptación al espectro es un punto crucial en el diseño futuro de las células MJ para conseguir mayores rendimientos.

La contribución tecnológica que se pretende con esta tesis va encaminada al desarrollo de un dispositivo experimental que permita medir directamente la relación de corrientes en las uniones superior e intermedia de células MJ, puesto que en la actualidad no existen dispositivos que realicen una medida directa. De este modo, se pretende establecer una relación entre el espectro solar incidente y la corriente generada de manera fiable y sencilla.

Por lo tanto, esta tesis pretende ofrecer soluciones a la tecnología fotovoltaica desde dos perspectivas bien diferentes, con el ánimo de ampliar el espectro de posibles contribuciones a la tecnología.

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Glossary

List of Abbreviations

AM1.5D	Direct Irradiance terrestrial reference spectrum
ASTM	American Society for Testing and Materials
BIPV	Building Integrated Photovoltaic System
BOE	Spanish Official Gazette
BOS	Balance of the PV System
CSOC	Concentrator Standard Operating Conditions
CSTC	Concentrator Standard Test Conditions
DPBT	Discounted Payback Time
FiT	Feed-in Tariff
GIS	Geographical Information system
HCPV	High Concentrator Photovoltaics
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IRR	Internal Rate of Return
EU	European Union
FFT	Fast Fourier Transform
JRC	Joint Research Center
LCA	Limiting Current Ammeter
LCOE	Levelised Cost of Electricity
LEC	Levelised Electricity Cost
MJ	Multijunction Solar Cell
MTBF	Mean Time between Failures
NET	Net Electricity Generation
NOCT	Nominal Operation Cell Temperature Conditions
NPV	Net Present Value
O&M	Operation and Maintenance

OA	Operational Amplifier
PCB	Printed Circuit Board
PV	Photovoltaic
PVGCS	Photovoltaic grid-connected system
PVGIS	Photovoltaic Geographical Information system
RE	Renewable Energy
Si-PV	Silicon based photovoltaics
STC	Standard Test Conditions
UNEF	Spanish PV Union association
VAT	Value Added Tax
WACC	Weighted average cost of capital
WMO	World Meteorological Organization

List of Symbols

A	Cell's active area
A_{MID}	Averaged value of the middle demodulated output signal
A_{TOP}	Averaged value of the top demodulated output signal
$B_{dm}(0)$	Horizontal beam monthly average daily irradiation
CM	Current-matching (ratio)
d	Nominal discount rate
$D_{dm}(0)$	Horizontal diffuse monthly average daily irradiation
d_i	Dividends rate (annual retribution rate for the own capital)
DNI	Normal Direct Irradiance
E (λ)	Spectral Irradiance
$E_{AM1.5D}$ (λ)	Spectral Irradiance under AM1.5 conditions
E_{GS}	Annual Average sun energy received on the generator's surface
E_{PV}	Annual PV electricity yield
E_{PVe}	PV Excess Electricity injected to the grid
E_{PVs}	PV Self-consumed Electricity

E_{PVsd}	PV electricity Self-consumed in a deferred time
E_{PVsi}	PV electricity Self-consumed instantaneously
EQE	External Quantum Efficiency
f_M	Red LED powering frequency
f_r	Reference frequency
f_T	Blue LED powering frequency
g	Annual inflation rate
$G(\propto,\beta)$	Effective irradiance within the PV generator surface
G_{NOCT}	Effective irradiance at nominal operation cell temperature condition
$H_d(0)$	Daily horizontal global radiation
$H_{dm}(0)$	Monthly average value of horizontal daily global radiation
H_S	Annual Normal Global radiation on the generator's surface
I_{AC_led}	AC current component from the LEDs
i_l	Annual Loan interest
I_{MID}	Middle subcell current
I_{MJ}	Multijunction current
I_{MPP}	Current at the maximum power point
$I_{ph\_i\text{-}subcell}$	i-subcell Photocurrent
$I_{SC\_i\text{-}subcell}$	Short-circuit i-subcell current
I_{SC_MJ}	Short-circuit multijunction current
I_{TOP}	Top subcell current
L	Length of the collimator tube
LCC	Life-cycle cost of a PV system
MM	Spectral Mismatch Error
N	Lifetime of a PV system
N_l	Time duration of the loan
p_e	Unitary price for the excess PV electricity.
P_M	Maximum PV power
$P_{M,STC}$	Maximum PV power at standard test conditions
p_{sd}	Unitary price for the deferred PV electricity Self-consumed
p_{si}	Unitary price for the PV electricity Self-consumed instantaneously
p_{tax}	Unitary price (taxes) for the PV electricity Self-consumed
PV_{AOM}	Annual operation and maintenance
PV_{EC}	Portion of the investment financed with external capital
PV_{IN}	Initial investment cost of the PVGCS

PV_{OC}	Portion of the investment financed with own capital
PW[CIF(N)]	Present worth of the cash inflows
$PW[PV_{OM}]$	Present worth of the annual operation and maintenance cost
$PW[PV_{EC}]$	Present worth of the external capital
$PW[PV_{IN}]$	Present worth of the initial investment cost
$PW[PV_{OC}]$	Present worth of the own capital
R	Aperture of the collimator radius
r	Radius of the receiver
SR	Spectral Response
T_a	Ambient temperature
T_{amdm}	Monthly average minimum daily temperature
T_{aMdm}	Monthly average maximum daily temperature
T_{amdr}	Minimum daily temperature of the representative day
T_{aMdr}	Maximum daily temperature of the representative day
T_C	Cell temperature
T_{NOCT}	Nominal Operation Cell Temperature
V_{BIAS}	Voltage bias
V_{MPP}	Voltage at the maximum power point
V_{OC}	Open-circuit Voltage
Y_{AV}	Average energy yield
γ	Power temperature coefficient
ε_e	Annual increase rate of the unitary cost of the PV Excess Electricity injected to the grid
ε_{pl}	Annual decrease (degradation) rate of the power
ε_{PVAOM}	Annual escalation rate of the operation and maintenance cost
ε_{sd}	Annual increase rate of the unitary cost of the PV electricity Self-consumed in a deferred time
ε_{si}	Annual increase rate of the unitary cost of the PV electricity Self-consumed instantaneously
θ_0	Opening Angle
θ_s	Slope Angle

Chapter 1

Introduction

1.1. Contextualization

Photovoltaic solar energy (PV) based on crystalline Silicon cells has a great technological maturity as a result of a long research period and a host of years of experience. It has also been favored by several expansion plans, policies and support mechanisms promoted by many countries. For all of these reasons, we assisted, during the last years, to an exponential growth of PV power installed especially in Spain and within several European countries (International Energy Agency, 2013) (Martinez de Alegría Mancisidor, et al., 2009).

Without particularizing in the bureaucratic or economic details of this growth in PV installations, nowadays there is an inflection point regarding the continuity of its development, which is mainly related to the fact that energy conversion efficiency levels close to its maximum theoretic value are being achieved. This maximum limit for the Silicon is relatively low, around 31% (Shockley & Queisser, 1961), and nowadays there are Si solar cells manufactured at laboratories that reach efficiencies of 25%, which decrease down to 22.9% when they are implemented in modules, so attending to this figures, we are close to the efficiency limit mentioned (Green, et al., 2014) (Landsberg & Markvart, 2003). Therefore, under this technology, large progresses in efficiency are not expected, so the most easily achievable mechanism for its price reduction is through the improvement of the manufacturing process. Another alternative application and approach comes from the self-consumption of the electricity generated by means of PV modules within the user's network. This is the most promising solution to the

integration of PV in the electricity generation network and it is in line with the European and National Renewable Energy Plans or directives (European Comission, 2009) (Ministry of Industry, Tourism and Trade, 2010).

Although the grid-parity is a consolidated reality, it is recommendable to undertake particularized profitability analysis in order to state the feasibility of installing a PV system under certain consumption profiles and electrical tariffs.

Beyond these new approaches, there are other available technologies for the use of the PV effect. Although currently, they provide worse results regarding efficiency or cost, so their level of technological or commercial deployment is lower. On the contrary, they offer theoretical characteristics that allow us to forecast better efficiency or cost trends in the mid-term. Among the alternative PV technologies, two separate ideas are followed: the first one deals with the cost reduction at the expense of lowers efficiencies (thin-film) while the second is directed to develop very efficient devices, although expensive too.

Under this second premise, the multijunction solar cells can be found, which are composed by several layers. This combination permits theoretical limits much higher than the Silicon based cells (Yamaguchi, et al., 2008) (Baur, et al., 2007). Companies such as Sharp, Soitec, Spectrolab, Amonix or Solar Junction, and laboratories like Sandia, NREL, the Fraunhofer Solar Institute or the Solar Energy Institute from the UPM (IES), have developed multijunction devices with efficiency conversion figures close to or beyond 40% (Green, et al., 2014).

These high-efficiency cells, together with advance optical elements that reduce the surface of solar cell needed, compose the High Concentrator Photovoltaic Systems (HCPV). Although this concept has been historically addressed, it was really introduced in the 80's, with the purpose of cost reduction. Spain is one of the pioneering countries in the development of HCPV systems, partially thanks to the research carried out in the Solar Energy Institute from the UPM (IES) during the last decades (Sala & Luque, 2007). Nevertheless, the relatively low efficiencies of the cells used in those times, made the CPV did not achieve the proper technological maturity for its commercial deployment.

The appearance of the aforementioned MJ high-efficiency cells during the last years, means a new boost in this research field, although it is still necessary

to delve into its operational characteristics. One of the aspects still not fully addressed is the sensitivity of these multijunction cells to the incident solar spectrum (Martí & Luque, 2004) (Kinsey & Edmondson, 2009).

The solar spectrum varies throughout a natural day and it is also dependent on the characteristics of the surroundings, the optics of the concentrator and the sun tracking precision. The most immediate effect of the spectral variation in the operation of the MJ cell is the limitation of the current generated by any of its junctions, thus reducing the total output current. This effect is negatively translated into energy losses at those moments where there is no current matching under specific spectral conditions; therefore, the adaptation of the photovoltaics energy delivered and the meteorological spectral changes are a crucial point regarding the achievement of high-efficiency levels.

A wide research field to explore is related to the proposal of technical solutions for the spectrum measurement or the improvement of other techniques already existing in the PV literature for the analysis of the MJ cells' spectral response (Metzdorf, 1987) (Adelhelm & Bücher, 1998) (Meusel, et al., 2003).

Under this contextualization framework, we can further continue technologically progressing with the aim of supporting the solar electricity as a real alternative to conventional sources of energy, both in efficiency levels and productions cost (Hegedus & Luque, 2011) (Cristobal López, 2012)

It seems adequate to continue promoting the great capacity and research tradition of this sector (Unión Española Fotovoltaica, Noviembre 2013) and also to invest in knowledge in order to reduce the cost of solar electricity through the PV effect by searching other alternatives within this technology.

1.1.1. Relevance of the proposal

Bearing the previous brief contextualization in mind, the thesis proposal is intended to achieve the following relevant milestones, which can be gathered in the following categories:

- Scientific and technological: The analysis and outdoor characterization of a MJ cell, in terms of its spectral response, will enable, on the one hand, the

deepening in the knowledge of the operational characteristics under standard environmental features and on the other hand, the results and conclusions extracted from the current-spectrum relation, which could be used for the estimation of the electrical production of this incipient technology. Regarding the self-consumption concept, the technical relevance will be directed to the development of the proper tools for a massive design and implementation of the PV integration in the current urban context.

- Socioeconomic and technology transfer: The previous results will be useful for the multijunction cell's manufacturers and the optical designers too. because they can propose modified CPV designs with the aim of both reducing prices and increasing efficiency.

1.2. Aims of this research

The realization of this thesis pursues the attainment of two main objectives corresponding to the different approaches focused on this research.

First of all, the objective related to the economic trend of the PV technology is the adaptation of energy and economic simulation tools to satisfy the requirements of the self-consumption theory in order to contribute to the assessment of the grid-parity profitability.

Concerning the CPV approach and its spectral dependency, the second objective of this thesis falls on the analysis of the relationship between the wavelengths of the sun spectrum and the response of the multijunction solar cell. Specifically, this objective will be focused on the detection of the limiting subcell of the MJ device in outdoor and realistic conditions. Under this objective, a spectral measurement instrument will be implemented in order to match the response of commercial MJ cells with a realistic on-site measurement.

1.3. Hypothesis

Nowadays, PV technology is presented as an alternative energy ready to compete against other traditional sources of energy. Anyway, its flattering learning curve shows a reality where a necessity to find other alternatives applications is detected. In this sense, the questions arising about the profitability of the mechanism of electricity self-consumption and the grid parity accomplishment are a trending topic when these solutions are searched.

Additionally, within the PV technology, the concentrator photovoltaic seems to mean a promising alternative capable of notably increasing the efficiency of the system and lowering the generation costs in the short and mid-term respectively.

There is a solid theoretical base that allows us to be optimistic regarding the development of new solar cells, specifically designed for operating in high concentration conditions and under a sensitivity to the solar spectral bands which is becoming larger, so the photons from the Sun can be more efficiently captured.

Nevertheless, the complexity of matching the theoretical background, the testing measurements and the dispersion of some of the parameters complicate the correlation between the experimental measurements with the real operational behavior of the MJ devices under test, especially all the research fields related to the spectral dependence of each one of the junctions which form a high efficiency MJ solar cell.

Under these two scenarios, different hypothesis are issued. On the one hand, the economical hypothesis is based on the development of the proper simulation tools that allow us to assess the profitability of the grid parity in a specific case, while the technical CPV hypothesis is based on the capacity of adapting and experimentally measuring the existing relation between the solar spectrum and the MJ electrical output.

1.4. Thesis outline

Once the contextualization and relevance of the proposal has been discussed and the aims and hypothesis have also been established in this introductory chapter, the remaining distribution of this manuscript is going to be outlined.

The technological standstill of the traditional PV systems combined with their level of maturity reached, makes this market find other growth alternatives that may go beyond the search of increasing their energy conversion efficiency levels. Obviously, these new trends will require different technological innovations, most of them related to adjacent engineering fields, such as the energy management systems or the smart grid implementation.

Nowadays, under this premise, the most innovative application for the PV is related to its potential integration within the energy generation networks and its matching with the electricity consumption habits of the end users. The self-consumption of the electricity generated by means of PV modules is considered a feasible solution in line with the European and National Renewable Energy Plans or directives (European Comission, 2009) (Ministry of Industry, Tourism and Trade, 2010).

The comparison of the levelised cost of producing a unit of PV electricity with the retail electrical tariff will require a combined energy and economic analysis, because, although the grid-parity is a reality due to the PV unitary cost and the good sun radiation levels available in Spain, there are some specific cases where its degree of profitability will be dependent on the consumption profile of the end user and the electrical tariff applicable.

Additionally to this analysis, in chapter 2 it is also stated that all this market penetration will be fully dependent on the policy and regulatory framework established by the corresponding Governments, so the supporting mechanism will be critical for the proper deployment of the technology. A brief overview of the temporary evolution of the legal supports or constraints will be undertaken.

After the previous exposition gathered in chapter 2 of this thesis, a new section is dedicated to one of the promising research alternatives regarding the PV technology in its aim of increasing the conversion efficiency, that is, the Concentrator Photovoltaic. Although in the scientific literature the spectral

dependency of the multijunction solar cells used in this technology is deeply studied, the standardization and creation of measurement procedures and the implementation of instrumental tools is still a wide and productive research field to cover.

Once a summary of the efficiency and standardization status and the spectral dependencies has been made, together with a review of the tools for the spectral response measurement, a device for the on-site measurement of the limiting subcell in multijunction solar devices is proposed. This device is theoretically and experimentally capable of detecting which junction is limiting and also the quantity of photocurrent generated by both the top and the middle subcells.

Finally, once these two different contributions regarding the PV technology have been exposed, the conclusions regarding the two research lines addressed in this manuscript will be described, including those achievements still left to accomplish and the suggestion of future research in the light of the results achieved as well.

As a conclusion, the results obtained in this work are related to the theoretical application and adaptation of an economic procedure for the proper grid parity verification, and a more tangible one related to the creation of a prototype for measuring the currents generated by the top and middle subcell in a MJ solar device.

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Chapter 2

Trends in the policy and economy of the Photovoltaic technology

2.1. Brief policy and regulatory framework

Nowadays, the combination of different sources of energy in the electricity generation mix is having an expanding impact in the development of the energy balance and policies within the European countries. In this scenario, the technologies from renewable origin are the responsible of this electrical generation concept change.

Since the early 1970's there have been efforts within the members of the European Union to establish a common energy policy where, after a faint starting implication, the technological maturity and the costs reduction of some renewables sources have produced that most of the regulations and directives regarding the energy policy are focused on the integration and massive use of these sources of energy (Kanellakis, et al., 2013).

The publication of the directive 2009/28/EC has supposed the definition of a common position regarding the promotion of renewable energies, where it is well known that a 20% of the final energy consumption must be provided with Renewable Energies (RE). For that reason, it establishes the mechanism for prioritizing the access to the grid for these sources as well as defining a binding percentage for the use of RE in any country within the European territory (European Comission, 2009).

Additionally, the directive highly emphasizes with the integration of RE on buildings, because they mean a 40% of the energy consumption in the EU. This support has been reinforced with other directives (European Comission, 2010) where the future for the integration of RE is foreseen for the nearly zero-energy building concept, which should be implemented from 2018 onwards. There is a trend for buildings to be seen as positive power plants and with a main role in the development of smart grids (Krajacic, et al., 2011).

The characteristics of the photovoltaic technology achieve a privileged position in the RE supply in general and in the building integration in particular; thus, it represents a realistic alternative in the energy market and targets of the EU.

Nevertheless, the definition of several rules or directives is not enough for the effective promotion of RE. It has to be defined a supporting economic mechanism that, in the case of Europe, has been translated into a Feed in tariff (FiT) retribution support for the energy injected originating from renewable sources. This mechanism promotes the minimization of the consumer's cost, but it does not deal with the generation cost reduction.

The distinguishing approach proposed by some authors comes from the coupling of the energy and economics analysis with the optimization of the place for the installation of a certain renewable energy source. It is intended to strengthen the philosophy that the installation of renewable energies should not be made at any price in a massive intervention, regardless the suitability of the location. The principles of equimarginality and lowering the cost of governmental support should be combined, and thus to adapt the PV plant to the places with best renewable energy resource, giving benefit to both the minimization of generation and consumer's costs (del Río & Cerdá, 2014).

The FiT scenario have caused that several countries have reached the photovoltaic grid parity, as the price of producing a unit of electricity with RE can be compared with their local retail electricity prices in a competitive way. Moreover, these policies have boosted the industry up to a level where, in certain cases, this parity has been reached without any subsidy or feed-in tariff incentive, but a favorable regulatory framework has also been necessary, through net-metering or self-consumption laws (Pérez, et al., 2013).

Despite this promotion of Renewable Energies, Europe faces an enormous competitiveness challenge because the priority imposed on renewables energies in the short-term has exacerbated the energy generation cost (Helm, 2014), especially when there is some skepticism concerning the possibility and feasibility of running Europe just on the basis on RE (Trainer, 2013).

Nevertheless, beyond the extra charges, a critical issue that should be faced is the security of supply, its sustainability and the economic competitiveness, as they seem to be unbalanced in the energy policy targets of the European members (Spiecker & Weber, 2014). In that sense, policies for distributed generation penetration levels market must be developed (Peter Vahl, et al., 2013).

Focusing again on the European renewable energy policy, and despite a common position within the countries, member states are the ultimate responsible for their national energy mix, and the energy resources within a country are a national, not European, resource (European Comission, 2008).

Proceeding to the analysis with the Spanish situation, the target assigned for share of energy from renewable sources in the gross final consumption by 2020 is 20%, where the role of buildings is also taken into account.

In the Spanish legislative framework, with the application of the Royal Decree 1578/2008, the benefits of Building Integrated Photovoltaic systems (BIPV) were recognized, not only because they do not increase the land occupation, but also because of the advantages of the distributed electricity generation as well as their contribution to a social spreading of renewable energies. Moreover, the Spanish Renewable Energy Plan of 2011 encourages the promotion of self-consumption of electricity generated by renewables sources under the mechanism of net-balance (Ministry of Industry, Tourism and Trade, 2010).

Although in Spain the grid parity is a reality (Lettner & Auer, 2012), partially thanks to past renewable electricity policies (del Río, 2008), the excessive bureaucracy and the changing and confusing regulatory framework is a pending task in order to avoid barriers for the success of the photovoltaic technology (Garbe, et al., 2012)

In this section, is outstanding that since 2007 an average of two different Royal Decrees has been published each year, which either derogated past laws or even had a retroactive application, particularly affecting the economy of the PV technology.

The main reason of constantly changing the Spanish legislation was to rationalize the deployment of PV in Spain and to control the impact of the feed-in tariff in the national economic situation.

According to the inflection-point law that boosted the PV deployment in Spain, the Royal Decree 661/2007 from 2007, the following RD 1578/2008 implied a 30% reduction of the feed-in tariff and further progressive cuts, which could reach 10 % annually.

Lately, in September 2010 and due to the economic situation of the country, the Spanish feed-in tariff regime was modified for those systems not gathered in the 2011 first quarter registry. The Royal Decree 1565/2010, apart from further promoting PV systems integrated in buildings, either on façades or on top of roofs, implied an additional reduction in feed-in tariffs of 5% for installations of type I.1, 25% for type I.2 and 45% for type II.

Additionally, a following Royal Decree-law (RD 14/2010), from December 2010, limited the energy entitled to the feed-in tariff, as it fixed the number of hours of operation, according to the type of installation (fixed, one-axis and two-axis tracking) and the climatic zone established by the Spanish Building Technical Code law

In December 2011, the Royal Decree 1699/2011 was published, which regulates the network connection of small power electricity production systems of less than 100 kW. The possibility of total or partial self-consumption of the electricity generated by these systems is also mentioned. Later on, the Royal Decree-Law 1/2012, published in January 2012, postponed the pre-assignment procedure for the remuneration of renewable systems and it removed the feed-in tariff incentives for the new electricity installations which either use combined heat and power, renewable energy sources or waste. Nowadays, several drafts have been published, which aim is the regulation of the administrative, technical and economic conditions for the self-generation of the electrical energy produced within the consumer´s network (Comisión Nacional de la Energía, 2013) (Ministry of Industry, Energy and Tourism, July, 2013), but according to

some authors, the last draft, published in July 2013, contains elements which considerably worsen the economic viability of the PV systems used for self-generation, as the user will have to pay for the energy self-consumed (Mir-Artigues, 2013).

According to the constantly changing renewable energy laws and the inclusion of the self-consumption concept, prospective owners, big investors or regular householders, are concerned that any further modification of the regulatory framework of the photovoltaic grid-connected systems (PVGCS) may affect the profitability of their investment.

Either way, the boom and the bust of the Spanish PV market has to be used as an example for the proposal of policy recommendations for solar PV deployment (del Río & Mir-Artigues, 2012) (Ciarreta, et al., 2011).

The conclusion to the Spanish situation regarding the PV is that, although the technology is mature enough to compete against other sources of energy, if this technology is expected to reach the power estimations of the Spanish Renewable Energy Plan, where more than 5900 MW of accumulative power is planned to be installed by 2015, it is necessary to find other economic alternatives, especially when all the incentives or subsidies have been interrupted.

At this point, the novel concept of self-consumption is the promising alternative, not only for the promotion of the PV technology, but as a solution of sustainable and geopolitically independent source of energy.

2.2. Potential PV integration: an energy-economic analysis

The integration of grid-connected PV systems into buildings or public areas is one of the most usual applications of the photovoltaic solar energy in developed countries (Sick & Erge, 1996) (Chivelet, 2007). This reality has been reinforced lately through the policies, directives and regulatory frameworks aforementioned.

The uncertainties in the energy development within Europe or in Spain, make similar previous studies to become soon outdated and it should be updated with the recent and gradual introduction of the self-consumption reality.

In this section the technical constraints that a massive integration of renewable energies in general, or the photovoltaic technology in particular, may cause in the national grid distribution system, have been avoided. This study will be set aside in future research lines.

2.2.1. Grid-parity reality: a matter of unitary costs and PV energy yield

One of the objectives in the development of any new technology is to reach a certain degree of maturity that makes it prepared to compete against other traditional sources of energy. Obviously, in the case of the Photovoltaic technology, although it has been present in the energy sector for more than 25 years, it is in the last decade when a stable level of technical robustness is being reached, which translated into economic terms, it leads to assess that the energy generation based on photovoltaics means an alternative to the present forms of electricity production.

At this point, the concepts “Grid-parity” and “Levelised Cost of Electricity (LCOE)” play the role of competitiveness and costs referees. Grid-parity is the time point when the cost of producing a unit of electricity, in this study by means of photovoltaic modules, reaches the average end-consumer price for electricity. Grid-parity should not be misunderstood with Generation-parity, as the later concept includes the transport and distribution of the electricity generated off the grid (Pérez, 2011). In the case of the photovoltaic technology this omission does not represent a substantial additional value because its main advantage is that the energy source is within the consumption point’s network, the so-called distributed generation sources of energy.

The LCOE, or Levelised Electricity Cost (LEC), is defined as a constant present cost of a unit of electricity ($€ \cdot kWh^{-1}$) produced by a given system over a specified number of years, normally throughout its whole operational lifetime. This cost is expressed in current monetary units and it is levelised for all the

years that the system is intended to be generating electricity (Short, et al., 1995). In the LCOE analysis the cost of transport and maintenance of the network is not considered, and then it is possible to compare it with the grid-parity definition. Moreover, this method is not suitable for assessing the profitability or cost efficiency of a specific PV power plant (Kost, et al., 2013)

Therefore, the main issue in this analysis is to establish the relationship between the life-cycle cost of the PV system (LCC, €) and the annual energy produced until its lifetime estimation (N, years). The LCOE can be defined then by the following expression:

$$\mathrm{LCOE}(€ \cdot \mathrm{kWh}^{-1}) = \frac{\mathrm{LCC}}{\sum_{i=1}^{N} \frac{E_{PV} \cdot (1-\varepsilon_{pl})^{i}}{(1+d)^{i}}} \tag{1}$$

In the previous equation E_{PV} is the annual PV electricity yield (kWh · year^{-1}), where it has been considered an annual decrease rate of the power generated ε_{pl} (%). Likewise any investment, it is necessary to establish a value for the capital invested by the system's owner, so d (%) is the nominal discount rate, which intrinsically considers the annual inflation rate g (%)

The life-cycle cost of the PV system *(LCC)* will depend on the initial investment (PV_{IN}, €) and the annual operation and maintenance *(O&M)* cost *(PV_{AOM}, €)* associated with the selected PV technology. In the literature it can be found that the life-cycle of the system could be defined from the user's standpoint or the grid's standpoint, depending on if the application of supporting measures, such as tax exemptions, buy-down or grant policies are considered or neglected (Nofuentes, et al., 2002). Nowadays this differentiation is not applicable in the case of Spain as there is an absence of any sort of incentives or grants to the photovoltaic technology.

Unless the project is not financed, the initial investment will be affected by an annual interest rate during a period of time, and the O&M will extend until the lifetime of the technology, so the sum of these annual costs has to be translated to the present worth of the initial investment cost of the PV system *($PW[PV_{IN}]$, €)* and the present worth of the operation and maintenance cost *($PW[PV_{OM}(N)]$, €)* associated with the PV technology (Talavera, et al., 2013).

$$\text{LCC (€)} = \text{PW}\,[\text{PV}_{\text{IN}}] + \text{PW}\,[\text{PV}_{\text{OM}}(\text{N})] \tag{2}$$

The annual operation and maintenance cost is assumed to be proportional to the initial investment, according to some authors. Additionally, an annual escalation rate (ε_{PVAOM}) of the operation and maintenance cost of the system has been defined, so $PW[PV_{OM}(N)]$ may be re-written as:

$$\text{PW}\,[\text{PV}_{\text{OM}}(\text{N})] = \text{PV}_{\text{AOM}} \cdot \frac{\text{K}_{\text{PV}} \cdot (1 - \text{K}_{\text{PV}}{}^{\text{N}})}{1 - \text{K}_{\text{PV}}} \tag{3}$$

Where $K_{PV} = (1+\varepsilon_{PVAOM})/(1+d)$.

The investment can be financed either with own capital ($PW[PV_{OC}]$, €) or external capital ($PW[PV_{EC}]$, €), thus, the initial investment cost can be expressed as:

$$\text{PW}\,[\text{PV}_{\text{IN}}] = \text{PW}\,[\text{PV}_{\text{EC}}] + \text{PW}\,[\text{PV}_{\text{OC}}] \tag{4}$$

The present worth of the own capital could have been invested in any other financing product, so it is suitable to assign this amount of money an annual retribution in form of dividends (d_i), similar to the interest that a risk-alike project could have offered. The assumption that the investment will be amortized at the end of the life-cycle of the system has been made and for its calculation the following equation is used, considering the factor $q = 1/(1+d)$:

$$\text{PW}\,[\text{PV}_{\text{OC}}] = \left(\text{d}_{\text{i}} \cdot \text{PV}_{\text{OC}} \cdot \frac{\text{q} \cdot (1 - \text{q}^{\text{N}})}{1 - \text{q}} + \text{PV}_{\text{OC}} \cdot \text{q}^{\text{N}} \right) \tag{5}$$

The rest of the investment, $PV_{EC} = PV_{IN} - PV_{OC}$, may be financed with an annual loan interest i_l (%) and loan term N_l (years)

$$\text{PW}\,[\text{PV}_{\text{EC}}] = \left((\text{PV}_{\text{IN}} - \text{PV}_{\text{OC}}) \cdot \text{i}_{\text{l}} \cdot \frac{(1 + \text{i}_{\text{l}})^{\text{N}_{\text{l}}}}{(1 + \text{i}_{\text{l}})^{\text{N}_{\text{l}}} - 1} \cdot \frac{\text{q} \cdot (1 - \text{q}^{\text{N}_{\text{l}}})}{1 - \text{q}} \right) \tag{6}$$

The discount rate used in both equations has been matched to the weighted average cost of capital (WACC) to reflect the cost that the owner of the PV system must pay for using the available financial resources.

The previous step for the calculation of the LCOE is the assignment of values to the parameters identified above. Starting with the purely financial variables, any sort of subsidy or grant has been removed as it corresponds with the present Spanish legislation and it is also more realistic concerning the trends for the rest of the countries.

Among all the parameters defined, it is interesting to oversee the separate influence that they individually have on the variation of the LCOE, thus a sensitive analysis will contribute to this purpose based on the premise of a general standard case.

The assignation of values to these parameters will start with the purely financial data. In this chapter an amount of 80% of the initial investment has been considered to be borrowed at an annual loan interest $i_l = 4.13\%$ and a loan term N_l of 20 years. In this mixed-financed formula the remaining part (20% of PV_{IN}) is supposed to be defrayed with own capital (PV_{OC}), to which an annual retribution in form of dividends, $d_i = 3\%$, will be assigned and it will be amortized at the end of the life-cycle of the system (European Central Bank, February 2014).

The annual inflation rate should be adapted not to the last data available, which in the case of Spain is not very realistic owing to the inflection point in the economy (g=0.3% at December 2013). The historical average data in Spain from 2001 can be approximately averaged to g=2.8%, so this value is more appropriated for this analysis (Bank of Spain, 2014) (Eurostat. Statistical office of the European Union, 2014).

Finally, the last purely cost parameter is the discount rate *(d)*, which in prior lines was matched to the weighted average cost of capital (WACC). This cost will approximately be dependent on how the proportion of the dividends required to the own capital and the interest rate used for the external capital is set, so it will vary depending on how the financial resources are chosen. In this analysis, focused on a household general case, the $WACC$ is approximately equal to 3.9%.

The second set of parameters for the LCOE sensitive analysis is more related to the PV system itself. The energy yield of a regular PV household system was assumed from the data available at the Joint Research Center, through its Photovoltaic Geographical Information System (PVGIS), where the estimations of the global irradiation data and the solar potential for the case of Spain are quite properly approximate and a good overview of the Spanish characteristics is also given.

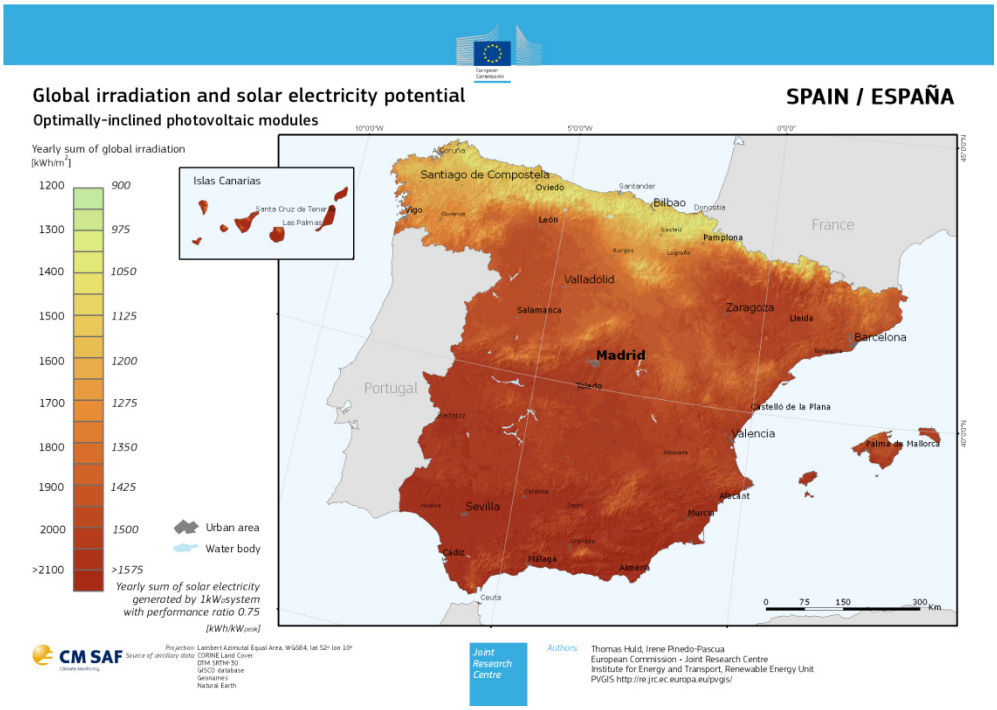

Figure 2.1. Global irradiation and solar potential in Spain (Courtesy of JRC, Ispra)

In this sense, an average annual yield of 1350 kWh · KWp^{-1} installed has been taken. The relation of this yield with the global irradiation for an optimally tilted PV system can be observed in the previous figure (Joint Research Centre. Institute for Energy and Transport (IET), 1998-2011).

Additionally, an annual degradation rate (ε_{pl}) of the power of 0.5% has been considered, which lies within the range defined by some photovoltaic experts

(Jordan & Kurtz, 2013); meanwhile, the lifetime of the PV modules and the BOS have been assumed to be for 25 years, even though experimental evidence of longer operational systems under an acceptable range of power losses has been proven (Chianese, et al., 2003) (Dunlop, et al., 2005). For the purposes of our study, we set the number of years according to the guaranty offered by the modules and inverters' manufacturers.

Another parameter with big influence in the LCOE value is the initial investment cost per kWp, which variability will depend on the country, the PV modules stock at the moment of the analysis and the scenarios assumed. Concerning the analysis carried out by the EurObserv'ER database barometer, a price of 1751 € · kWp^{-1} for roof-PV systems installed in Germany in the last quarter of 2012 was defined (EuroObserv'ER, 2013), meanwhile the Fraunhofer Institute for Solar Energy Systems assess a range of prices oscillating in Germany between 1000-1800 € · kWp^{-1}, depending on if its referred to utility or residential scale (Kost, et al., 2013). Other sources estimate a scenario for utility scale plants of 1220 € · kWp^{-1}, meanwhile the residential PV systems reach a value of 1700 € · kWp^{-1} (Ossenbrink, et al., 2013)

It is recommendable to analyze the evolution of the installed PV system prices in Spain, so some economic data from 2006 to 2012 have been compiled, when the price of installed PV systems ranged from 2 - 2.5 € · Wp^{-1} (International Energy Agency, 2013). According to the slowdown of the Spanish PV industry, the economic crisis in the country and some PV Spanish economic reports and news (Unión Española Fotovoltaica, Noviembre 2013), it has been assumed that in the first quarter of 2014 the prices experienced an annual decrease of 9% when compared to 2012, so the investment per kWp in Spain could range between 1.6-2 € · Wp^{-1}, with a possible forecast of 0.94-1.18 € · Wp^{-1} for 2020. For the sensitivity analysis purposes, a unitary price of 1.9 € · Wp^{-1} has been chosen.

The last photovoltaic parameter necessary for the analysis is the annual operation and maintenance cost estimation, normally referred to a percentage of the initial investment and its annual increment too. All the PV systems proposed are medium size and lacking of moving parts, so according to the literature consulted, this parameter may represent annually a 1.5% of the initial investment cost (Ossenbrink, et al., 2013). We have avoided the possible cost for the substitution of certain modules or inverters. There is no consensus about

the suitability of the inclusion of this cost under the annual O&M parameter or if it is already included in this estimation.

A different varying element has also been introduced, as an annual escalation rate of the O&M cost has been considered. It has been proposed to be equal to the value of the annual inflation rate, so $\varepsilon_{PVOM} = 2.8\%$.

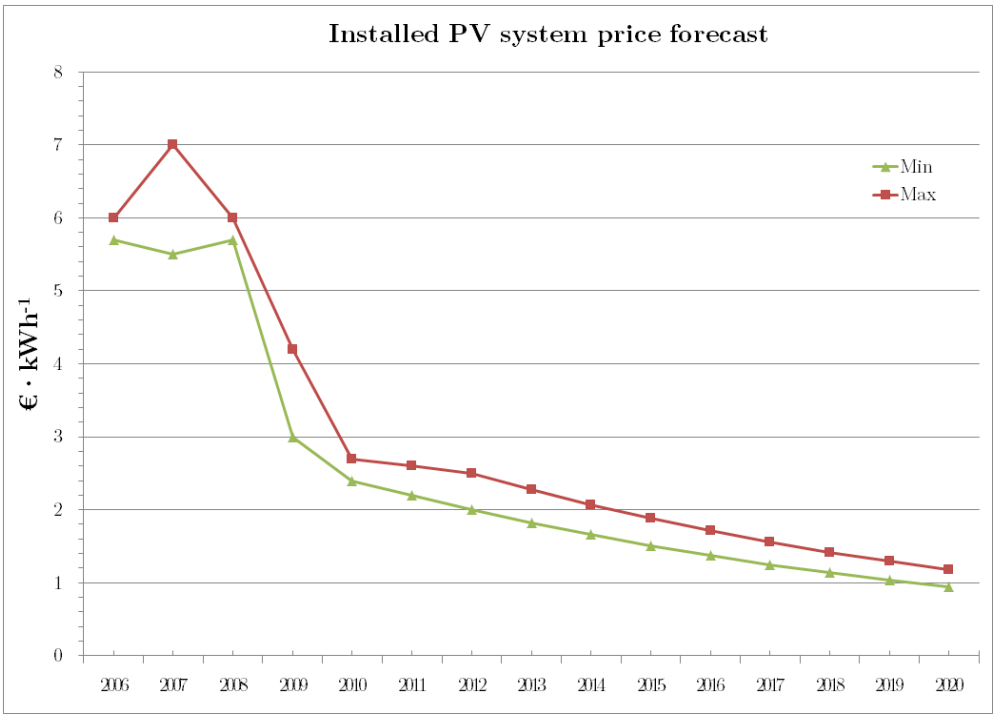

Figure 2.2. PV system price evolution and forecast in Spain

A summary of the parameters used can be observed in the following table, which produces a result of $LCOE_{2014} = 0.1239$ € · kWh^{-1} under the premises considered for the year 2014. This value agrees about the forecast and available data for the case of Spain (Pérez, et al., 2013) and it is very similar to other European countries despite the differences in energy generation profiles and the PV installation prices (Kost, et al., 2013) (Ossenbrink, et al., 2013).

Factors assumed for 2014								
				Financial				
PV_{IN} ($€ \cdot kWp^{-1}$)	E_{PV} ($kWh \cdot kWp^{-1}$)	PV_{OM} $\% \cdot PV_{IN}$	ε_{PVOM} (%)	Interest loan (80% PV_{IN})		Dividends (20% PV_{IN})	g (%)	ε_{pl} (%)
				i_l (%)	N_l (years)	di (%)		
1900	1350	1.5	2.8	4.13	20	3	2.8	0.5

Table 2.1. Costs factors summary for a general case

Although the retail electricity price in Spain is very volatile and variable, as well as affected by constantly changing laws and the electricity market itself, in general terms it can be asserted that grid-parity has been achieved in Spain and it is consolidated for household facilities, because the last Spanish Official Gazette (BOE) set a price of 0.124107 $€ \cdot kWh^{-1}$ (excluding taxes) for non-hourly discriminatory residential tariff for the first quarter of 2014 (Ministry of Industry, Energy and Tourism, February 2014), so adding the extra tax to the electricity consumption ($€ \cdot kWh^{-1} \cdot 1.05113 \cdot 4.864\%$) and the Value Added Tax (VAT), the unitary price that the end-user is paying rises up to 0.157847 $€ \cdot kWh^{-1}$

However, the grid-parity statement has to be cautiously taken because although is a reality, the retail electricity price may hide a non-profitable scenario. The LCOE is dependent on the assumptions made regarding the cost and photovoltaic parameters, with their corresponding uncertainties.

If a base case is defined with constant cost parameters, within the Spanish territory the location variable will affect the LCOE value. The level of radiation falling on the PV surface will vary, thus the electricity yield, and in a minor way also the operational and maintenance cost and the lifetime of the system.

Therefore it is more clarifying to widen the LCOE analysis by considering a range of possible scenarios, through a proper sensitivity analysis. For this purpose, variations in the main factors of ±20% have been introduced which results are visualized in Figure 2.3. The effect of the increment or decrement in the parameters mentioned follows a similar trend when compared to other studies (Aldo Orioli, 2014).

Under a certain financial scenario, which it is very unpredictable, the most influential parameters are the one related to the energy yield and the PV price. This particularity justifies the similarities in the LCOE values among the European countries, where the decrease in the availability of solar radiation could be compensated by the PV installation prices decrease or not; therefore this sensitivity analysis could be translated to the peculiarities of a certain location within the European territory.

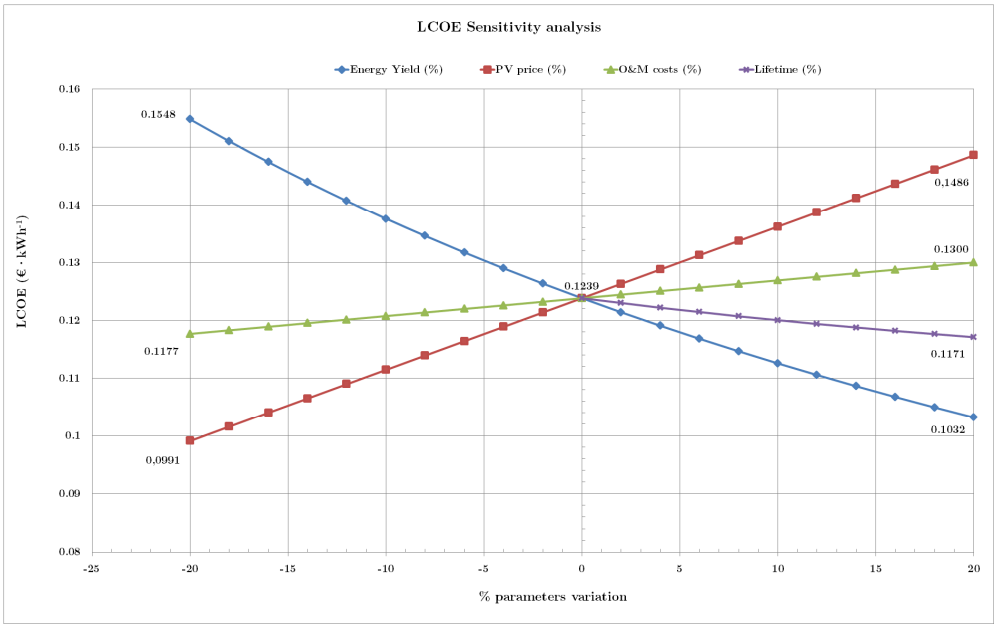

Figure 2.3. $LCOE_{2014}$ sensitivity analysis results

It should be emphasized that in any of the individual variations of the parameters, the LCOE is lower than the electricity retail price, thus the spectrum of the grid-parity feasibility extends.

The combination of a possible pessimist and optimist scenarios is gathered in the following table which can be used as an extreme leeway for the statement of the grid-parity profitability depending on the scenarios considered. Only in the worst scenario possible there would be a non-profitable grid-parity for the LCOE in 2014, but the learning curve predicted by some authors (Kost, et al.,

2013), and the increasing electricity prices would soon overcome this pessimistic scenario.

Pessimistic Scenario				Optimistic Scenario			
PV_{IN} (€ · kWp^{-1})	E_{PV} (kWh · kWp^{-1})	PV_{OM} % · PV_{IN}	N (years)	PV_{IN} (€ · kWp^{-1})	E_{PV} (kWh · kWp^{-1})	PV_{OM} % · PV_{IN}	N (years)
2280	1050	1.8	25	1520	1620	1.2	30
LCOE = 0.195 € · kWh^{-1}				LCOE = 0.074 € · kWh^{-1}			

Table 2.2. Pessimistic and optimistic scenarios in the sensitivity analysis

Likewise the Spanish situation, the comparison of the different LCOE for each country with the local retail electricity prices could be used to draw a map of the grid-parity profitability in the EU (Ossenbrink, et al., 2013)

Nevertheless, from a practical and technical point of view, the real impact and materialization of this reality in the residential market could only be achieved by means of measurements like net-metering or net-billing, which will not be object of study in this thesis.

2.2.2. Grid-parity profitability, a financial issue depending on the consumption profile

Despite the grid-parity feasibility, it cannot be immediately translated into the same message regarding financial terms. It is recommendable to undertake an economic analysis that assesses the profitability of the investment, although a reduction in the money to be paid to the electricity company may appear in the electric bill if the PV generation substitutes the incomes from the grid. Savings in the electricity consumption or in the electric bill may not overcome the investment and operation and maintenance costs of the system.

A financial evaluation of the most common profitability indices is required for the evidence of the grid-parity profitability; these are the Net Present Value (NPV), the Discounted Payback Time (DPBT) and the Internal Rate of Return (IRR).

The economic calculation procedures for the PV technology have been elsewhere explained in the literature (Talavera, et al., 2010), and thus the Net Present Value is usually written as follows:

$$\mathrm{NPV} = \mathrm{PW}[\mathrm{CIF}(\mathrm{N})] - \mathrm{LCC} \tag{7}$$

The costs of the system were defined in the prior section, and the cash inflows are generated by the product of the electricity produced with the PV systems times the unitary price received for each unit of energy generated and self-consumed (kWh).

The approach of this study is focused on those PV installations where the energy produced is used for counteracting the consumption of electricity from the user's standpoint, thus meaning some savings to the end user as he avoids the consumption of electricity from the grid once the balance of consumption minus generation is done.

The application of PV plants for the integration in the generation pool as a regular energy source is not viable yet in the short-term because the generation parity is still unreachable.

Under a scenario where the net or bill-metering is introduced, the PV electricity generated has to be divided mainly in two terms. Self-consumed electricity (E_{PVs}, kWh) and the excess of electricity injected into the grid (E_{PVe}, kWh). Depending on the sort of end-use electricity installation, the self-consumed electricity in turn should be decomposed into the electricity self-consumed instantaneously (E_{PVsi}, kWh) and consumed in a deferred time (E_{PVsd}, kWh) when there is a lack of sun availability.

Therefore, in this study there are distinguished three unitary prices: p_{si} ($€ \cdot \mathrm{kWh}^{-1}$), defined for the instantaneously self-consumed share, which is set at the retail electricity price of the market at the moment of consumption; the proportion of deferred self-consumed energy, p_{sd} ($€ \cdot \mathrm{kWh}^{-1}$), and the remaining excess electricity generation fed into the grid, which may be compensated at a different price (p_e, $€ \cdot \mathrm{kWh}^{-1}$) and with certain limitations regarding its magnitude during a specific period of time, so the cash inflows PW[CIF(N)] are defined as:

$$PW\,[CIF(N)] = p_{si} \cdot E_{PVsi} \cdot \frac{K_{si} \cdot (1 - K_{si}^{N})}{1 - K_{si}} + p_{sd} \cdot E_{PVsd} \cdot \frac{K_{sd} \cdot (1 - K_{sd}^{N})}{1 - K_{sd}} + \\ + p_e E_{PVe} \frac{K_e \cdot (1 - K_e^{N})}{1 - K_e} \tag{8}$$

In the previous equation, K_{si}, K_{sd} and K_e are factors related to the rises of the electricity price, where ε_{si}, ε_{sd} and ε_e stand for the annual increase rate of the electricity price that is saved (either instantly or deferred self-consumed) and injected into the grid respectively. In each one of them a factor for the annual decrease rate of the power of the grid-connected PV system ε_{pl}, is also included which was defined in previous sections.

$$K_{si} = (1 + \varepsilon_{si}) \cdot (1 - \varepsilon_{pl}) / (1 + d) \tag{9}$$

$$K_{sd} = (1 + \varepsilon_{sd}) \cdot (1 - \varepsilon_{pl}) / (1 + d) \tag{10}$$

$$K_{e} = (1 + \varepsilon_{e}) \cdot (1 - \varepsilon_{pl}) / (1 + d) \tag{11}$$

In the previous equations, although the price of the annual excess electricity generation fed into the grid, p_e, is important in the profitability of the PV systems, the relevant and most influencing variables are the instantaneously self-consumed electricity price, p_{si}, and the deferred consumed energy, p_{sd}.

Normally, the lack of legal regulation or the existence of confusing policies regarding the deferred consumed energy, makes both self-consumed prices match the retail electricity tariff, at least in the Spanish regulating framework, although some reports (Comisión Nacional de la Energía, 2013) and some royal decree drafts have been published on that subject including extra taxes (Ministry of Industry, Energy and Tourism, July, 2013)

The link of self-consumption prices with the electricity retail prices has an immediate consequence, because likewise the electricity market, it will be also subjected to the possible fluctuations (real or induced) in the purchase-selling market, and consequently the conditions of the initial investment.

The expected ascending trend of the electricity prices versus the LCOE constant value, regarding the specific year of the investment, could offer a favorable scenario for any investment, but nothing further from the truth, highs and lows swings of the electricity tariffs may become a threat to these

previsions. For example, a Spanish household proprietary of a PV system in the beginning of 2013, may have observed how its PV installation could face different profitability scenarios along the same year. Modifying the $[PV_{IN}]_{kWp}$ to the estimations for the 2013 ($[PV_{IN}]_{kWp}$=2000 €$\cdot$kWp^{-1}), and with the variations in the retail electricity price, the percentage oscillations between can be observed in the next figure (Ministry of Industry, Energy and Tourism, 2014).

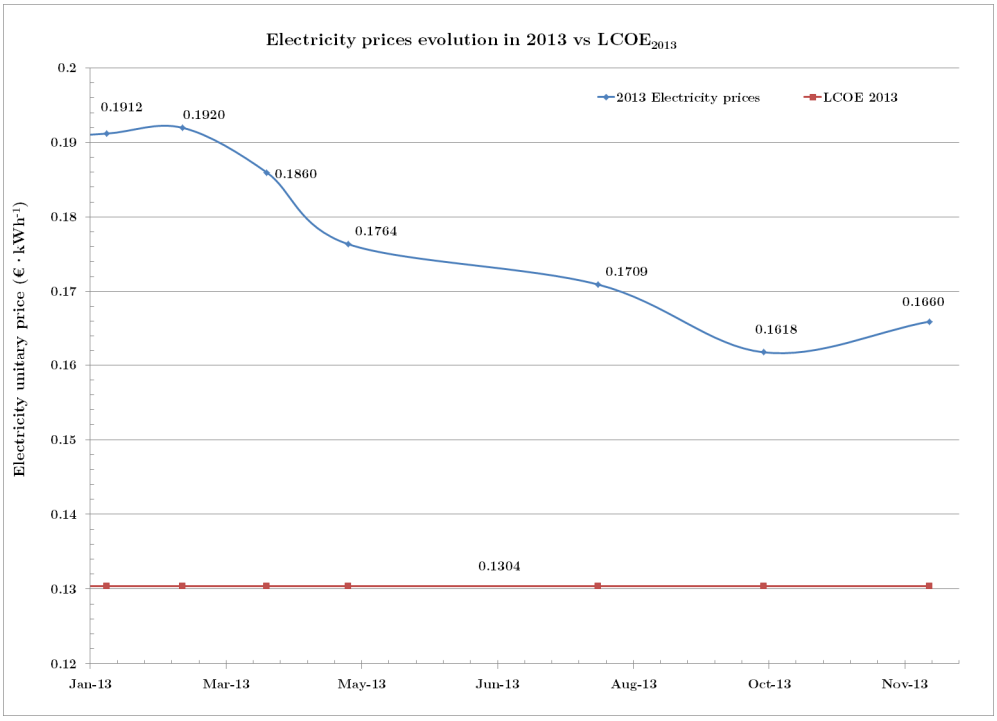

Figure 2.4. $LCOE_{2013}$ vs Electricity prices for 2013

Moreover, the grid-parity feasibility is not only affected by the fluctuations in the electricity market, but it is also subjected to the tariff contracted by the end-user as it was glimpsed previously. It may occur that two household users, with the same PV system, regarding its size and assumptions, may encounter divergences in their profitability calculations of the grid-parity depending on the tariff contracted.

This approach has a challenging application because, at the current date, most of the household consumers which have a low-medium power contracted are provisionally gathered in the denominated “Voluntary retail prices for the small consumer” which regulates the price the consumer must pay to the electricity company. In this tariff, both the power fee and the energy price are set by the Government and although it is predicted to chance in the following months, it is normally a fixed price throughout the whole day; but it also contemplates two variations with hourly discrimination tariffs (Ministry of Industry, Energy and Tourism, February 2014), so the analysis will be influenced. This analysis gets complicated in high power and high voltage consumers, where up to six different periods are defined depending on the hour, day and month of the year.

Table 2.3 shows the possible virtual non-profitability of the grid-parity in the hourly discriminated household tariffs. Whether this situation really exists or not will mainly depend on a conscientious energy consumption profile analysis. An additional point of uncertainty arises, because not only two household users with the same PV system may encounter divergences in their profitability indexes depending on the tariff contracted. Even these two households now under the same tariff may obtain different results regarding the profitability of their PV installations according to their consumption profile.

Household Tariffs	Energy price ($€ \cdot kWh^{-1}$)	Energy price with taxes ($€ \cdot kWh^{-1}$)	h/day	Average Energy price ($€ \cdot kWh^{-1}$)	$LCOE_{2014}$ ($€ \cdot kWh^{-1}$)
Hourly discriminated (3 periods)	0.150812	0.191812	10	0.124432	0.1239
	0.071879	0.091420	8		
	0.044146	0.056148	6		
Hourly discriminated	0.148832	0.189294	10	0.1219	
	0.057995	0.073762	14		
Single Tariff	0.124107	0.157847	24	0.157847	

Table 2.3. Retail electricity prices for household consumers distributed in periods

The cash inflows defined previously in the equation 8 only take into consideration one single tariff per addend, which it could be only applicable in households' users according to the single tariff in the voluntary retail prices for the small consumer. Therefore, the new contribution in the present worth of the cash inflows (PW[*CIF(N)*]) is the introduction of the different price periods adapted to the consumption profiles as equation 12 shows:

$$\begin{aligned} PW\,[CIF(N)] = & \left(\sum_{i=1}^{p} p_{si} \cdot E_{PV_{si}}\right) \frac{K_{si} \cdot (1 - K_{si}^{N})}{1 - K_{si}} + \left(\sum_{i=1}^{p} p_{sd} \cdot E_{PV_{sd}}\right) \frac{K_{sd} \cdot (1 - K_{sd}^{N})}{1 - K_{sd}} + \\ & + \left(\sum_{i=1}^{p} p_{e} \cdot E_{PV_{e}}\right) \frac{K_{e} \cdot (1 - K_{e}^{N})}{1 - K_{e}} \end{aligned} \tag{12}$$

This modification complicates the calculation procedures because it does not only affect the price applied, but it also influences in the photovoltaic energy prediction and the consumption profile measurement, as it will have to be done in hourly periods, but on the contrary, a more precise forecast in the financial feasibility of a PV system will be possible.

Another term regarding the balance of cash inflows versus cash outflows, concerns the addition of taxes or fees for the self-consumed energy. So far, the use of self-produced energy has been considered a net positive input in the NPV equation, but several countries, like Germany, have created a Tax for consumers for the use of clean energy (Bloomberg, 2014). Spain is also programming a charge for solar electricity producers in terms of a back-up toll fee that the user will have to pay to the Electrical company for the energy that it is self-generated, regardless if it is used for self-consumption or injected the excess to the grid (Ministry of Industry, Energy and Tourism, July, 2013).

Obviously, this measure would decrease the present worth of the cash inflows, adding a negative term in the previous equation

$$\begin{aligned} PW\,[CIF(N)] = & \left(\sum_{i=1}^{p} p_{si} \cdot E_{PV_{si}}\right) \frac{K_{si} \cdot (1 - K_{si}^{N})}{1 - K_{si}} + \left(\sum_{i=1}^{p} p_{sd} \cdot E_{PV_{sd}}\right) \frac{K_{sd} \cdot (1 - K_{sd}^{N})}{1 - K_{sd}} + \\ & + \left(\sum_{i=1}^{p} p_{e} \cdot E_{PV_{e}}\right) \frac{K_{e} \cdot (1 - K_{e}^{N})}{1 - K_{e}} - p_{tax} E_{PV} \frac{K_{tax} \cdot (1 - K_{tax}^{N})}{1 - K_{tax}} \end{aligned} \tag{13}$$

$$K_{ptax} = (1+\varepsilon_{ptax}) \cdot (1-\varepsilon_{pl}) / (1+d) \tag{14}$$

Although the LCOE studied previously is independent of the electricity price cost, another point of view would be to include this back-up toll fee as a cash outflow of the system, this is, an addend of the life-cycle costs equation of the PV system. Under this scenario, the LCOE would increase, thus reducing the profitability of the grid-parity statement, but this focus is out of the scope of the thesis.

The PV project will be profitable provided there is a positive NPV and the Internal Rate of Return (*IRR*) is greater than the WACC. For its calculation it is necessary to solve the following equation for the variable *d*, which stands for the value of the discount rate that makes $NPV = 0$ and it can be solved by an iterative methodology.

$$0 = \mathrm{PW}[\mathrm{CIF(N)}] - \mathrm{LCC} \tag{15}$$

It is important to clarify that if the parameters involved in the calculation of IRR in the previous equation have been considered in current currency, which considers the inflation, the nominal IRR is obtained ($\mathrm{IRR}_{\mathrm{nominal}}$).

Concerning the finance liquidity, the discounted payback time (*DPBT*) index is widely used, as it refers to the required number of years (N=*PB*) that satisfy that the cash-inflows are at least equal to the life-cycle cost of the system. It is important to highlight that the cash flows beyond that moment are not considered.

$$\mathrm{PW}[\mathrm{CIF(PB)}] \geq \mathrm{LCC} \tag{16}$$

Once these parameters have been defined, the statement of the grid-parity profitability has to be delegated to a financial analysis combined with the study of a certain consumption profile, as the one it will be proposed in the following section.

2.3. Proposal of base case studies in energy and economic terms

The generalist economic point of view described previously is going to be particularized for a relatively large PV intervention in a specific and real location. In this section, an economic and cost analysis of several grid-connected PV systems on buildings has been carried out similar to other studies made in Germany or Italy (Spertino, et al., 2013), but in this case it has been adapted to the last Spanish legislation because the examples found in the literature relative to the country are referred to a really different legislative scenario and it also differs in the technical solution because in those reports there were analyzed household facilities (Colmenar-Santos, et al., 2012).

Following the discussion on the LCOE and financial feasibility for the hypothetical and general base case, the analysis is going to delve into the real or virtual grid-parity profitability, where the concepts self-consumption and net-metering will be deeply studied. The intention of the following lines is also to reinforce the possibilities of the distributed generation and smart grids, at least from a general view.

The procedure for the reviewing of the economic parameters, combined with the proper sensitive analysis will be similar to other studies published previously (Aldo Orioli, 2014), but as a point of novelty, more than a single electricity retail tariff under the same consumption profile will be introduced to reinforce the new approach related to the grid-parity profitability. Moreover, the energy estimations will be corroborated and complemented with measured energy data of already installed systems that are alike.

Several reports asses that PV tracking has become an attractive alternative for those regions of high share of direct irradiation **(International Energy Agency, 2013)**, so in this section it is also intended to include a brief energy and economic comparison between fixed and tracking PV, and whether the increments in the energy yield compensate the rise in the initial investment.

2.3.1. Identification of areas and their energy production estimation for fixed systems

The study of the photovoltaic potential or massive PV interventions of a certain area has become a classical approach for the deployment of the technology. Several ambitious projects were carried out in Jaén (Almonacid, et al., 1995) and large scale analyses are published within the Spanish territory regarding roof surfaces (Izquierdo, et al., 2008) as well as in the European Union (Súri, et al., 2007). The issue is that either these analyses are outdated or several assumptions were made (in energy and economic terms) which may distort a proper yield and profitability conclusions.

The Campus of the University of Jaén, with the coordinates 37.73N and 3.67W, is the location chosen to carry out the energy analysis that will be used as one of the base case to the forthcoming cost and financial results for PV grid-connected systems (PVGCS). The sufficient radiation levels in the zone are taken for granted, so the technical analysis will mainly consist on the identification of potential areas where the PVGCS ensure that the Spanish law is upheld among other aspects, and subsequently each area is analyzed in order to study its profitability in energy terms.

In an preliminary stage and making use of online tools within reach such as Google Maps™, there have been identified the feasible areas for the installation of the possible PV modules, but this step has just be done in a rough guess. The usage of this sort of techniques for measuring the useful roof surface area of a certain building sample has been previously implemented (Ordóñez, et al., 2010). In this identification stage, there have been rejected buildings that were not updated and also those locations whose future usage and shape might be modified according to the urban development in the area.

A first criterion to adjust the identification of suitable areas to the PV systems comes from the grid-connection supply characteristics of the Campus, therefore an analysis of the electrical grid of the University will allow us to identify possible points of connection of the likely PV systems.

The study of the electrical configuration has to be combined with space availability requirements and the usefulness of the selected zones besides taking into account the future urban development of the Campus. Additionally, the

simplicity of the intervention will also be a key criterion for a finer selection of the areas, by means of reducing to the extreme any unnecessary civil work and maximizing the already existing structures, like the parking lots.

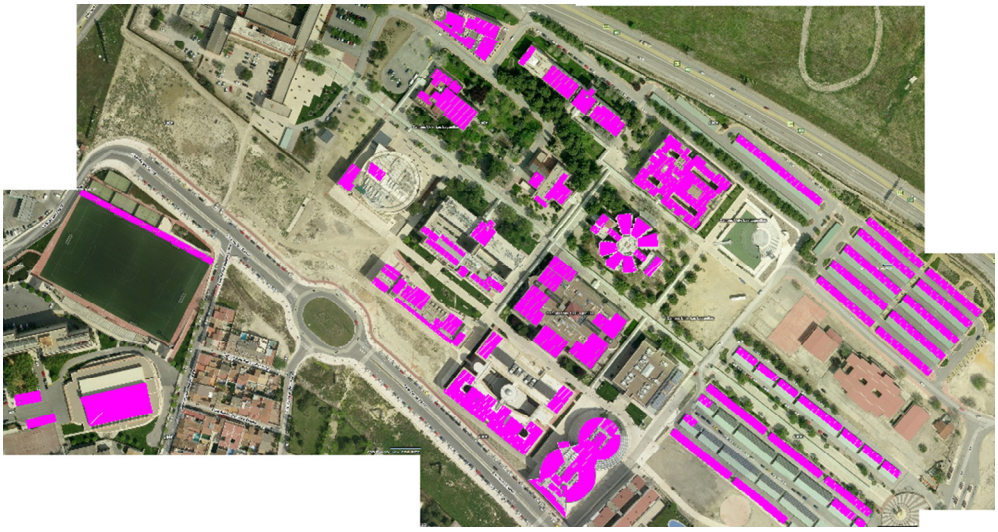

Figure 2.5. Gross identification of possible PV areas (adapted from Google MapsTM)

Figure 2.6. Potential PV areas of the Campus (adapted from Google Maps™)

The Campus has been divided into four different potential areas, as it can be

observed in Figure 2.6, after the analysis of the electrical grid distribution, the locations of the transformer stations that are property of the University and those owned by the local Electricity Company, together with the structural constraints.

This satellite photography also allows, in a preliminary stage, the distribution of the modules on top of the surfaces of some of the locations chosen, and therefore to make a first round check of the possible photovoltaic power to be installed. On the basis of selecting a standard PV module and its location, following either optimal tilt and azimuth rules, or taking benefit of any pre-existing structure, a gross distribution of the PV modules has been done as the one observed in the Figure 2.7.

Figure 2.7. First approximation of PV capacity in a certain location

The maximum shadow that it may happen among files of modules has been calculated by applying simple equations on the day of the year where the sun is at its lower position and those places where they clearly mean a problem have also rejected, for example due to shadows from other objects of the building, bad orientation or leaning of the strings and access obstacles or heat evacuation due to the air-conditioning machines installed on top of the roofs.

One of the most important steps was the subsequent tridimensional description of the elements that configured the space selected which might condition the photovoltaic exploitation, because the gross selection of PV areas are influenced by surrounding buildings, other urban elements or the vegetation that can cause self-shadowing which, at first glance, it is not detectable by means of the Google Maps™ tool.

The use of classic cartography only gets data at a planimetric level; this is, with no information regarding the height and elevation of the elements under study, so a most powerful tool should be chosen with the aim of building a complete planimetric and altimetric map of the area.

For that purpose a GIS platform for the integration of the graphical information has been used, which it was obtained through the application of photogrammetry and orthopicture, similar to other studies published (Hofierka & Kanuk, 2009) (Izquierdo, et al., 2008).

The photogrammetry starts from vertical aerial pictures that have been processed to eliminate all sources of deformations and thus obtaining an improved orthogonal projection of the area. Thereupon, the orthopicture tool has been used in order to obtain an accurate topographic uplifting of the buildings, parking lots, vegetation and other elements of the Campus. This tool gathers under the same system real pictures (satellite images), in the absence of errors or deformations, with geometric properties similar to the ones offered by traditional cartography, allowing the measurement of angles and distances.

A previous step for the calculation of the energy that each PV system could produce is either the real measurement of the available radiation falling on the modules' surface or its estimation. Regarding the later, the minimum and most common information necessary consists on the monthly average values of horizontal daily global radiation ($H_{dm}(0)$).

There is no reference regarding an official radiation data base, as the solar radiation depends on random phenomena which are based on average statistical data from several years of measurements. The differences in the measurement devices and in the averaging techniques make the available data offer a large dispersion when they are compared among them, rising up to 14% (Lorenzo, 2006). The monthly average radiation data used in this methodology have been obtained from the free service offered by the NASA research center in Langley, where these parameters have been measured for more than two decades (Atmospheric Science Data Center, 2013).

From the reduced set of data mentioned, it is possible to extrapolate the behavior of each day of a selected month by defining firstly the denominated "representative day". This is an hypothetic day located in the middle of the month under consideration, in which it is assumed that its daily horizontal global radiation value ($H_d(0)$) matches the monthly average value of horizontal daily global radiation ($H_{dm}(0)$) for that month (Lorenzo, 1994) (Iqbal, 1983). Subsequently, every day within the month under study is considered to have an identical temporary evolution, related to those environmental parameters, than its representative day.

Despite the simplification and assumption of this methodology, the estimations are reliable and the differences are below 3% if it is compared with other methods (Perpiñán, et al., 2007).

Prior to the calculation of the radiation on a tilted surface, it is necessary to obtain the horizontal beam and diffuse monthly average daily irradiation components ($B_{dm}(0)$ and $D_{dm}(0)$). In the case of a lack of these data, there are several methods for their calculation. Among them, the expressions proposed by Liu y Jordan have been used (Liu & Jordan, 1960), together with the correlations obtained by Page (Page, 1979).

Although the ideality is to have the hourly distribution of the irradiation for each day of the month, and hence the irradiance (in term of power), in the case of unknowing the data there are procedures for the estimation of the hourly evolution of the irradiation according to the method proposed by Whillier (Whillier, 1956).

The PV systems proposed in the base case have a defined inclination and azimuth angles, so for the effective calculation of the hourly distribution of the irradiations components within the PV generators' surfaces, they have been modeled according to the method proposed by Pérez for the diffuse component on an arbitrary oriented surface (Pérez, et al., 1987). In this procedure, the level of dirt on the generator has been supposed to be low-medium and the energy losses due to the incidence angle have been taken into account (Martin & Ruiz, 2005).

Once the meteorological inputs of the systems have been defined, the energy generated by each installation proposed is calculated using the Osterwald method (Osterwald, 1986), which allows the determination of the PV maximum operating power under certain incident irradiance and cell temperature. Although it is a simple approximation model, its good behavior has been validated by several studies (Fuentes, et al., 2007) (Fuentes, 2009). Nevertheless, the divergences and differences in the energy results depending on the calculation methodology are under the percentage of uncertainty that it should be assumed in any PV prediction model, which is normally rated below ±3% (Herrmann, et al., 1997).

The energy generated is the result of the integration of the maximum power calculated using the following equation, where there is a minimum irradiance threshold of 100 $W \cdot m^{-2}$ for its reliable use:

$$P_M(W) = P_{M,STC}(W) + \frac{G(\alpha,\beta)\,(W \cdot m^{-2})}{G_{NOCT}\,(W \cdot m^{-2})} + [1 + \gamma\,(^{o}C) \cdot (T_C\,(^{o}C) - 25^{o}C)] \qquad (17)$$

The cell's temperature is related both to the incident irradiance and the surrounding ambient temperature by using the equation (18), where the influences of the wind have been omitted:

$$T_C(^{o}C) = T_A(^{o}C) + G(\alpha,\beta)\,(W \cdot m^{-2}) \cdot \frac{NOCT\,(^{o}C) - T_{NOCT}(^{o}C)}{G_{NOCT}\,(W \cdot m^{-2})} \qquad (18)$$

The calculation of the ambient temperature's evolution has been estimated assuming that it changes following two semi-cycles of two cosine functions. For that purpose twelve monthly average values have been used, from the same

NASA database, corresponding to the maximum daily temperature (T_{aMdm}) and the minimum daily values (T_{amdm}) which have been matched to the maximum and minimum temperatures of this representative day (T_{aMdr} and T_{amdr}). (Lorenzo, 2006).

The PV power calculated would be real under the omission of additional losses rather than the one caused by the influence of the temperature, the incidence angle and dirt on the modules' surface. Nevertheless, the real AC power generated by these systems is influenced by inherent different sources of losses.

In Table 2.4 there are summarized the losses considered for our energy analysis, according to the characteristics of the PV potential system locations and the wide experience with real PV measurements found in the literature (Drif, et al., 2007) (Pérez-Higueras, et al., 2010).

DC Losses	
DC Wiring Losses	1.5%
Mismatch Losses	1.5%
Nominal power reduction	1%
Inverter Losses and other losses	
Maximum power point tracking losses	1%
DC/AC Conversion Losses	4%
AC Wiring Losses	1%
Maintenance and breakdown stops	3%
Shadowing	4%

Table 2.4. Additional power losses considered in the energy estimation

Under this calculation procedure and according to the potential power estimations with the inclinations and azimuth constraints and the power limits, the results for this base case are shown in Table 2.5

Potential Areas	Location	PV Power (kWp)	Azimuth (º)	Inclination (º)	Annual Yield (kWh · kWp^{-1})
Area I	Building 1	101	0	30	1435
	S Parking lot 1	110	40	8	1255
	S Parking lot 2	110			
	S Parking lot 3	110			
Area II	Building 2	91	0	30	1435
	N Parking lot 1	100	42	8	1253
	N Parking lot 2	100			
	N Parking lot 3	100			
	N Parking lot 4	98			
Area III	Pergola	110	25	12	1308
	Building 3	74	0	30	1418
Area IV	N-W Parking lot	105	39	8	1256

Table 2.5. Annual energy yield of the locations identified

Location	Annual Yield (kWh · kWp^{-1})	PVsyst Annual Yield (kWh · kWp^{-1})	Classic PVGIS Annual Yield (kWh · kWp^{-1})	Climate-SAF PVGIS Annual Yield (kWh · kWp^{-1})
Building 1	1435	1526	1376	1515
S Parking lot	1255	1379	1263	1382

Table 2.6. Energy yield divergences among several simulation tools

If the aforementioned data are compared with other available simulations tools (see Table 2.6), it is highlighted that our calculated energy yield has been slightly underestimated, mainly because there are three sources of uncertainties:

1.- Different meteorological data, joined with the differences in the calculation of the beam and diffuse components; 2.- divergences in the power translation method used and finally, 3.- assumptions in the quality and quantity of the power losses.

The South parking lot designed in this potential study was intended to be just an extension of the already installed operational system at the same location, implemented by the so-called UNIVER project (Pérez-Higueras, et al., 2001). The validation of the energy yield estimations in out procedure has been corroborated by the comparison of the simulation of the South parking lot with some historical measurements of the PV installation (table 2.7).

		Parking 1 (34.74 kWp)	Parking 2 (48.67 kWp)
2011	E_{yield} ($kWh \cdot kWp^{-1}$)	1453	1494
	H(0) ($kWh \cdot m^{-2} \cdot year^{-1}$)	1746	
2012	E_{yield} ($kWh \cdot kWp^{-1}$)	1525	1532
	H(0) ($kWh \cdot m^{-2} \cdot year^{-1}$)	1739	
2013	E_{yield} ($kWh \cdot kWp^{-1}$)	950	1317
	H(0) ($kWh \cdot m^{-2} \cdot year^{-1}$)	1691	
average	E_{yield} ($kWh \cdot kWp^{-1}$)	1309	1447

Table 2.7. Real energy measurements in the S. Parking lot

The conservatism of the yields proposed in the present document represents more an opportunity rather than a disadvantage, as the lower the energy yield, the greater the LCOE and the lower the cash inflows regarding the self-consumed energy, so the scenario suggested here is a bit pessimistic, so our yield forecast will improve in those scenarios where a tighter analysis is carried out.

Focusing again on the self-generated electricity, the annual yield times the potential PV power can be meaningful for a gross estimation of the savings in electricity at the University throughout a year, but the whole energy balance will act as a black box, thus resulting unrepresentative concerning the consumption profile.

In this thesis the consumption profile of the university throughout a complete year has been studied, concretely from the period corresponding from May 2013 until April 2014. Although it is not averaged data, it is very representative regarding the consumption of the University after several efficiency energy measurements were introduced; so regardless the uncertainties in the consumption linked to meteorological conditions, the consumption should be similar.

Electricity consumption	8,484,229 (kWh · year^{-1})
PV Electricity generated	1,570,684 (kWh · year^{-1})
Potential savings in Electricity	18.51 %

Table 2.8. Figurative electricity savings

Table 2.8 shows the potential savings according to the gross data of the electricity consumed at the University and the PV generation calculated, but normally this figure is overestimated because the consumption and the PV generation profiles are not in phase.

The main approach and achievement of the self-consumption concept is when the hourly load matching is studied, that is, how large the differences between the consumption profile and the energy generated with the PV systems are. For this purpose, the term Net Electricity Generation (NET) will be used according to the energy differences mentioned.

In the base case proposed in this thesis, this electricity balance will allow the identification of the self-energy instantly consumed, the excess of energy injected to the grid and the moments where the energy generated as a self-consumed term in a deferred period could be used, whenever there is a net-

balance mechanism. The importance of this information was previously explained for the definition of the cash inflows in an advanced financial analysis.

The following curve (Figure 2.8) shows the differences between the electricity consumed for a random day (April 9th, 2014) and the theoretically expected curve of the PV systems considering the generation of all the PV systems proposed. At the points where both curves coincide in time, the needs for importing electricity from the grid would be reduced, so all the energy produced with the PV plant is instantly consumed.

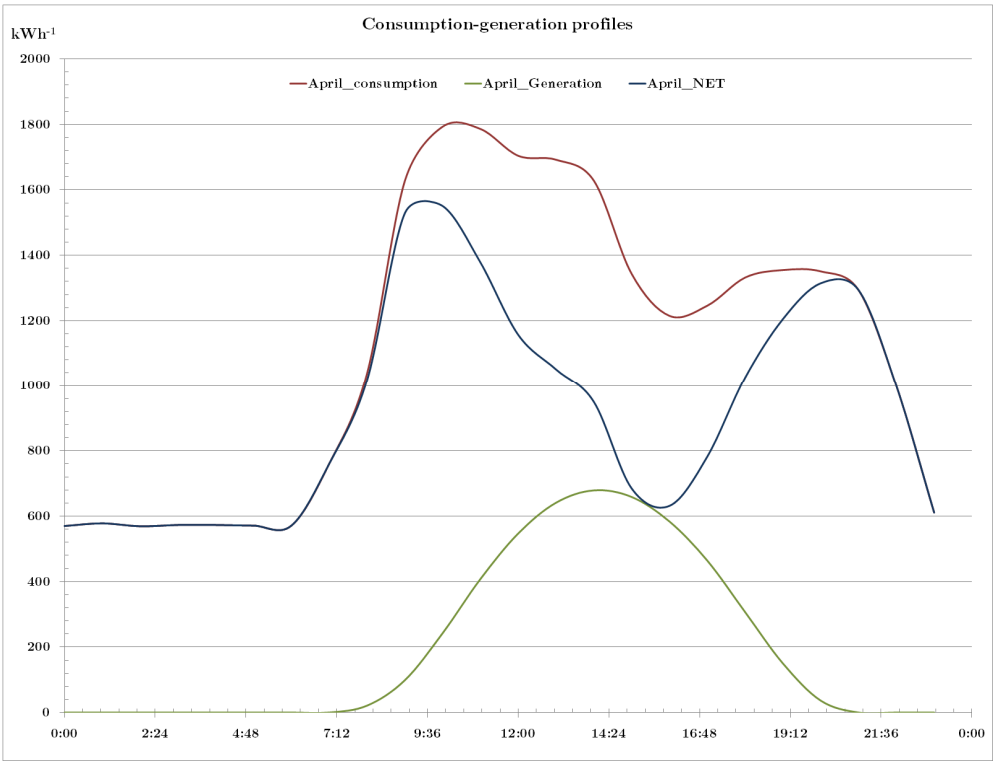

Figure 2.8. Generation and consumption curves for a random day (positive NET)

On the other hand, a different day of the same month (April 15th, 2014) a completely different behavior is observed (Figure 2.9) as there are periods of

time with a negative NET curve, so part of the electricity produced could be exported to the grid.

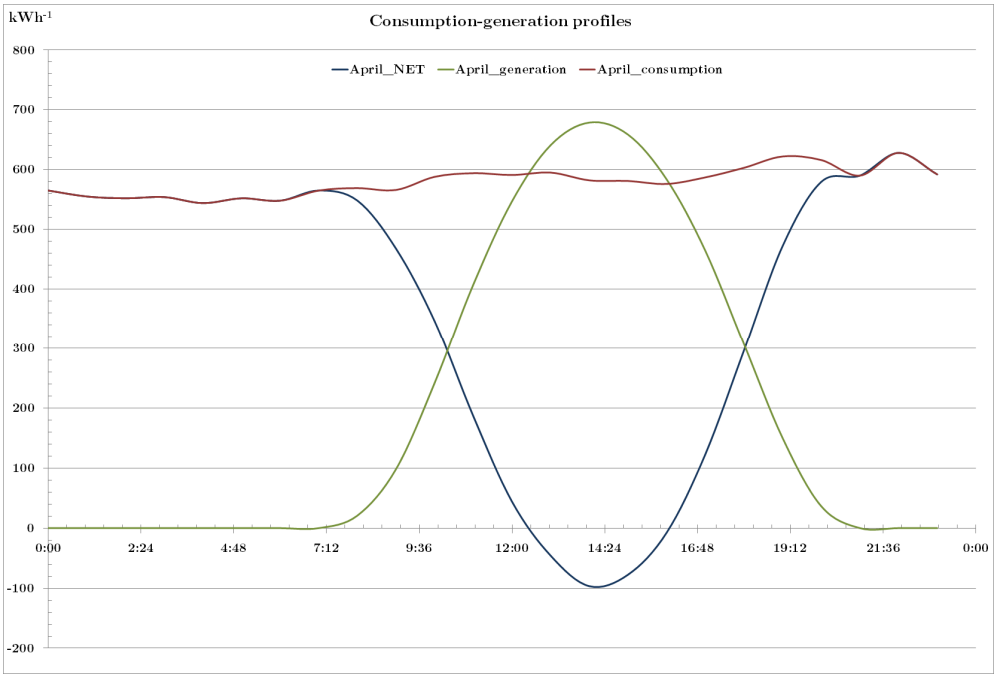

Figure 2.9. Generation and consumption curves for a random day (negative NET)

The consumption profile in the University differs depending on the occupation and usage of the electrical resources, so it can be concluded that it will follow the working calendar. Therefore, the analysis of this hourly profile depending on the following classification is more interesting: 1.- Working days (from Monday to Friday) and 2.- Public Holidays, Saturdays or Sundays. The University is an educational institution, so into the classification of working days, those corresponding to non-school days should be extracted. Normally, the difference between school and the rest of working days are due to holidays at Christmas, Easter and the month of August, when most of the facilities of the University are closed. The following figure shows the different behavior of the load curve for a random day depending on the month selected.

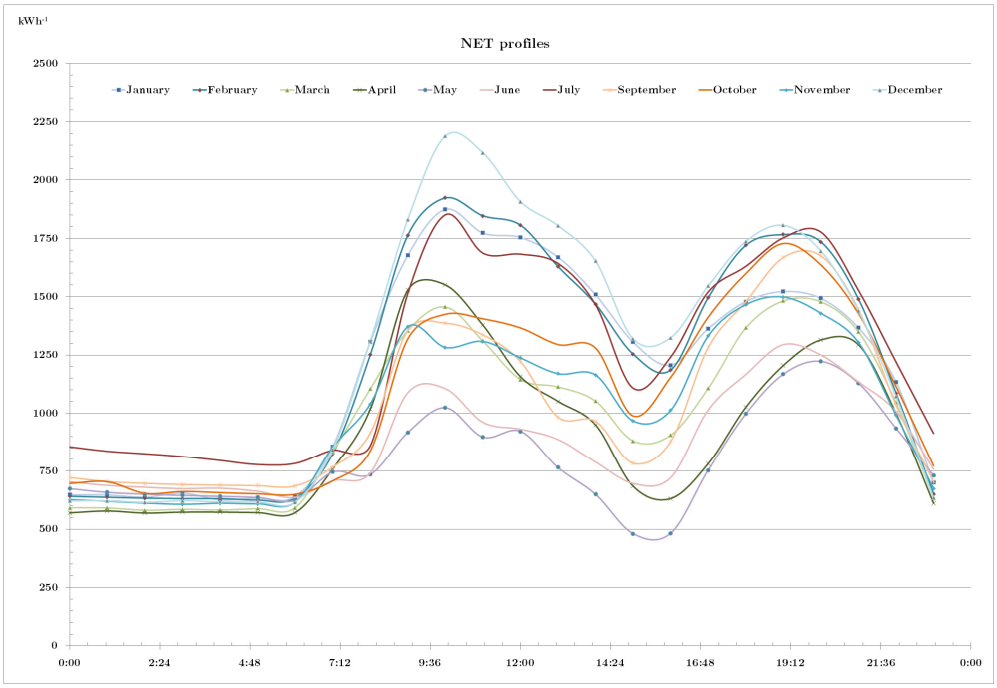

Figure 2.10. Net Electricity balance in a random school working day

As an average pattern, there will always be a positive energy balance in every hour of a school working day, which means that it is necessary to import electricity from the grid.

A similar result is obtained for a non-school working day, therefore, it can be deduced that all the energy produced within any working day (either school or non-school day) is completely used for instantaneous self-consumption at the facilities of the University.

On the other hand, if Saturdays, Sundays and public holidays are analyzed (see Figure 2.11), there is an excess in the energy generated. This excess could be sold to the electricity company at a price stipulated (normally at the market´s pool) or its consumption can be delayed when the balance becomes positive again using the electrical grid network as an energy storage and paying to the company a certain price for its use; anyway the need of purchasing electricity directly from the company is avoided.

This unused electricity might be easily absorbed within a small area surrounding the University Campus where there are several factories, a hospital, and a shopping mall. This fact comes to reinforce the feasibility of distributed generation concept, thus reducing the losses of the power lines.

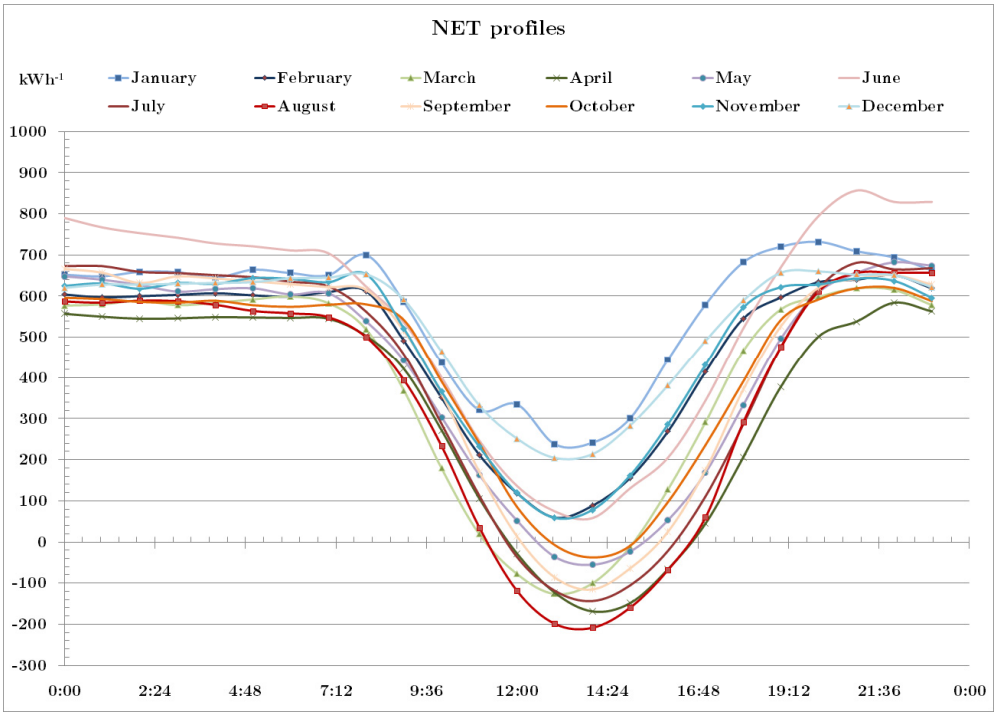

Figure 2.11. Typical Net Excess Electricity generation on a random Sunday

In spite of the University savings in the electricity consumption, this fact does not necessarily turns into economic savings or even that these PV systems are profitable in the mid-long term, so an hourly electricity cost production analysis combined with a profitability analysis must be carried out prior to assess the suitability and viability of these sorts of systems.

2.3.2. Tracking energy yield

By extension to the estimated energy yield of the potential PV areas identified, together with the later real measurements brief comparison, the introduction of the energy yield increment produced by a tracking PV device is valuable with the aim to identify different scenarios.

Moreover, the results analyzed come from an empirical measurement campaign, so the uncertainties of any energy forecast method were avoided, thus it is intended to complement the variety of simulated tracking studies found in the literature (Narvarte & Lorenzo, 2008) (de Simón-Martín, et al., 2013).

The grid connected PV system is based on a two-axis pedestal type tracker whose characteristics are summarized in the next table.

Parameter	Subgenerator	Generator
Total number of modules	16	48
Serial–connected modules in each array	8	8
Number of branches in parallel	2	6
Maximum power P_M (W)	3200	9600
Voltage at the maximum power point V_{MPP} (V)	210.4	210.4
Current at the maximum power point, I_{MPP} (A)	15.22	45.66

Table 2.9. PV tracker configuration and nominal values at STC

The photovoltaic generator has been divided in three 3.2 kW subsystems, each one connected to a different phase of the grid through three single-phase inverters, with a nominal power of 3.3 kW each one, so the whole performs like a three-phase system.

The tracking control unit is based on the internal calculation of solar ephemeris; settled in open loop to the irradiance and in close loop to the

position. The system develops a tracking precision lower than two degrees and a 0.001º solar ephemeris precision.

The income energy falling on the surface has been calculated based on real measurement of the horizontal radiation from a nearby weather station, so at some extents, possible divergences with the extrapolation of data from external and distant stations are avoided. Anyway, the tilted energy has been estimated following the procedure mentioned in the previous section, so there are also some assumptions made.

Under this premise, the two-years average global irradiation over horizontal surface measured was H(0)=1733 $kWh \cdot m^{-2} \cdot year^{-1}$. This value, translated into the irradiation on the PV generator's surface, indicates an annual normal global radiation of $H_S = 2861$ $kWh \cdot m^{-2}$. Considering the PV generator surface (around 67.72 m^2), the estimated yearly average energy received is E_{GS} = 193,747 kWh.

The energy figures are summarized in Table 2.10, where a comparison between each one of its two years of operation and the global data of the complete period is additionally shown.

Parameters	1st Year	2nd Year	Total
H(0) ($kWh \cdot m^{-2}$) (measured)	1745	1720	1733 (averaged)
H(S) ($kWh \cdot m^{-2}$) (estimated)	895	2827	2861 (averaged)
Energy received (kWh) (estimated)	196,049	191,444	193,747 (averaged)
E_{AC} injected (kWh) (measured)	20,538	19,620	40,158
E_{Yield} ($kWh \cdot kWp^{-1}$)	2139.4	2043.8	2091.56 (averaged)

Table 2.10. Two years Energy yield comparison

It is outstanding the stable operation of the PV-tracker throughout these two years with minimum variations in the value of the data calculated, although a longer period of observation would have been very valuable for defining O&M needs and degradation problems or failures.

The total measured energy injected by the system along the two years selected reached a value of E_{AC} = 40,158 kWh, so the yield of the system, averaged by the whole operational period, Y_{av}, is 2091.56 kWh · kWp^{-1} · year^{-1}. In the parameters calculated the energy consumption of the auxiliary devices, such as the solar tracker unit, is implicitly included because its power supply is done before the energy meter, and all the AC energy data used in the analysis are referred to the global output of the system, which is given by the energy meter.

The productivity corresponds to the high efficiency achieved by the system and all the possible real effects that could reduce the energy generation have been included. The shadows at dawn and dusk have not been avoided, so although in this section the ground cover ratio issues are not treated (Narvarte & Lorenzo, 2008), a realistic tracking situation comparable to real PV trackers fields is analyzed. Additionally, the modules have not been cleaned during the period selected, thus they were left to be self-cleaned with the rainwater.

Analyzing the simulated scenarios found in the literature, in some cases an energy yield of 2062 kWh · kWp^{-1} · year^{-1} and a productivity increase of 37% has been forecasted (Aste & del Pero, 2010). If a nearer location, with similar meteorological conditions is chosen, the gain reaches a 41 % in the best scenario (Narvarte & Lorenzo, 2008) with respect to a fixed system. Previous simulated research in the tracking PV field shows that the percentage gain from a two-axis tracking system relative to a fixed one varies depending on the latitude. The proportional gain is larger in Northern latitudes than in Southern ones (<45ºN), offering simulated values that range between 40-60% for Northern locations and 30-40% for the Southern ones (Huld, et al., 2008).

If the tracker yield is compared with one of the optimized slope and South azimuth BIPV proposed in the former section, then the gain improves 47.5%, a figure greater than the percentages mentioned previously, which stands for one of the highest yield reported in PV systems. In order to eliminate any source of atypical meteorological conditions, the average radiation measured has been

checked with other radiation databases (Atmospheric Science Data Center, 2013) (Joint Research Center. PVGIS, 2014), and it is around the stipulated data for the annual radiation of Jaén, so the productivity data corresponds to the high efficiency achieved by the system and not to a year with special high radiation. This circumstance suggests that similar results during the following years would be obtained.

The high operation reliability data offered during this period, with no outstanding incidents, match the claim of some reports, which advocate that PV trackers systems are a good technological alternative for the traditional flat silicon PV, at least in energy terms (International Energy Agency, 2013).

Despite the optimistic conclusion regarding the energy increment, it has to be carefully taken and subjected to a final and definite statement based on a proper financial feasibility analysis.

2.3.3. LCOE results and financial feasibility

The first step in this section is the definition of the magnitudes and how they are going to change in relation to the general cost analysis of previous sections.

The share of equity and the share of debt maintain the same proportionality as the general sensitive case analyzed in previous sections (20%-80%), but the magnitude of the intervention makes the risk of the financial investment higher, so the dividends claimed by the investors or the own capital, should raises up to a 5%, while the interest loan is set to i_l= 6% and the loan term is fixed to N_l=15 years. As a consequence of this change in the financial parameters, the WACC is also modified, because its value depends on how the resources are chosen to finance the initial investment cost, so after this modification, the WACC is calculated to be 5.6%. Although the base case of the University has been divided into PV systems of 100 kWp, which can be considered a standard installation, the intervention act as a whole, so from the end-user's point of view the investment is more demanding in terms of costs and profitability, thus the value of WACC is higher than other similar reports (Kost, et al., 2013).

Yet the operation and maintenance cost of the systems are assumed to

decrease down to a 1% annually of the investment, mainly because it would be integrated in the already existing maintenance protocol and team of the University.

Assuming the factors summarized in Table 2.11, the LCOE results for each location identified are shown in Table 2.12, where similar figures as the LCOE of the Section 2.2.1 are obtained.

Location	Factors assumed for 2014					
			Financial			
			Interest loan (80% PV_{IN})		Dividends (20% PV_{IN})	
	PV_{IN} ($€ \cdot kWp^{-1}$)	PV_{OM} $\% \cdot PV_{IN}$	i_l (%)	N_l (years)	di (%)	g (%)
Building 1	1900					
S. Parking lot (1 to 3)	1700					
Building 2	1900					
N. Parking lot (1 to 4)	1700	1	6	15	5	2.8
Pergola	1800					
Building 3	1900					
N-W Parking lot	1700					

Table 2.11. Parameters for the cost analysis

In a first approximation according to the data obtained, it can be confirmed that the grid-parity regarding these installations is a fact as the average LCOE obtained ranges around 0.13 $€ \cdot kWh^{-1}$, but it is recommendable to undertake a financial analysis combined with the consumption profile study of the University.

Location	LCOE (€ · kWh^{-1})
Building 1	0.12805
S Parking lot (1 to 3)	0.13101
Building 2	0.12805
N Parking lot (1 to 4)	0.13122
Pergola	0.13309
Building 3	0.12958
N-W Parking lot	0.13090

Table 2.12. LCOE results for the systems proposed

The LCOE is mostly influenced by the electricity yield and the initial investment cost variations as in the general case was seen. Similar results regarding the figures and the trends are obtained if the sensitivity analysis is repeated.

Location	LCOE (€ · kWh^{-1})			
	-25% PV_{IN}	+25% PV_{IN}	-25% E_{PV}	+25% E_{PV}
Building 1	0.09604	0.16006	0.17074	0.10244
S Parking lot (1 to 3)	0.09826	0.16376	0.17468	0.10481
Building 2	0.09604	0.16006	0.17074	0.10244
N Parking lot (1 to 4)	0.09841	0.16402	0.17495	0.10497
Pergola	0.09982	0.16637	0.17746	0.10647
Building 3	0.09719	0.16199	0.17278	0.10367
N-W Parking lot	0.09817	0.16363	0.1745	0.10472

Table 2.13. LCOE Sensitivity analysis results

Once the most influencing parameters in the LCOE have been widely proven, it is reasonable to bring the PV tracker into contention, because although it inherently represents an increment in the energy collected as it can be seen in the following table, its added value also leads to a corresponding increment in the initial investment.

Location	Annual Yield ($kWh \cdot kWp^{-1}$)	Annual Yield increment (%)
Buildings 1-2	1435	45.75
S Parking lot (1 to 3)	1255	66.66
N Parking lot (1 to 4)	1253	66.92
Pergola	1308	59.91
Building 3	1418	47.50
N-W Parking lot	1256	66.53
General Case	1350	54.93

Table 2.14. Yield comparison between tracking and fix PV systems

Despite the energy benefits of a PV tracking system can be easily calculated, the information regarding how the tracking structure influences the rise of the installed system is scarce, outdated and confusing.

The last report published by the Spanish PV association (UNEF) estimated that the cost for the structure and the civil works concerning a fixed PV installation in Spain are $0.31€ \cdot kWp^{-1}$ and $0.29€ \cdot kWp^{-1}$ respectively, and this price has remained constant since 2010 an in the predictions up to 2020 (Unión Española Fotovoltaica, Noviembre 2013). Therefore, it would not suppose much

error the assumption that the prices concerning the tracking structures have remained constant in the last years and so will they.

In 2007, in the middle of the boom of the PV technology in general and the tracking devices in particular, a survey with several manufacturers was published, and according to the data, it reported an average value of 164 € · m^{-2} or 1.1 € · Wp^{-1} (Siemer, 2007).

In 2006 other sources predicted that at the end of 2013 the price for a two-axis tracker would oscillate around 100-150€ · m^{-2}, which can be translated into 0.7-1.01 € · Wp^{-1} (Bett, et al., 2006). At 2010, among the price of single-axis tracker, some estimations for the two-axis one were also published, and ranged around 0.9-1.2 € · Wp^{-1} (Aste & del Pero, 2010). If the single axis trackers are compared with some Spanish manufacturers that publish their prices, the estimations for 2010 can be validated in the present year (Optim-Top, 2014).

In summary, the literature revised comes to reinforce the low variability in the tracking prices. Nevertheless, there are some reports that have assumed lower prices down to 0.5 $ · Wp^{-1}, but it was focused on 100 MW systems, and its representation is very doubtful (Duquette & Otanicar, 2013).

Based on the information studied, in the following brief LCOE analysis an increment of 1 € · Wp^{-1} for a two-axis tracker has been supposed, so deducting the structural prices from a fixed installation, it can be assumed that a 2-axis PV system could cost 2.59 € · Wp^{-1}.

Obviously, the movable parts and the software control unit will demand higher rates of maintenance. According to some authors, an annual O&M cost of 5% of the initial investment has been proposed (Bett, et al., 2006). The rest of parameters have been maintained regarding the LCOE analysis done for the University.

	LCOE (€ · kWh^{-1})				
	-25% PV_{IN}	+25% PV_{IN}	Base case	-25% E_{PV}	+25% E_{PV}
PV tracker	0.15389	0.24047	0.19237	0.24047	0.15389

Table 2.15. LCOE for a two-axis PV system

The main result is that the LCOE for these sort of systems surges up to 0.19237 € · kWh^{-1}. Avoiding the variability in the assumptions made, in the previous table a brief sensitive analysis is summarized, where figures up to 0.24263 € · kWh^{-1} are obtained.

Obviously, the comparison with the fix plants is not fully rigorous because tracking systems are not capable of being installed at the locations tagged due to structural and space constraints, but the aim of this superficial comparison is to bring out that in previous years the investment in tracking PV generators was more interesting as the cost of the whole system was sufficiently high, considering that the tracking mechanism only supposed a small portion of the expenses, but nowadays, the reduction in the installed PV module unitary price makes the share of the structure become significantly more important.

Despite the unviability of installing tracking PV systems under the current market scenario and the cost associated to the mechanical parts, it was previously indicated that though the presumably grid-parity profitability for flat-PV systems could be also virtually not accomplished, the energy and financial study should be adapted to the tariffs and to the consumption profile of the end user, in this case the University.

In Section 2.2.2 a possible discussion regarding the virtual non-profitability of the grid-parity in the hourly discriminated household tariffs was suggested. In the case of the University of Jaén, which is a high-power-high-voltage consumer, the present Spanish regulatory framework defines several consumption profiles and tariffs (Ministry of Industry, Energy and Trade, 207). Concretely, there are six different price periods (P1 to P6), according to the definition of electrical seasons and type of days, each one with a certain number of hours attached. Table 2.16 gathers the hourly price profile from Monday to Friday, excluding public holidays, for each month of the year. Saturdays, Sundays and public holidays are applied the period P6.

		Hours of the day																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Jan.		p6	p6	p6	p6	p6	p6	p6	p6	p2	p2	p1	p1	p1	p2	p2	p2	p2	p2	p1	p1	p1	p2	p2	p2
Febr.		p6	p6	p6	p6	p6	p6	p6	p6	p2	p2	p1	p1	p1	p2	p2	p2	p2	p2	p1	p1	p1	p2	p2	p2
Mar.		p6	p6	p6	p6	p6	p6	p6	p6	p4	p4	p4	p4	p4	p4	p4	p4	p3	p3	p3	p3	p3	p3	p4	p4
Apr.		p6	p6	p6	p6	p6	p6	p6	p6	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5
May		p6	p6	p6	p6	p6	p6	p6	p6	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5
June	1-15	p6	p6	p6	p6	p6	p6	p6	p6	p4	p3	p3	p3	p3	p3	p3	p4	p4	p4	p4	p4	p4	p4	p4	p4
	15 - 30	p6	p6	p6	p6	p6	p6	p6	p6	p2	p2	p2	p1	p1	p1	p1	p1	p1	p1	p1	p2	p2	p2	p2	p2
July		p6	p6	p6	p6	p6	p6	p6	p6	p2	p2	p2	p2	p1	p1	p1	p1	p1	p1	p1	p1	p2	p2	p2	p2
Aug.		p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6
Sept.		p6	p6	p6	p6	p6	p6	p6	p6	p4	p3	p3	p3	p3	p3	p3	p4	p4	p4	p4	p4	p4	p4	p4	p4
Oct.		p6	p6	p6	p6	p6	p6	p6	p6	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5	p5
Nov.		p6	p6	p6	p6	p6	p6	p6	p6	p4	p4	p4	p4	p4	p4	p4	p4	p3	p3	p3	p3	p3	p3	p4	p4
Dec.		p6	p6	p6	p6	p6	p6	p6	p6	p2	p2	p1	p1	p1	p2	p2	p2	p2	p2	p1	p1	p1	p2	p2	p2
Satur Sund Holy.		p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6	p6

Table 2.16. Hourly profile of price periods applicable in Spain for high-power-high-voltage consumers

In relation to the electricity price paid by the University, the power fee is fixed by the Ministry of Industry, Energy and Tourism but the variable term price, that is, the proper energy consumption, is contracted freely between the

University and the supplier. Table 2.17 summarizes the last energy price, only the variable term, paid by the University since August 3rd, 2013, when the Ministerial Order IET/1491/2013 was introduced.

The period selected (May 2013-April 2014) for the energy-economic analysis is affected by two different tariffs according to the new prices previously mentioned. In order to simplify the analysis it has been made the assumption that all the electricity consumed and generated is ruled by the last retail prices published.

Under this scenario, the average retail paid by the university should be around 0.097 € · kWh^{-1}. In a first approximation, the grid-parity is not profitable for this sort of consumer, as the average LCOE calculated, taking into account the whole intervention, is around 0.13 € · kWh^{-1}. So in spite of the presumably energy savings in the electricity bill (gross calculation), the indications address to a possible economic losses scenario.

P1 (€ · kWh^{-1})	P2 (€ · kWh^{-1})	P3 (€ · kWh^{-1})	P4 (€ · kWh^{-1})	P5 (€ · kWh^{-1})	P6 (€ · kWh^{-1})
0.144513	0.120356	0.106787	0.097498	0.093744	0.071927
Total Annual Electricity cost				824296	€
Average retail price				0.09716	(€ · kWh^{-1})
Average LCOE for the whole PV intervention				0.13	(€ · kWh^{-1})

Table 2.17. Energy prices applied to the University including taxes

The profitability assumption of the grid-parity is questionable and in this case it will be subjected to the period where the contribution of the photovoltaic self-consumption electricity substitutes the corresponding energy supply from the grid. Apparently, there will be no grid-parity if the generation-consumption is done in all the periods except in period 1, so the hourly NET profiles should be analyzed and discussed if this is a real or a virtual non-profitable grid-parity situation.

At this stage of the study of reasoning established, the hourly analysis of the generation versus consumption profiles is then justified.

Table 2.18 shows the sum of the energy consumed at the University facilities each month of the selected time and it has been gathered according to the metering periods.

	Month	Periods						Monthly Consumption (kWh)
		P1 (kWh)	P2 (kWh)	P3 (kWh)	P4 (kWh)	P5 (kWh)	P6 (kWh)	
2013	May	0	0	0	0	397,828	238,584	636,412
	June	144,561	111,356	84,044	114,506	0	295,144	749,611
	July	319,066	237,880	0	0	0	277,651	834,597
	August	0	0	0	0	0	512,693	512,693
	Septemb.	0	0	214,088	280,442	0	251,025	745,555
	October	0	0	0	0	469,215	237,865	707,080
	Novemb.	0	0	170,018	309,061	0	249,388	728,467
	Decemb.	192,404	259,290	0	0	0	256,071	707,765
2014	January	230,871	307,505	0	0	0	254,482	792,858
	February	222,826	292,044	0	0	0	233,404	748,274
	March	0	0	161,884	302,884	0	254,542	719,310
	April	0	0	0	0	383,530	218,077	601,607
Annual consumption (kWh)		1,109,728	1,208,075	630,034	1,006,893	1,250,573	3,278,926	
Total Annual electricity consumed (kWh)								8,484,229

Table 2.18. Electricity consumed at the University

The PV electricity yield estimated for each installation, under the premises and assumptions defined, allow us to calculate the complete photovoltaic production and grouped it under the six periods as it is provided in Table 2.19.

	Month	Periods						Monthly PV generation (kWh)
		P1 (kWh)	P2 (kWh)	P3 (kWh)	P4 (kWh)	P5 (kWh)	P6 (kWh)	
2013	May	0	0	0	0	120,264	41,836	162,100
	June	48,074	8,460	29,993	26,540	0	56,798	169,865
	July	121,592	20,078	0	0	0	49,409	191,079
	August	0	0	0	0	0	183,107	183,107
	Septemb.	0	0	58,704	48,293	0	45,856	152,852
	October	0	0	0	0	85,302	29,670	114,972
	Novemb.	0	0	7,826	50,319	0	24,919	83,064
	Decemb.	16,485	29,238	0	0	0	18,705	64,428
2014	January	21,118	37,825	0	0	0	20,502	79,446
	February	23,555	41,672	0	0	0	26,091	91,318
	March	0	0	15,823	74,521	0	43,021	133,366
	April	0	0	0	0	106,398	38,690	145,088
Annual PV generated (kWh)		230,824	137,273	112,346	199,673	311,964	578,604	
Total Annual PV electricity generated (kWh)								1,570,684

Table 2.19. Energy distribution of the expected PV generation

The exhaustive and rigorous PV generation analysis is useful to detect the periods where the excess of electricity is produced which cannot be guessed under a gross calculation of the energy yield times the PV power installed.

	Month	Periods						Monthly PV excess (kWh)
		P1 (kWh)	P2 (kWh)	P3 (kWh)	P4 (kWh)	P5 (kWh)	P6 (kWh)	
2013	May	0	0	0	0	507	1,671	2,178
	June	0	0	0	0	0	1,085	1,085
	July	936	332	0	0	0	2,376	3,644
	August	0	0	0	0	0	11,527	11,527
	Septemb.	0	0	0	0	0	2,464	2,464
	October	0	0	0	0	0	120	120
	Novemb.	0	0	0	0	0	0	0
	Decemb.	0	0	0	0	0	0	0
2014	January	0	0	0	0	0	0	0
	February	0	0	0	0	0	0	0
	March	0	0	0	0	0	2,462	2,462
	April	0	0	0	0	1,025	3,006	4,032
Annual PV excess (kWh)		936	332	0	0	1,532	24,712	
Total Annual PV electricity excess (kWh)								27,512

Table 2.20. Excess PV energy generated

The combination of the data collected in the previous tables let us calculate the overall balance, resulting in a positive net consumption profile, or in other words, the instantaneous self-consumed electricity which can be translated into real energy saving.

	Month	Periods						Monthly Self-consumed (kWh)
		P1 (kWh)	P2 (kWh)	P3 (kWh)	P4 (kWh)	P5 (kWh)	P6 (kWh)	
2013	May	0	0	0	0	119,757	40,165	159,922
	June	48,074	8,460	29,993	26,540	0	55,712	168,780
	July	120,656	19,746	0	0	0	47,033	187,435
	August	0	0	0	0	0	171,580	171,580
	Septemb.	0	0	58,704	48,293	0	43,391	150,388
	October	0	0	0	0	85,302	29,550	114,852
	Novemb.	0	0	7,826	50,319	0	24,919	83,064
	Decemb.	16,485	29,238	0	0	0	18,705	64,428
2014	January	21,118	37,825	0	0	0	20,502	79,446
	February	23,555	41,672	0	0	0	26,091	91,318
	March	0	0	15,823	74,521	0	40,559	130,904
	April	0	0	0	0	105,372	35,684	141,056
Annual Self-consumed (kWh)		229,887	136,942	112,346	199,673	310,432	553,891	
Total Annual PV electricity self-consumed (kWh)								1,543,172

Table 2.21. Self-Consumed profile divided in period

The first conclusion is that the electricity savings are slightly reduced to a more realistic situation. The second conclusion is that the virtual non-profitable grid-parity is still unsolved.

This analysis is focused in the Spanish territory, where the net-metering law is still in a draft stage, so the PV electricity injected to the grid is not regulated in economic terms (neither in bureaucratic nor technical). In other words, the energy not used at the moment is given, free of charge, to the electricity

company. There is no remuneration or economic savings (in electricity bonus) from the user's standpoint.

Independently from the net-metering laws, and according to the current renewable energy laws, we could convert the University into an electricity producer with the target of obtaining any benefit from the excess of current injected. Normally, the kWh generated in excess is paid at the current market price. In this case, we would have to compensate the system with an access fee for the permission of injecting this electricity, so according to the small amount of over excessed electricity, for our study, it has been assumed that this energy excess will be injected into the public electricity net at no cost.

Studying the previous tables, the net photovoltaic electricity generated will be exclusively for instantaneous self-consumption, so the energy saving noticed in the electrical bill can be translated into cost savings, where the self-consumed electricity produced in each period is rewarded with the official retail tariff (from August 2013).

In the following table (3.22), the invoice received from the Electrical Company has been divided into the six periods. The same procedure has been followed if the self-consumed concept is taken into account, so in this case, we need to split the cost associated with the NET energy imported from the grid and the contribution of the self-consumed PV energy, which according to the net-metering concept, will be rewarded at the same price as the official electricity retail tariff.

Obviously, the sum of the total NET (imported energy) cost and the contribution of the self-consumed PV electricity should be balanced with the original invoice received from the electricity utility. In a first analysis, the PV self-consumed costs mean a saving, because this electricity is produced with our systems, thus reducing the needs of importing energy from the Electricity Utility. These savings are easily demonstrable when the monthly invoice is charged.

Nevertheless, these savings are only apparent and it is explained by the virtual non-profitable grid-parity aforementioned. Although the kWh of instantaneous self-consumed is paid at the stipulated retail price, it does not have to coincide with the real cost of producing a kWh of photovoltaic energy.

	P1	P2	P3	P4	P5	P6
Last electricity tariff (€ · kWh^{-1})	0.144513	0.120356	0.106787	0.097498	0.093744	0.071927
Invoice (€) (official electricity tariff)	160,370.12	145399.07	67,279.44	98,170.05	117,233.72	235,843.31
PV cost (self-consum.) (€)	33,221.71	16,481.77	11,997.11	19,467.75	29,101.11	39,839.75
Net cost (€)	127,148.41	128,917.30	55,282.33	78,702.30	88,132.61	196,003.56
Total invoice with PV self-consumption (€)	160,370.12	145,399.07	67,279.44	98,170.05	117,233.72	235,843.31
Total original invoice (€)					824,295.72	€
*Total PV self-consumed cost (**Apparent savings**)*					*150,109.20*	*€*
Total NET(imported electricity) cost					674,186.52	€
Total invoice with self-consumed PV					824,295.72	€

Table 2.22. Cost Balance using the last University Electricity tariffs (from August 2013)

From the user's standpoint, the price that is being paid for the self-consumed electricity is the LCOE, independently from the period (P1-P6) considered, meanwhile, the rest of the imported NET electricity is paid at the regular price.

Table 2.23 shows this modification, where the file containing the information regarding the cost associated with the PV generation has been modified taking into account the real price of producing a kWh with this technology. Thereupon, the total invoice when considering the self-consumption with

photovoltaic will be modified and it can be compared against the invoice under the official retail tariff.

	P1	P2	P3	P4	P5	P6
$LCOE_{2014}$ ($€ \cdot kWh^{-1}$)	0.130584	0.130584	0.130584	0.130584	0.130584	0.130584
Invoice (official electricity tariff)	160,370.12	145,399.07	67,279.44	98,170.05	117,233.72	235,843.31
PV cost (€) ($LCOE_{2014}$) (self-cons.)	30,019.61	17,882.41	14,670.61	26,074.14	40,537.41	72,329.37
Net cost (€) (official electricity tariff)	127,148.41	128,917.30	55,282.33	78,702.30	88,132.61	196,003.56
Total invoice with PV self-consumption	157,168.02	146,799.72	69,952.94	104,776.45	128,670.02	268,332.92
Total original invoice (€)					824,295.72	€
Total PV self-consumed cost					201,513,54	€
Total NET(imported electricity) cost					674,186.52	€
Total invoice with self-consumed PV					875,700,07	€
Real "savings"					-51,404.35	€

Table 2.23. Cost Balance using the LCOE tariff for the year 2014

As it was expected, only the period P1 produces a saving because it is where the retail price is higher than the $LCOE_{2014}$; meanwhile in the rest of periods, it is more expensive to use the electricity generated from the photovoltaic plants.

The sum of the NET cost and the contribution of the PV with its real generation cost for 2014, results in a more expensive invoice when it is compared with the official one, so the apparent savings detected in table 2.22 are transformed into economic losses for the owner of the installation.

This negative result has also to be taken in perspective, because an electricity tariff has been used which should vary in time against a levelised cost of the electricity generated with photovoltaic, which is assumed to keep constant throughout its operational lifetime.

Avoiding the uncertainties that the electricity yield calculation may have introduced, this scenario will obviously be dependent on the assumptions made for financing the whole intervention, and the most critical factor is the forecast for the annual increment of the electricity price, that in our study will influence on the money received for the self-consumed energy.

It is difficult to foresee the behavior of the electricity markets. However, it seems that the rising trend of energy consumption, mainly due to the emerging economies, will make the world's energy demand increases. This fact, together with the increase of oil prices, will push up electricity rates (International Energy Agency, 2011). In this financial analysis two scenarios have been proposed: the first one, where the prices rise at the same proportion as the annual inflation rate expected, g=2.8% in our prediction, and a more realistic scenario, although still conservative, where the annual increase rate of the PV electricity unitary price has been supposed to be 5%. The rest of parameters have been maintained as the one shown in Table 2.11.

In the equation of the present worth of the incomes (eq. 12), only the first addend has been used, because the instantaneously self-consumed energy was the term considered.

ε_{psi}	$IRR_{nominal}$ (%)	NPV (€)	DPBT (years)
ε_{psi} = g=2.8%	5.25	-85471.03	>25
ε_{psi} = 5%	7.63	492384.81	20

Table 2.24. Economic analysis summary

The results are shown in Table 2.24, where depending on the scenario considered the project is economically feasible or not.

Although obtaining questionable positive results considering an increment of electricity prices of 5%, the project will not be financially feasible due to the negative incomes received at the beginning.

	P1	P2	P3	P4	P5	P6
$LCOE_{2014}$ ($€ \cdot kWh^{-1}$)	0.130584	0.130584	0.130584	0.130584	0.130584	0.130584
2012 retail tariff ($€ \cdot kWh^{-1}$)	0.225200	0.183900	0.153800	0.131400	0.119900	0.095000
Invoice (€) (2012 retail tariff)	249,910.75	222,164.99	96,899.23	132,305.74	149,943.70	311,497.97
PV cost (€) ($LCOE_{2014}$) (self-cons.)	30,019.61	17,882.41	14,670.61	26,074.14	40,537.41	72,329.37
Net cost (€) (2012 retail tariff)	198,140.11	196,981.39	79,620.39	106,068.67	112,722.95	258,878.28
Total invoice with PV self-consumption	228,159.72	214,863.80	94,291.00	132,142.81	153,260.35	331,207.64

Total original invoice with 2012 retail prices (€)	1,162,722.38	€
Total PV self-consumed cost	201,513.54	€
Total NET(imported electricity) cost	952,411.79	€
Total invoice with self-consumed PV	1,153,925.33	€
Real "savings"	+ 8,797.05	€

Table 2.25. Cost Balance using the $LCOE_{2014}$ and the electricity retail prices before December 2012

It is important to notice that these parameters have been calculated without taking into account the corporation taxes that may be applied. Either way, its application means an additional worsening of these parameters, so the conclusion will be reinforced.

According to the results shown, although the grid-parity is a reality for residential consumers, in the case of high-power-high-voltage ones and according to the consumption profile of the University, the grid-parity reality is not accomplished in the short-term.

As a conclusion, it should be mentioned that this situation is merely circumstantial and suspiciously artificial, because during the last two years (2013 and 2014) the electricity prices for the University-alike consumers have been artificially decreased in favor of a surge increase in the fix-power term.

If the cost balance of previous tables is repeated, maintaining the $LCOE_{2014}$ and the electricity consumption-generation profiles but using the retail tariffs valid until December 2012, the results are more inspiring as it can be observed in the following table

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Chapter 3

Focusing on new approaches. Concentrator Photovoltaics

3.1. Deployment and standstill of the CPV technology

Concentrator Photovoltaic technology (CPV) has always been proposed in the short-mid-term as a promising alternative to traditional PV technology (Luque, et al., 2006). After some years of an impressive industrial growth where several tens of MWs were installed, meaning its commercial deployment, this market is facing nowadays a standstill situation which may be partially explained by the great reduction in cost of Silicon based modules and the saturation of some markets related to traditional flat-PV. Whatever it is the combination of factors for this standstill, the reality is that the whole PV industry is facing a tremendous inflection point (Wesoff, 2013).

Nevertheless, the opportunities and challenges for the development of CPV technology are optimistic and present more leeway than Si-PV (Kurtz, 2012). This is mainly explained by the proximity to the efficiency limit of the Silicon solar cells (Shockley & Queisser, 1961).

The constant efficiencies record achievements and the recent news of future CPV plants (SOITEC, 2014) encourage to predict a less standstill period in the mid-term. Among the optimistic forecast, the LCOE is found to have a main role, where there are estimations for 0.15 $€ \cdot kWh^{-1}$ corresponding to the year 2013 (Kost, et al., 2013).

3.1.1. Efficiencies status

Multijunction cells, which are the basis of the CPV systems, split their sensitivity to the sun's spectrum, so they are better matched throughout its wavelength distribution than single junction devices. This fact produces a better and more efficient conversion of the sunlight into PV electricity. The high efficiency achieved by multijunction solar cells is also explained by the reduction of thermalization and transmission losses in solar cells when the number of p-n junctions is increased (Bett, et al., 2007). Obviously, these efficiency levels are possible at the expenses of a substantial increment of the price up to levels where its profitability is questionable when using bare cells for the module composition. This fact explains the reason of using concentrating optic devices, so the cell's area can be reduced while the sun flux is increased.

The theoretical efficiencies calculated for these devices depend on the number of layers and the considerations estimated. As a global vision, and within a thermodynamic context, the limit is close to 95%, while a detailed balance theory leads to a limit around 86.8% under the black-body consideration or 85% if it assumed AM1.5 direct normal irradiance (Henry, 1980) (Martí & Araújo, 1996).

It is important to mention that we should distinguish theoretical efficiency of the MJ cells and the efficiency for a specific structure (Kurtz, et al., 2008). Among the monolithic MJ cells there are several structures depending on the manufacturing process and the bandgap combination. Under the current state of art, the metamorphic cells seem to achieve slightly higher efficiencies levels regarding the most extended lattice-matched cells (Tobías & Luque, 2002) (Philipps, et al., 2010).

The historical evolution of best research-cell efficiencies can be observed in Figure 3.1 (NREL, 2014). It is outstanding that the efficiency trend for Crystalline Silicon cells have been flattened, which means that it is close to its maximum theoretical limit (Landsberg & Markvart, 2003). In the meanwhile, the efficiency records regarding the MJ cells have experienced an incremental trend in the last decade, clearly surpassing the 40% barrier and with an optimistic roadmap potential because it still exists a long gap until getting close to the theoretical limit efficiencies mentioned previously.

The record efficiency of a solar cell reported up to the current date is 44.4% for an inverted metamorphic monolithic 3-junction cell under a concentration ratio of 302 suns and manufactured by Sharp with the composition InGaP/GaAs/InGaAs (Green, et al., 2014). On the other hand, the company Soitec and the research center Fraunhofer Institute for Solar Energy Systems have reached a 44.7% efficiency by means of a 4-junction cell composed by GaInP/GaAs/GaInAsP/GaInAs at 297-times concentration (Dimroth, et al., 2014).

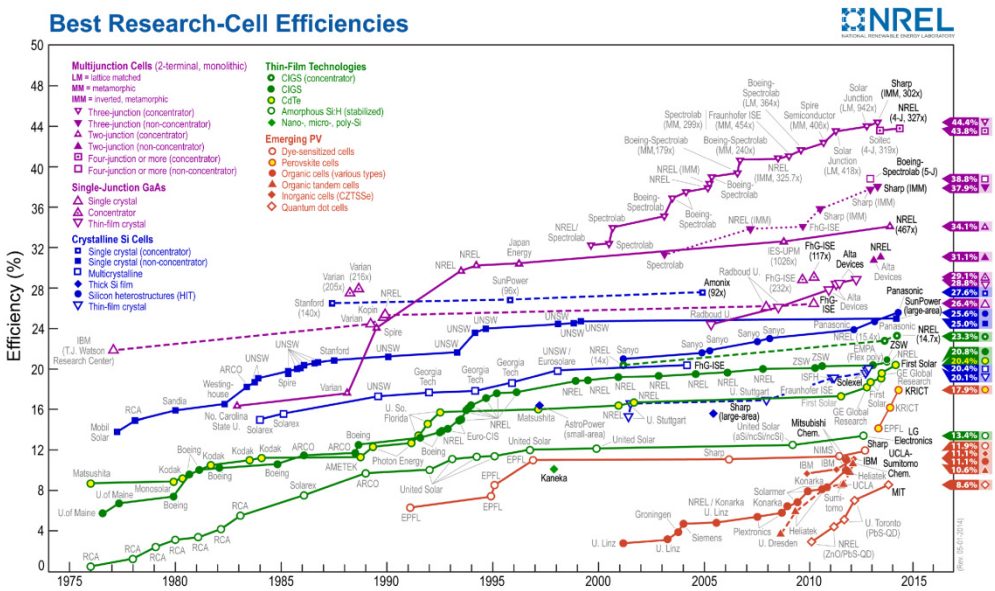

Figure 3.1. Best research-cell efficiencies chart (courtesy of NREL)

Nevertheless, the efficiencies of commercial MJ solar cells are slightly below the previous figures because the quality of the manufacturing process is diminished in the interest of reducing prices and increasing production speed. A brief representation of the most extended commercial MJ solar cells is observed in the table 3.1.

New approaches in increasing the efficiency of MJ cells are also focused on the spectrum splitting concept that it is achieved when stacking more subcells in a MJ device, but in this case, a different technical composite solution is

proposed consisting on the physical implementation of several independent solar cells of different band gaps combined with spectrally sensitive mirrors that split the sunlight spectrum into the range of each cell (Green & Ho-Baillie, 2010).

Manufacturer	Efficiency (%)	Concentration (suns)
Emcore	39	1000
Spectrolab	40	500
Azurspace	41.9	500
Solar Junction	41.4	1000

Table 3.1. Most representative commercial MJ cell efficiencies

3.1.2. Standardization. A slowdown in the CPV deployment

The industrial deployment of the CPV is not only dependent on the efficiency improvement of the cells used, but also on the creation of standards that guarantee its operational behavior in real outdoor conditions.

The creation of standards that regulate the manufacturing process and quality of a particular technology, as well as other aspects regarding the energy rating or other measurement procedures, is essential when a product needs to achieve a significant and wide spread industrial and commercial growth.

These standardization and testing norms reinforce the operational behavior, safety and profitability in any system. The reliability and durability of a technology defines these characteristics; as the former measures the mean time between failures (MTBF) or the time needed to repair a certain failure, the later refers to the lifetime of the system, that is, the point in time from which it is not profitable to maintain the operation of the system.

Additionally its attempt of reducing electricity generation costs, if CPV technology wants to compete against Si-PV or even traditional energy sources, the levels of reliability and durability have to be similar in order to guarantee a good performance, because the accumulation of failures in the course of its

deployment can reject the establishment of the whole CPV industry due to its lack of reliability.

It is necessary to differentiate between standardization and certification. While standardization is a set of rules that unify the process, procedures and parameters of the CPV systems, certification is the action carried out to make sure that the CPV product observes the requirements of a specific standardization norm.

Regarding the CPV standardization status, the lack of CPV norms is outstanding, as only four standards have been released up to now (see table), which means that CPV technology is growing up using PV standards and sometimes with the total absence of norms when referred to some specific parts; but this reason is partially justifiable by the recent high deployment, in economic terms, of the technology.

Reference	Title of the norm	Publication date
IEC 62108 Ed. 1.0	Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval	2007-12
IEC 62670-1 Ed. 1.0	Photovoltaic concentrators (CPV) - Performance testing - Part 1: Standard conditions	2013-09
IEC/TS 62727 Ed. 1.0	Technical Specifications. Photovoltaic systems - Specification for solar trackers	2012-05
IEC 61701 Ed. 2.0	Salt mist corrosion testing of photovoltaic (PV) modules	2011-12

Table 3.2. Current standardization norms related to CPV

Nevertheless, since the operational experience with these systems has increased in the last years, the working group 7 from the IEC is developing

several drafts of norms that should improve the standardization of this technology. The most critical ones, regarding the energy measurement, are supposed to be published in less than a year.

Reference	Title of the norm	Estimated publication date
IEC 62670-2 Ed. 1.0	Concentrator photovoltaic (CPV) performance testing - Part 2: Energy measurement	2015-03
IEC 62688 Ed. 1.0	Concentrator photovoltaic (CPV) module and assembly safety qualification	2015-09
IEC 62787 Ed. 1.0	Concentrator photovoltaic (CPV) solar cells and cell-on-carrier (COC) assemblies - Reliability qualification	2014-07
IEC 62925 Ed. 1.0	Thermal cycling test for CPV modules to differentiate increased thermal fatigue durability	2015-08
IEC/TS 62108-9 Ed. 1.0	Concentrator Photovoltaic (CPV) modules and assemblies - Design qualification and type approval - Part 9: Retest guidelines	2014-10
IEC/TS 62789 Ed. 1.0	Specification of concentrator cell description	2014-07
IEC 62817 Ed. 1.0	Solar trackers for photovoltaic systems - Design qualification	2014-10

Table 3.3. Drafts of future norms related to CPV

Among the published standards, the IEC 62670 and the IEC 62108 are the most important ones because they establish the basis for the measurement and assemblies of the systems respectively.

The first one defines the concentrator standard operating conditions (CSOC) and the concentrator standard test conditions (CSTC), so that power ratings noted on data sheets and nameplates will have a standard basis. A summary of these conditions is gathered in the following table (IEC 62670-1, 2012)

Parameters	CSOC	CSTC
Irradiance	900 W · m^{-2} DNI	1000 W · m^{-2} DNI
Temperature	20ºC Ambient temperature	25ºC Cell temperature
Wind Speed	2 m · s^{-1}	-
Spectrum	Direct normal AM1.5 spectral irradiance distribution consistent with conditions described in IEC 60904-3	

Table 3.4. Operating and standard conditions defined for CPV (IEC 62670-1)

Regarding the IEC 62108, it determines the electrical, mechanical, and thermal characteristics of the CPV modules and assemblies and shows within reasonable constraints of cost and time that CPV modules and assemblies are capable of withstanding prolonged exposure in open air climates (IEC 62108, 2007)

This standard is a compendium of accelerated aging tests that identify long-term reliability problems in the CPV modules and assemblies, reducing the risk of failure of the system; in other words, the goal of this qualification standard is to guarantee the durability and reliability of the CPV systems (McConnell & Ji, 2007).

The tests applied in the Qualification Test Sequence can be gathered in five different groups according to the parameters they measure: Diagnostic Tests, Electrical Tests, Climatic Tests, Mechanical Tests and Irradiance Tests. All the tests include a pass criterion that the modules and assemblies must fulfill in order to get the qualification and type approval.

Historically, the standard is a mixture between two previously released standards: IEEE 1513 and IEC 61215. Related to the first one, IEC 62108 is an evolution of the IEEE 1513 Qualification Standard: "IEEE Recommended Practice for Qualification of Concentrator Photovoltaic (PV) Receiver Sections and Modules", published in 2001; but the requirements for the tests in the present IEC 62108 standard are stricter although the procedures of the tests are less complicated and better detailed.

Regarding the second standard mentioned, it can be said that the tests compiled in the CPV norm are partially based on the ones specified in the IEC 61215, which it is a flat-plane PV norm; but there are some differences between the tests described in both standards; for example, the outdoor exposure test, the UV conditioning test, the damp heat and humidity freeze tests, the maximum cell temperature and the thermal cycling tests have been modified significantly to be adapted to the particularities of the CPV technology.

Focusing on possible improvements of this IEC62108 standard, there are several points that should be taken under consideration and maybe included in the revision of the standard, which stability is dated until this year.

This standard gathers under the same norm five different CPV technologies to apply the tests. Firstly, new CPV systems are constantly emerging, so as it is impossible to revise the norm very frequently, it would be a good idea to write a norm or an annex in the present one that defines and delimits which systems can be gathered under the denomination of Concentrator PV. Additionally, it is not viable to consider under the same standard such a wide variety of CPV systems as IEC 62108 does, because the systems have different performance behaviors among them and there are tests that could be extremely restrictive with some systems that do not require the pass criteria levels defined. As the IEC 61215 standard for flat-PV modules differentiates in its scope the application of the norm between silicon modules and thin-film ones by defining a different norm, it should be similar with CPV technologies, especially when, under the same technologies described in the CPV standard, manufacturers uses different solar cell types, increasing the variety of possible CPV systems even more.

Beyond that, some organisms and laboratories are encountering technical problems when applying some of the tests described in the norm. For example,

in relation to the dark IV test, shunt effects could be induced and negative resistance behavior was detected under a certain current threshold (Timó, et al., 2008). Certification organisms are also having difficulties in the measurements of electrical performance because there is no definition on the measurement methods for the CPV modules power rating. They are also finding some critical circumstances for indoor testing such as the climatic chambers conditions and the climatic test duration, together with the versatility that their equipments must have in order to test the variety of CPV systems gather under the same standard (Petrina, et al., 2008).

Another critical point detected comes up with some degree of freedom in the application of certain tests. For instance, the possibility to test representative samples of the modules or assemblies if the full-size model is too large to fit into the testing equipment. It can be very expensive to develop a representative sample that achieves the same electrical, mechanical and thermal characteristics, and moreover, technically, it is almost impossible to achieve the same behavior and operational characteristics of the original model. Another point not clearly specified comes up when the IEC62108 allows the development of a comparable test program in those cases where the tests of the standard cannot applicable to a specific design.

The possible improvements in the present standard and the working teams for the development of the new ones, assure that CPV industry is running towards the commercialization stage with a solid foundation.

3.2. Spectral dependency and behavior

The output characteristics of a multijunction cell are strongly dependent on the spectral variations of the incident radiation. Commercial cells are usually designed for Air Mass 1.5D, under the spectrum defined in the ASTM standard G173-03, and a cell temperature of 25ºC. At this point, there is supposed to exist a current matching between the top and middle subcell of the MJ cell, while the bottom one, Germanium based, is working in an excess current generation, normally in the range of 30% regarding the top and the middle subcells. As the meteorological specifications previously mentioned are constantly varying, it is very likely that either the top or the middle subcell will

limit the output of the MJ cell at any moment, so the detection and measure of this limiting situation is needed to address how the MJ cell's output changes concerning the spectral content of the sunlight.

3.2.1. Spectral response measurement. MJ Photocurrent estimation

The theoretical explanation of the rise in the efficiency of multijunction cells is based on the partitioning of the incident solar spectrum, which results in the increment of the output voltage and the lowering of its current if it is compared to Silicon cells. Despite the expected efficiency benefits, this split turns into an increased sensitivity of the solar device to the spectral variations (Kinsey & Edmondson, 2009).

In order to define the energy output of a MJ solar cell, its spectral response (SR) to a certain incident solar distribution is needed to be known, that is, the current generated per incident unit of power (sun irradiance) at a specific wavelength. This concept can also be explained by means of the number of electrons collected per incident photon, which it is called external quantum efficiency (EQE).

Figure 3.2 shows a typical example of the EQE of a commercial three layers multijunction cell composed of GaInP/Ga(In)As/Ge, which is the most widely MJ cell used for the CPV modules implementation. Multijunction cells under the same technology will tend to have a similar shape regarding their spectral response.

The MJ cell is monolithic, which means that the subcells are not accessible individually, so the spectral response measurement of each subcell has to be done considering the possible influence and response of the rest of junctions.

The technique for measuring the spectral response of a MJ cell is well documented in the literature (Burdick & Glatfelter, 1986) (Adelhelm & Bücher, 1998) and it is based on the use of bias light combined with a monochromator, where the subcell under test has to be in a limiting current situation in order to be able to measure its quantum efficiency. The reason to include a monochromator is justified because a specific incident spectrum can be mechanically split into very narrow wavelength bands (around 5nm), so the

resolution for the EQE detection can be reduced. Nowadays there are some attempts to substitute this mechanism by LED based systems (Young, et al., 2008) (Rodríguez, et al., 2013).

Figure 3.2. EQE of the MJ cell under test in the thesis

If the spectral response in a tandem cell is performed with monochromatic light and with the absence of bias voltage or light that overexcites the cells not under test, instead of the expected response shown in the previous figure, the result will be similar to the Figure 3.3, where the bottom subcell has been avoided for clarifying reasons.

The explanation is because at short wavelengths, the incident monochromatic light will be absorbed completely by the top subcell, so there is no photon excitation of the following layer. Only at the intersection area there will be an output due to the combination of the proportional response of either top or middle subcell.

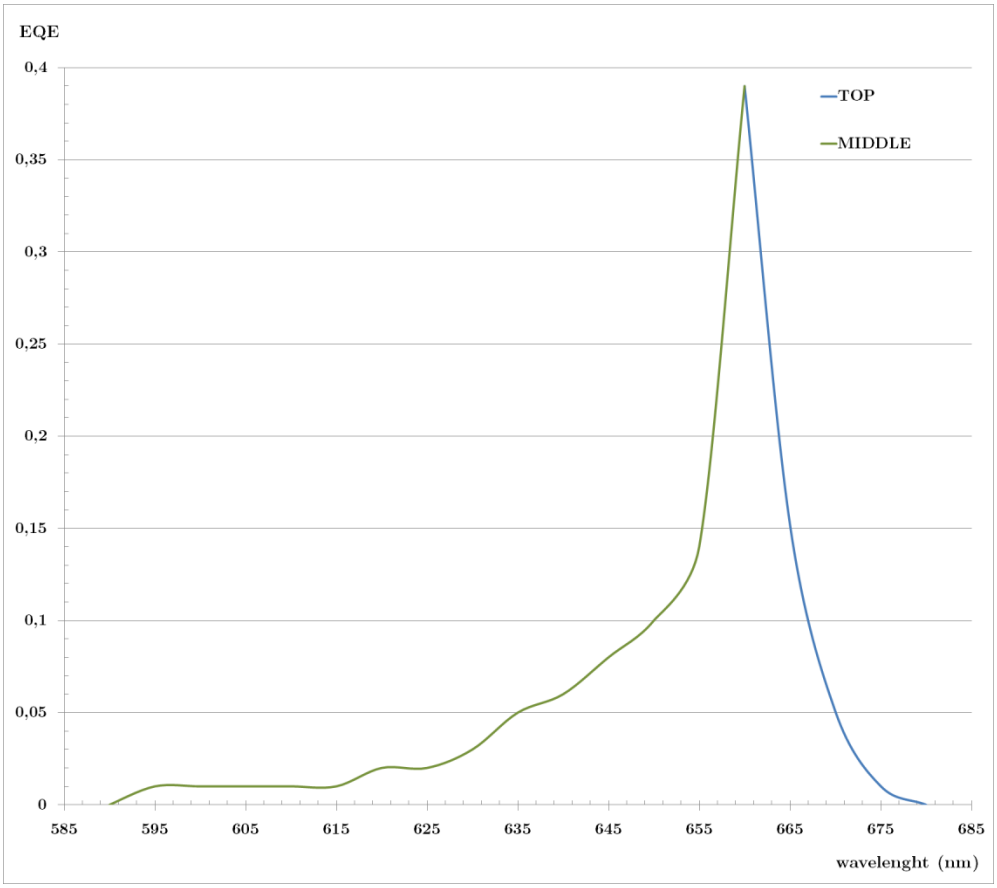

Figure 3.3. Possible Spectral Response of the cell with a non-light biased test

Therefore, the procedure consists on flooding the cells not under test with a particular spectrum by means of steady state filtered bias lights so the subcell under test generates the lowest photocurrent, while the rest of subcells are in a overexcitement condition. Additionally, it is important to mention that the monochromatic light should be chopped powered, so at the output of the cell, with the help of lock-in technology, the AC signal of the limiting cell produced at the chopped frequency can be detected.

The measurement procedure is performed assuming short-circuit conditions, so $V_{MJ}=0$. The subcells are serial-connected so the external voltage is the sum of the individual voltages ($V_{MJ}=\Sigma\ V_i$), but it does not imply that at short-

circuit conditions each subcell operates at V_i=0. In fact, the subcells with excess in photocurrent will be operating at a lower level than its nominal value, so attending to their individual IV curve, they will be closer to the open circuit region (Burdick & Glatfelter, 1986). This situation makes that the cell under test will operate at a reverse voltage close to the sum of the non-limiting subcells open circuit voltages. In order to measure the short-circuit conditions of the subcell under test, the MJ cell has to be voltage bias in forward $V_{BIAS} \sim \Sigma V_{OC}^j$, where j is referred to the non-limiting subcells. Some authors claim that V_{BIAS} has to be the sum of the mean values of open-circuit voltage and the voltage at the maximum power point of all the subcells not to be measured (Meusel, et al., 2003):

$$V_{BIAS} = 0.5 \cdot \Sigma (V_{OC}^j + V_{MPP}^j) \tag{1}$$

The reason of voltage biasing the MJ cell is that the spectral response may be influenced by the operating voltage of a subcell. Amorphous silicon triple-junction solar cells have a strong dependence on the voltage bias, but on the other hand, with the commercial MJ cells used in this theses, no significant differences at EQE measurements have been found when $V_{BIAS} = 0$ or $V_{BIAS} = \Sigma V_{OC}^j$, although some artifacts affecting the Ge bottom cell that may distort the measure of this bottom subcell have been detected (Meusel, et al., 2003).

In monolithic MJ cells it is not possible to directly measure the photocurrent generated by each subcell, because there are only two terminals at the extremes of the cell, but once the SR of each layer is known, it can be calculated through the application of the following formula, where *A* is the active area considered:

$$I_{ph,i} = A \cdot \int SR(\lambda) \cdot E(\lambda) \cdot d\lambda \tag{2}$$

The photocurrent of each subcell can also be estimated by using isotype cells, which are also known as component cells, thus avoiding the use of spectroradiometers and spectral response measurements.

Isotype (or component) cells have the same structure as their corresponding MJ cell, but there is only one PN-junction active, so the rest of subcells do not contribute or interfere in the total output, so the light absorption and photocurrent generated within each subcell of a MJ device can be precisely

reproduced. Therefore, to estimate the current of each subcell in a 3-junction device, three isotypes cells are needed, so $I_{ph,i} \approx I_{SC,i-component}$

Figure 3.4. Commercial isotype based spectral sensors (courtesy of Solar Added Value S.L and Black Photon Instruments GmbH)

However, on the one hand, the isotype cells will have an operational behavior slightly different than commercial cells produced in manufacturing batches as they have to be specifically modified for the elimination of the PN junctions. Additionally, it is very frequent that component cells have different EQE from the multijunction cells, so the current generation in the isotype cells could not be directly related to the real behavior of a MJ cell. That is why the use of an empirical mismatch function is needed in order to reduce the transformation errors (Jaus, et al., 2011)

Anyway, the method to characterized the photocurrent produced by a MJ cell based on isotypes sensors will only be done using an indirect measure (Leloux, et al., 2010), so according to the current technological development, a necessity has been detected in the direction of creating a device able to measure directly the photocurrent generated by each subcell in a commercial MJ solar device without modifying its internal composition or making correlations based on indirect measures.

3.3. On-site measurement of limiting subcell in multijunction solar devices

In a monolithic multijunction solar cell (either lattice-matched or metamorphic) the only method to distinguish the photocurrent generated by each subcell is through the estimated calculation of the spectral response manufacturer's data combined with Sun spectrum measurements, which are usually done either with isotype based pyrheliometers or with spectroradiometers (Dominguez, et al., 2013)

According to the literature consulted up to date, there is no commercial device dedicated exclusively for the direct measure of each subcell photocurrent in outdoors conditions, therefore the current mismatch between the top and middle bands of a MJ is only estimated.

Moreover, the use of MJ cells from different manufacturers, each one with different spectral response, would tend to the necessity of adapting the isotype based pyrheliometers to each technology or manufacturer, which is not very viable.

In this section a device (Limiting Current Ammeter, LCA) is proposed, which is able to identify the limiting subcell (junction) in a commercial MJ cell and it also measures the differences in photocurrent generation by each layer. Beyond that, it is intended to be easily adaptable to several manufacturers with minimum technical modifications.

In this first prototype it only detects the top and middle band relation, as according to the most extended commercial MJ devices, the bottom subcell will not limit the current generated in the overall output of the MJ cell.

3.3.1. Theoretical basis. Adaptation of an existing procedure

The theoretical basis of the device proposed is similar to the procedures used to measure the spectral response or the external quantum efficiency of MJ cells explained previously, but there have been some adaptations as the device is intended to be operating in outdoor conditions, so the use of a monochromator combined with a set of light sources plus filters seem to be unpractical.

The first difference is that neither artificial light to simulate the Sun spectrum will be used, nor filters or additional bias lights will be added to force the subcell under test to remain in a limiting current situation regarding the rest of layers in the MJ device. Except for the current matching situations, which uncertainties will be addressed in the following lines, the simple and direct application of the sunlight in real outdoor conditions will be enough to cause a subcell limiting situation, and it will be closer to a real operational behavior as the temperature effects will be inherent to the measure.

Beyond the origin of the light source, the main difference with respect to the EQE measurement lies in the modulation procedure. While in the former technique the incident light was the modulated income, in the LCA the direct sunlight remains unsteady, and the MJ cell is over-excited with a modulated light coming from two set of LEDs, whose emitting spectrums are only absorbed by a single subcell, either the top or the middle one, thus adding an AC content to the DC photocurrent signal.

This MJ cell plus the LCA, all gathered into a collimator tube, makes this device to become a pyrheliometer, giving the direct effective irradiance for the top and middle bands, which are the datum offered by commercial isotype spectral sensors (see Figure 3.5).

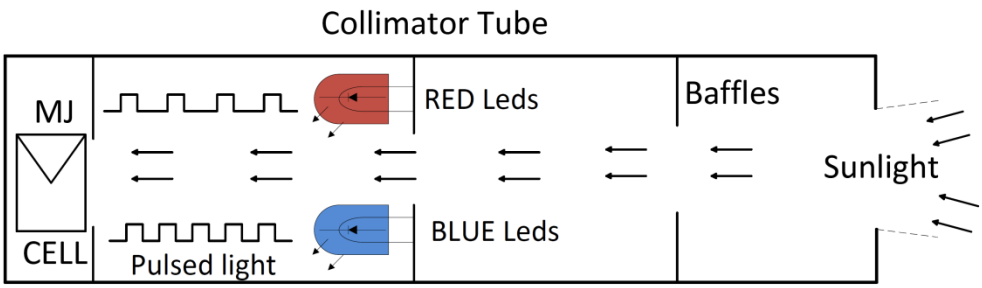

Figure 3.5. Outline of the pyrheliometer device

The main key in the theoretical basis formulation is the proper correlation between the dominant emitting wavelength of the LEDs and the spectral response of the multijunction cell under test. In this preliminary prototype used for the confirmation of the theory, the spectral distribution of the cell under

test could be observed in Figure 3.2, where the data of the external quantum efficiency offered by the manufacturer were used.

The relative spectral emission of the LEDs chosen, at the rated forward current, is shown in Figure 3.6, where the left-side distribution corresponds to a deep-blue LED and the right figure is the spectral emission of the Infrared emitter.

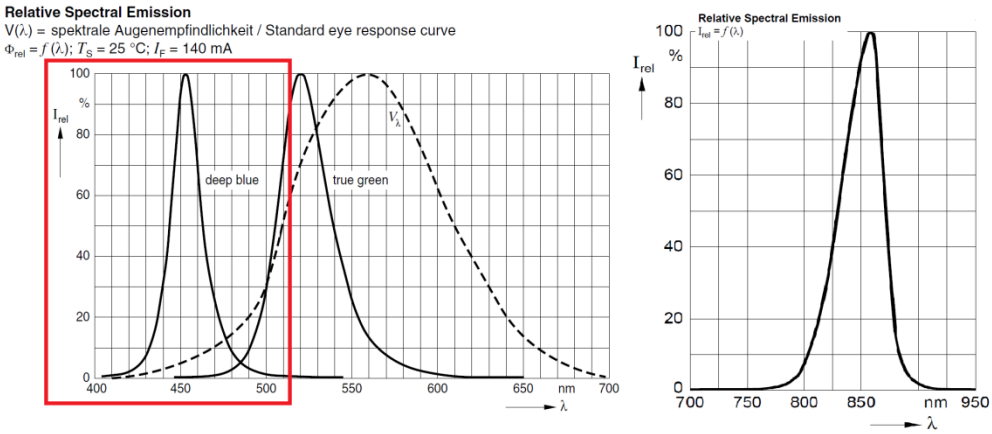

Figure 3.6. Spectral Emission charts of the LEDs

It is important to highlight the range where the overlapping of the spectral response curves for each subcell is produced, as these regions should be avoided when choosing the spectral emission of the LEDs because it may have influence on the response of the adjacent subcell and, in consequence, distort both the limiting detection procedure and the measurement of the photocurrent generated by each cell.

Under the current MJ technology, it does not matter if the emission of the LED that excites the middle subcell reaches the bottom layer, as it will only cause an additional overexcitement in this subcell, but it will not interfere in the calculation of the photocurrent for the limiting and non-limiting detection, because under realistic outdoor spectral conditions, the intrinsic regular behavior of this bottom layer makes it always remain in an overexcited state.

Figure 3.7 shows the overlapping of the spectral distributions of both the MJ and the LEDs involved.

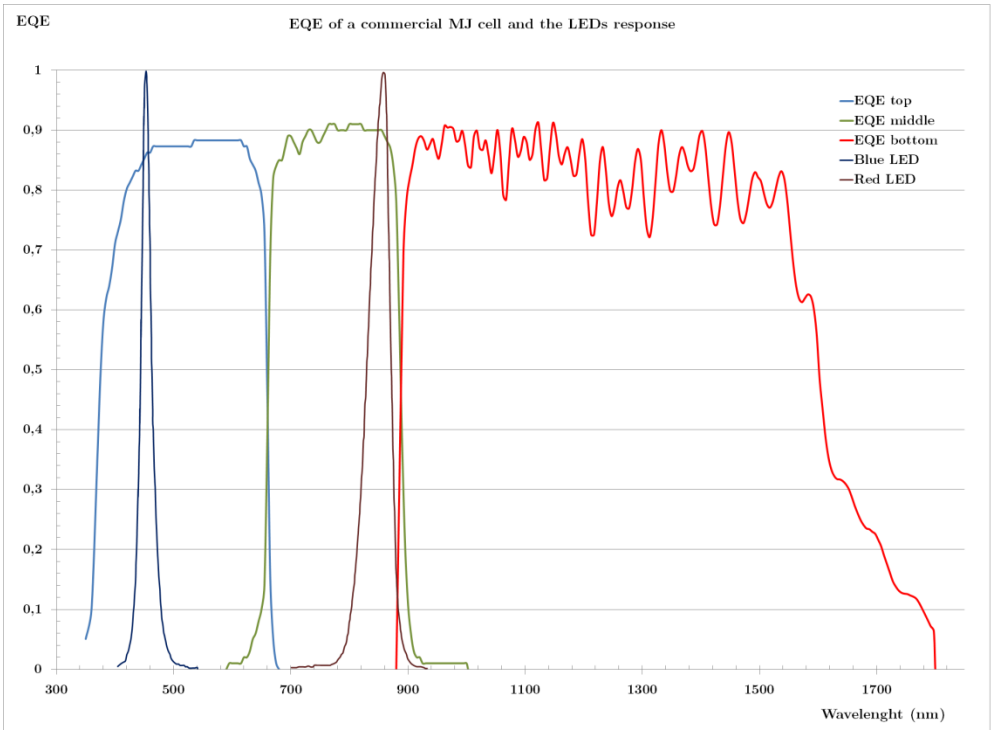

Figure 3.7. Superposition of the spectral response of the MJ cell and LED's emission

In order to measure the photocurrent generated by each layer properly, the MJ cell is biased, so it is working in the short-circuit region. This state, combined with the modulated light from the LEDs, results that the blue and red light emission from the LED will add an AC component in its corresponding top and middle subcell photocurrents (see Figure 3.8), but only the AC current from the limiting subcell will show up in the overall output of the MJ cell following the rule:

$$I_{MJ}(t) = \min[\, I_{TOP}(t)\ ;\ I_{MID}(t)\,] \tag{3}$$

An illustrative example of this effect is shown in the following figure where it has been assumed that the top subcell is under a limiting state and a pulsed light has been used for the modulation of the LED signals.

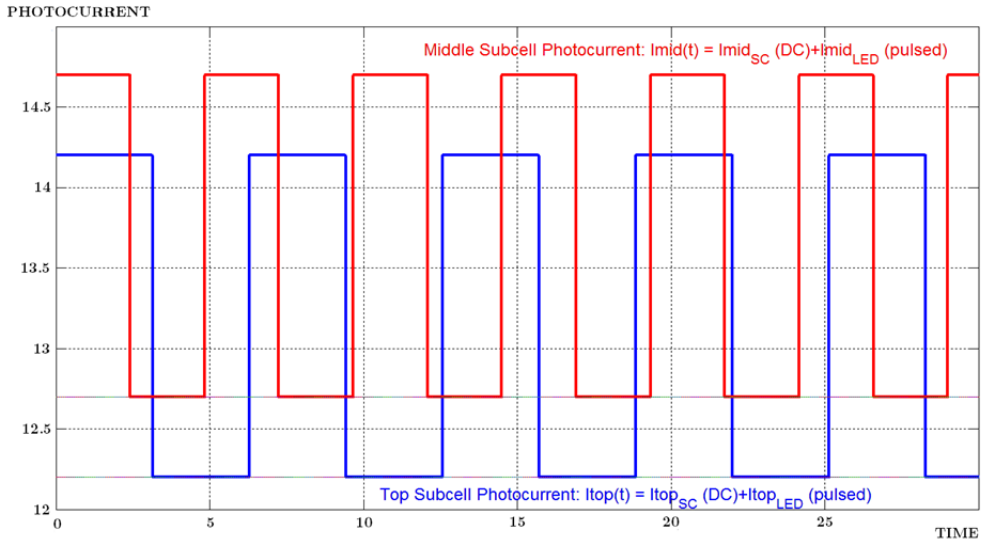

Figure 3.8. Photocurrent characteristics including the AC modulation from the LEDs

The expected signal to be measured should be ruled by the following expression, where the short-circuit output of the cell will correspond to the limiting subcell according to the equation (2).

$$I_{SC\_MJ}(t) = I_{SC\_i-subcell}(t) = I_{ph\_i-subcell}(t) + I_{AC\_led}(t) \tag{4}$$

In the mathematical formulation of this theory it has been assumed that the short-circuit current can be approached by the photogenerated current and the absence of the aforementioned V_{BIAS}, will not affect the measure.

Resuming the modulation concept, each LED set should be powered at a different frequency rate, because it is the only possible mechanism to detect which layer is the limiting subcell. Otherwise, if both LEDs are powered at the same rate, the interpretable information measured at the output of the MJ device will be indistinctly from the top or the middle subcell. Moreover, not only the frequency has to be different between powering signals, it also has to differ from the frequency of the electrical network and they should not be multiple between them, so the interference of any harmonic component of the signal from one frequency to another is avoided.

Visually, following the characteristics shown in the previous figure, the signal measurable at the output of the LCA device is expected to have a shape similar to the one shown in Figure 3.9. Three levels of the signal can be detected. The lowest photocurrent measured belongs to the limiting subcell (DC short-circuit term) and the next value in the waveform shows us the difference in photocurrent generated between the limiting and non-limiting subcell. In this figure, the output current is not saturated because both LEDs sets were on, so the highest current level shown in the figure corresponds and depends on the light emission power of the LEDs used.

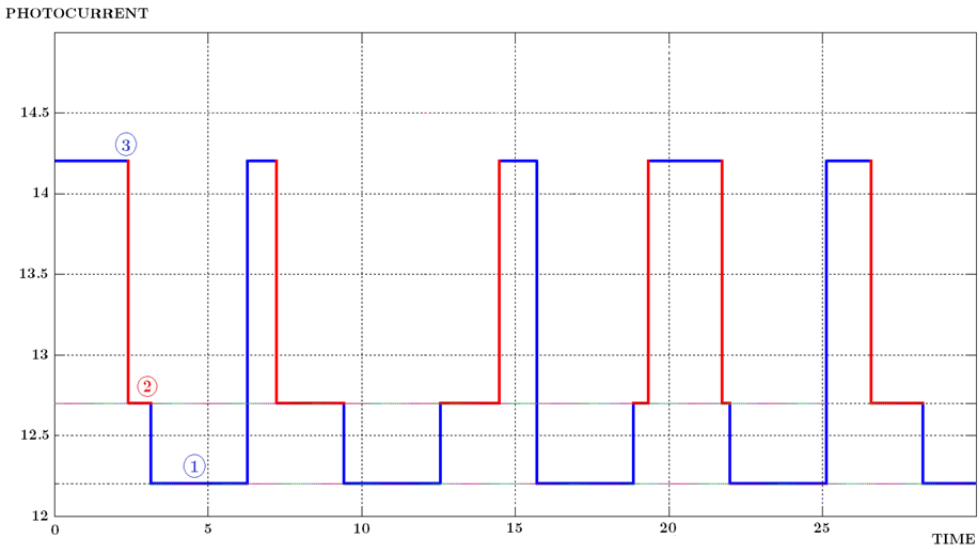

Figure 3.9. Expected theoretical output of the LCA

Normally, the frequency of this output signal is easily measurable, so it gives enough information whether it corresponds to the blue or the red LED frequency. Nevertheless, in a real operating environment, it is very likely to be affected by unknown several sources of noise.

In the cases where one of the subcells is clearly limiting the overall output of the MJ device, we can apply the previous reasoning of measuring the frequency of the output, but in the current matching states the output is not so intuitive

as in Figure 3.10 is illustrated; therefore, we must define a procedure capable of comparing the frequencies rejecting the undesired noise.

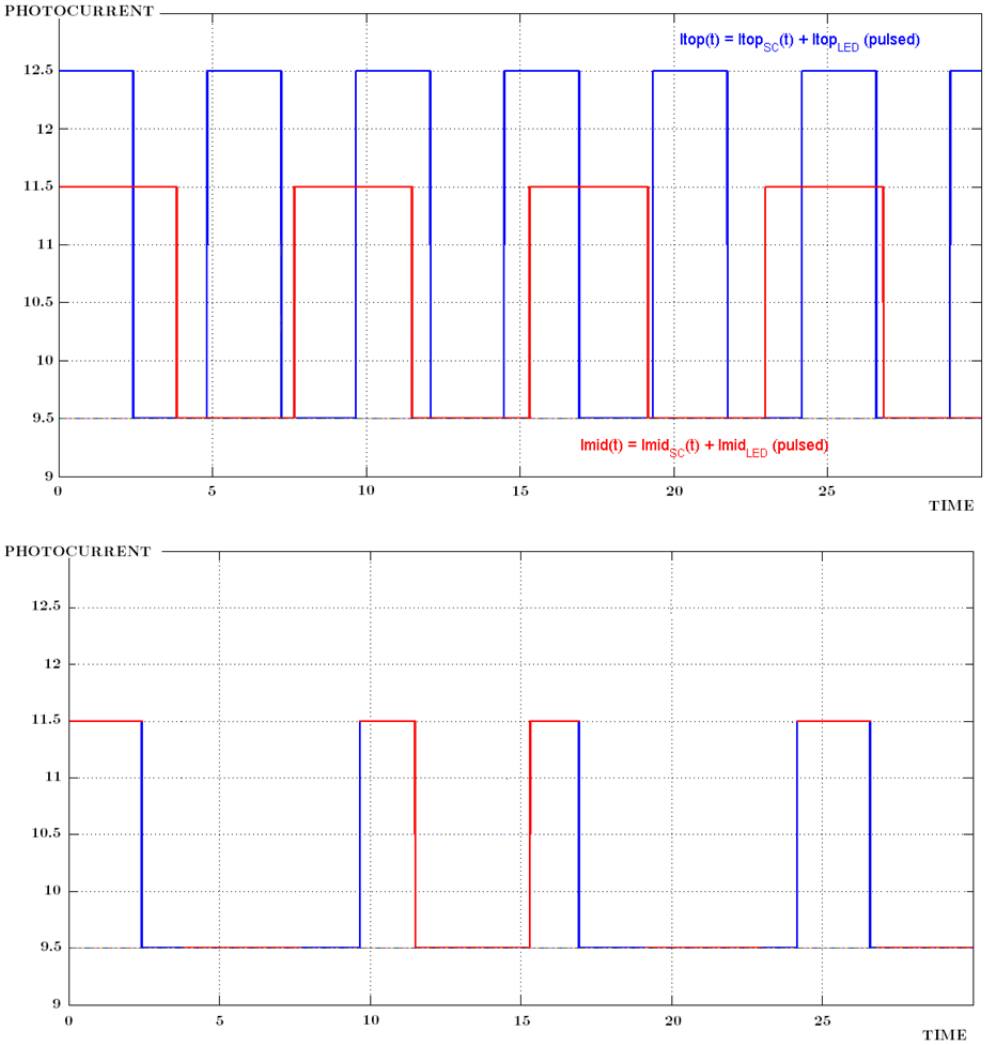

Figure 3.10. Theoretical MJ output at current matching state

Despite the pulsed LED light used in the previous figures, the theory of the procedure will be mathematically addressed considering that both LEDs are

powered with a sinusoidal signal of frequency f_M for the red LEDS or f_T for the blue ones. The signal produced at either subcell could be expressed as:

$$I_{SC\_TOP}(t) = I_{ph\_top}(t) + I_{blue\_led} \cdot \cos(\varpi_T \cdot t) \tag{5}$$

$$I_{SC\_MID}(t) = I_{ph\_mid}(t) + I_{red\_led} \cdot \cos(\varpi_M \cdot t) \tag{6}$$

In the previous equation, I_{ph_top} and I_{ph_mid} depend on the spectral response that each subcell is sensitive to regarding the income sunlight, thus producing a DC current (short-circuit condition); meanwhile, I_{blue_led} and I_{red_led} correspond to the radiant intensity of the LEDs and the spectral response of each subcell in the emission range of blue and red LEDs.

From the previous equations, the photogenerated DC current is only interesting as it gives information of the overall output of the MJ device, thus the ruling subcell, but it can be avoided for the limiting detection and the measurement of the difference in current generation from the limiting junction to the following non-limiting layer.

The remaining output signal (only the AC term), whose frequency may be known, can also contain other components of frequency from different sources of noise that may distort its output, so it is necessary to demodulate it to obtain the information which was transmitted and also to reject possible sources of noise attached to light measurements.

Following the similarities with the EQE measurement procedure explained in previous sections, a simple lock-in technique is used to detect this AC current and to suppress noise. For that purpose, the DC component of the signal should be removed.

The lock-in technique consists on the rectification of an AC signal and the application of a low-pass filter to smooth or average all the frequencies differing from the selected one to the mean value of zero. Therefore, the procedure will consist on multiplying the MJ output signal by a reference unitary signal, firstly with a frequency (f_r) like the one used for powering the blue LEDs ($f_r = f_T$), and subsequently with the frequency of the red ones ($f_r = f_M$).

The low-pass filter that should be applied afterwards is explained by the mathematical integration of the resulting waveform over a period of time much longer than the period of the reference signal. The expressions obtained for each frequency are:

$$A_{TOP} = \frac{1}{M} \cdot \int_0^M I_{MJ}(t) + F(\varpi_T \cdot t) \cdot dt \tag{7}$$

$$A_{MID} = \frac{1}{M} \cdot \int_0^M I_{MJ}(t) + F(\varpi_M \cdot t) \cdot dt \tag{8}$$

The solution of either averaging formula will result zero for those cases where the frequency of the MJ output signal does not coincide, because once the DC component of the signal has been rejected, the resulting waveform from the multiplication will be a periodical signal centered at y=0, so the mean value will always be zero. In the case of having the same frequency, both the MJ waveform and the reference one, the result of the multiplication will also be a periodical signal, but shifted from y=0, so the mean value is different from zero.

Since the reference signal is matched with the frequency of either blue or red LED, then which subcell is limiting can be identified just through the applications of the previous formulae, as it summarizes the following table.

Limiting subcell condition		
TOP	$\lvert A_{TOP}\rvert>0$	$\lvert A_{MID}\rvert=0$
MIDDLE	$\lvert A_{TOP}\rvert=0$	$\lvert A_{MID}\rvert>0$

Table 3.5. Mathematical integration results for limiting subcell detection

It is important that the reference signal is in phase with the input waveform, so the condition of maximum output can be achieved and a best signal to noise ratio is obtained. In real measurement the signals are expected not to be in phase, so normally lock-in amplifiers include a phase shifting circuitry with the aim to manipulate the reference waveform (Bentham Instruments, 2008)

Beyond the detection of which subcell is the current limiter, the same set-up can be used to measure the difference in current generation existing between the limiting subcell and the following non-limiting one.

If the amplitude of the LED light absorbed by the limiting subcell is increased, there will be a moment where the AC output of the overall current gets saturated. The reason for this saturation is because the other subcell now limits the increase in the amplitude of the LED.

The amplitude at which the saturation is reached gives the value of the difference between the limiting and the non-limiting photocurrents. As an example, Figure 3.11 shows a case where the top subcell is the current limiter and the power of the blue led has not reached the DC short-circuit value of the middle subcell, thus the amplitude of the LED can be increased until the saturation is reached. At this point, the increments in light intensity will not be reflected in the measurable output of the LCA until the middle subcell photocurrent is reached.

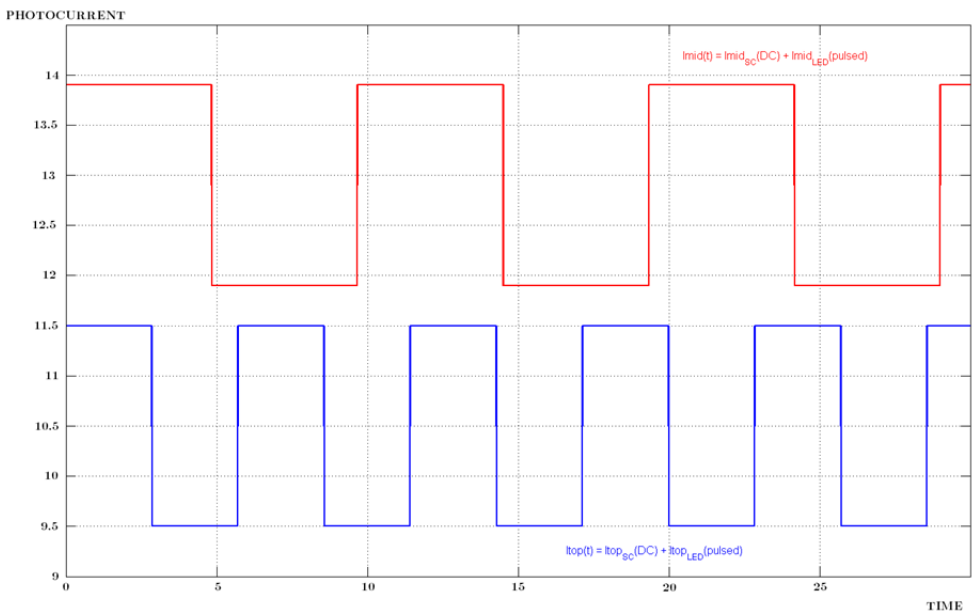

Figure 3.11. Non-saturated top subcell limiting situation

All the theory has been mathematically explained assuming sinusoidal waveforms for it easiness regarding the application of the lock-in tool, but in practice pulsed signals are normally used, which are equivalent to sine waves of the fundamental frequency together with all the odd harmonics of the fundamental.

The previous statement may complicate the mathematical formulation of the problem. However, following the Fourier composition, the harmonic components reduce their amplitude in a 1/harmonic rate, so the noise will be decreased as the harmonic component increases. Moreover, the modulated light will also transfer additional signal information to the output of the lock-in tool. The most dangerous situation is whether a harmonic coincides with a specific interference present at this point of the spectrum, or two harmonics components of the pulsed LED lights coincide in the same harmonic window (Bentham Instruments, 2008). This reason reinforces the importance of selecting the frequencies of the LEDs in a proper way.

Moreover, the use of sine waves is not recommended because it will be difficult to find a correlation between the amplitude of the signal and the difference in photocurrents between the top and middle subcells, as the following figure illustrates.

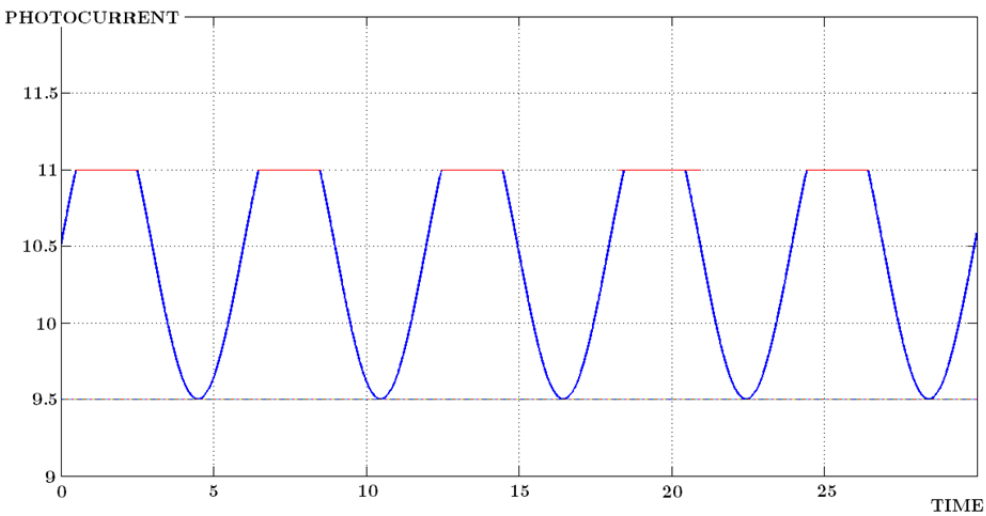

Figure 3.12. Truncated sine wave for detecting the difference in photocurrents

3.4. From theory to an experimental setup. Results

The experiments concerning the detection of the limiting subcell have been carried out using a sample of a commercial MJ cell (see Figure 3.13) which has the characteristics observable in Table 3.6 under the spectral distribution corresponding to AM1.5D and the ASTM standard G173-03.

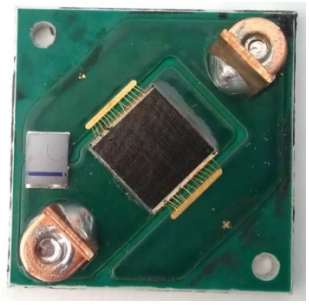

Figure 3.13. MJ cell used for the experiments

These characteristics corroborate the excess of current generated by the bottom subcell regarding the top and middle layers, and it is within the standard characteristics of nowadays commercial MJ cells. It also reinforces the assumption made regarding the choice of LEDs with respect to their spectral emission, where the possible shift in the bottom subcell caused by the red LED will not interfere in the definition of the top-middle limiting subcell.

MJ characteristics		
Subcell	Isc (mA)	SR range (nm)
TOP	9.496	350-675
MIDDLE	9.670	590-1000
BOTTOM	14.498	880-1798
Active Area= 0.758 cm^2		

Table 3.6. Electrical characteristics of the MJ cell under test

It must be emphasized that the MJ cell used is designed in a top layer limiting situation under the reference spectrum considered, because the mismatch between the top and mid subcell is CM=0.982. This data was also expected under the discussion of the easiness of the MJ cells manufacturing with lower CM, as some authors claim (Kinsey & Edmondson, 2009)

The technical characteristics of the LED have been chosen bearing in mind the constraints of the relation between the absorption spectral band of each subcell and the LED emissivity distribution. Although the radiant power and the viewing angle have not been taken into account for this first set of measurements, it should be studied in future new developments due to some uncertainties regarding homogeneity and local current mismatch that some studies have detected (Dominguez, et al., 2013) combined with internal reflexions inside the collimator tube that may distort the measured current.

Parameter	BLUE led	RED led
Dominant wavelength	453 nm (at I_F=140mA)	850 nm (at I_F=100mA)
Spectral bandwidth (at 50% of I_{MAX})	25 nm	42 nm
Radiant Intensity (I_E)	100-180 (mW/sr)	40-80 (mW/sr) (at I_F=100mA) 400 (mW/sr) (at I_F=1A)
Radiant Power	140 mW (at I_F=140mA)	50 mW (at I_F=100mA)
Viewing angle	60º	30º

Table 3.7. Main characteristics of the LEDs

The peak emission wavelength specified, together with the spectral bandwidth, will be dependent on the nominal forward current (I_F) and the duty

cycle applied to the modulating signal used for powering the LED, so in the reality, it would add a level of uncertainty not considered in this document but it should be addressed in future prototypes.

A better detailed visual figure of the spectral response of the MJ cell under test and the relative spectral emission of both sets of LEDs was already shown in Figure 3.7.

3.4.1. Preliminary gross results

A basic, non-sophisticated prototype (see Figure 3.14) was used for the preliminary experiments with the aim of identifying misconceptions regarding the premises described in the theoretical formulation and to discover technical faults regarding the design, which consisted on a halogen light, two pairs of each type of LED, a commercial MJ solar cell and the electronics for the power supply of the LEDs and the measurement of the cell's current.

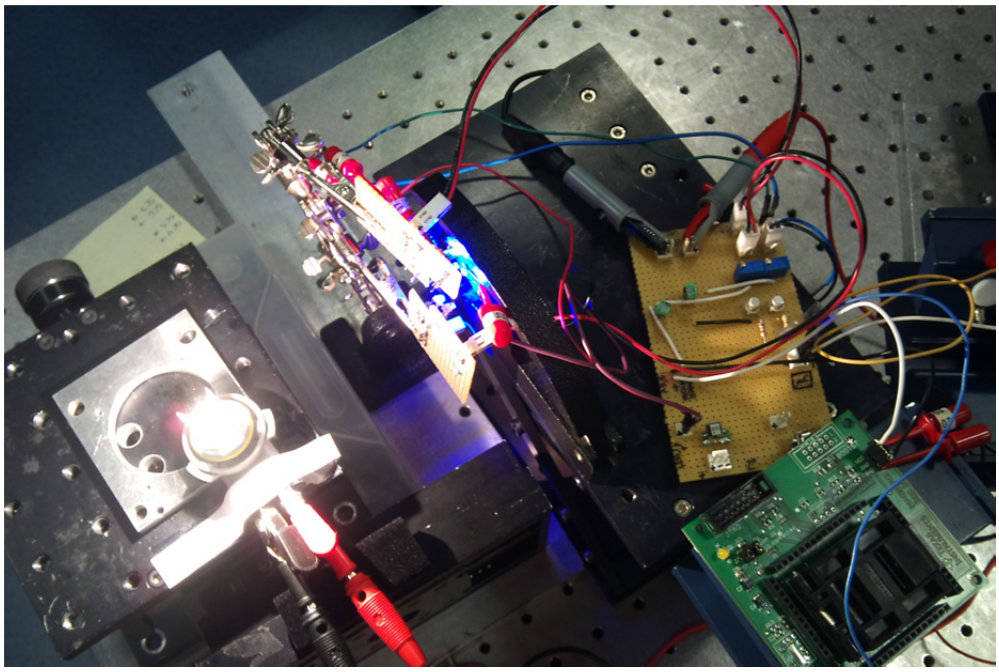

Figure 3.14. Initial setup of the LCA

In this first setup, the output of the MJ was connected to a current sensing transformer, therefore the PV cell will be short-circuited regarding the DC component, but it would let the AC current to appear in the secondary of the transformer, thus removing the DC component as the lock-in technique requires.

During these experiments a dynamic behavior of the MJ cell has been detected as exhibited in Figure 3.15. The dynamic output characteristics are related to the inherent capacitance of photovoltaic solar cells, where the MJ devices are more sensible to these effects than the silicon ones (Rueda, et al., 2003) (Friesen & Ossenbrick, 1997). The voltage at which the MJ cell is biased and the frequencies of the modulated light coming from the LEDs are also very related to this dynamic behavior.

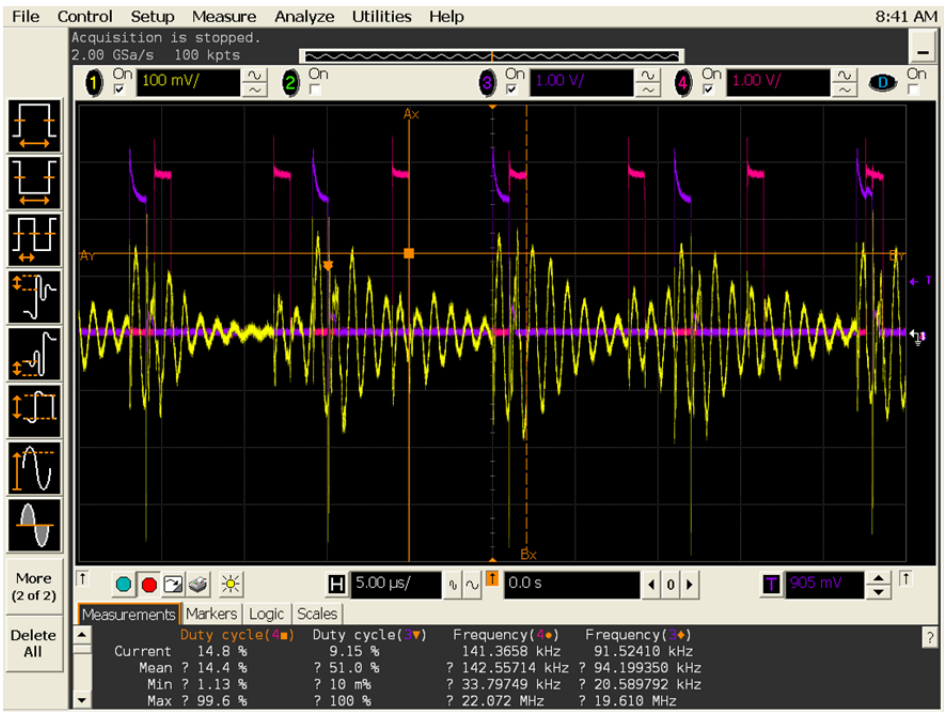

Figure 3.15. Dynamic behaviour of the MJ in the initial experiments

The combination of the circuit resistance, the inductance of the transformer and the capacitance of the MJ cell turned its output into a RLC filter shape-figure. Despite the appearance of this undesired effect, it is believed that a possible methodology of measuring the capacitance of a MJ cell may have been discovered, but this experimental line was postponed for future applications of this work.

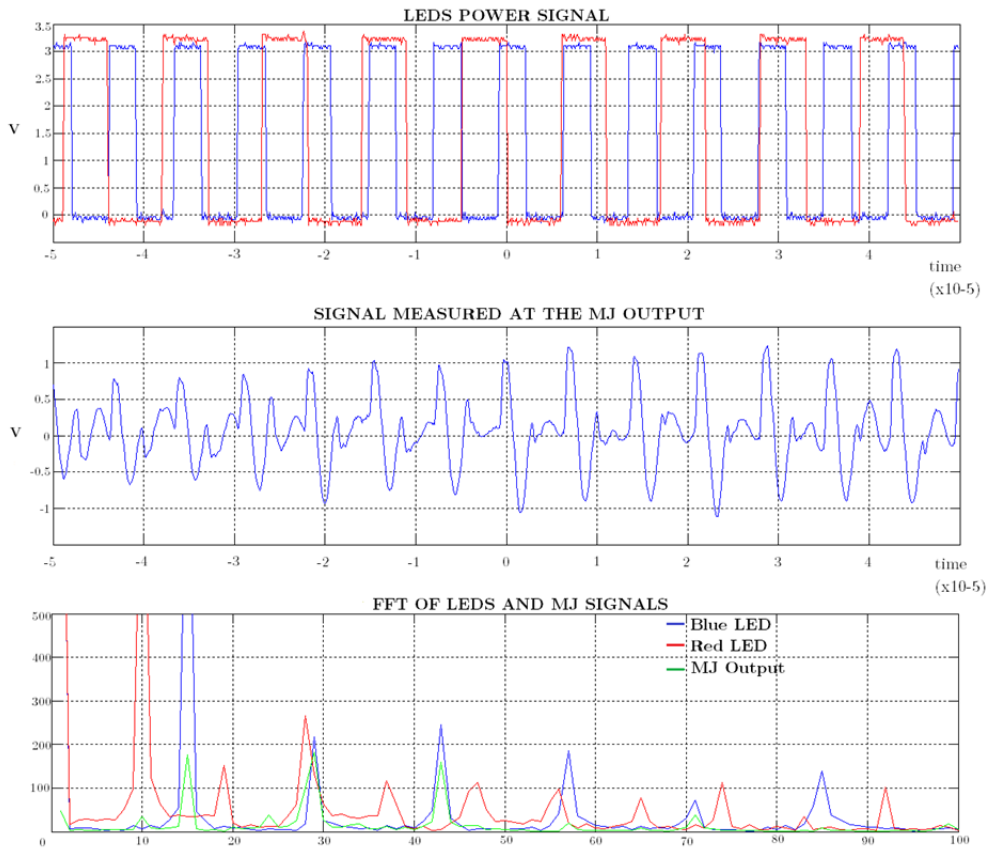

Figure 3.16. Frequency trend in the preliminary gross results

The measurements obtained could not be used as a proof of MJ subcell limiting detection, as these measurements lacked a technical solid background, but it should be highlighted that a certain trend could be glimpsed, as observed in Figure 3.16.

The MJ is assumed to be under a predefined and forced top limiting situation and its response (middle graph) seems to contain no relevant information, or even, there is a lack of connection when it is compared against the shape and frequency of the light supplied by the LEDs. Nevertheless, if a FFT analysis is carried out (bottom figure), the frequency content of the MJ signal (green line), seems to follow the harmonic distribution of the pulsed signal corresponding the blue LED, leading to predict that if a better prototype with the corresponding changes in the circuits is complemented, the results theoretically established could be somehow experimentally proven.

3.4.2. PCB prototype. Indoor experiments

Once some experimental measurements with basic circuits have been done, a first prototype of PCB was designed including all the improvements necessary to avoid the issues addressed in the preliminary experiments and also to join all the power, control and conditioning of the measured signals in a compact board (see Figure 3.17).

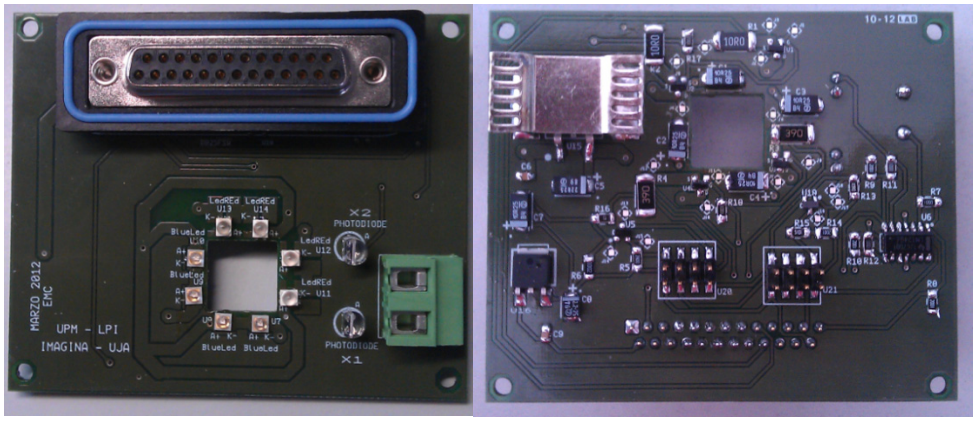

Figure 3.17. First prototype of the PCB implemented for the LCA

One of the main modifications translated into the design of the PCB, was the substitution of the current sensing transformer with a dedicated transimpedance operational amplifier, so the principle of virtual ground at the input terminals makes the MJ operates in a short-circuit situation and a voltage signal is obtained proportional to the photocurrent generated by the MJ device.

The DC rejection produced by the current transformer was intended to be substituted by a PNP transistor sub-circuit but its control and regulation was not correctly determined and some malfunctions regarding the measurement and instability in the signal were also detected. For this initial prototype, all the measurements were done including the DC component of the MJ output, and the results obtained are proven to be valid enough to support the theoretical basis of the LCA proposal.

Control and power signals share the same PCB, so the design of the ground or reference of the IC has to follow some rules to avoid signal integrity issues or ground loops that may distort the signal either introducing additional levels of voltage or undesired frequencies (Brooks, 2003) (Joffe & Lock, 2000).

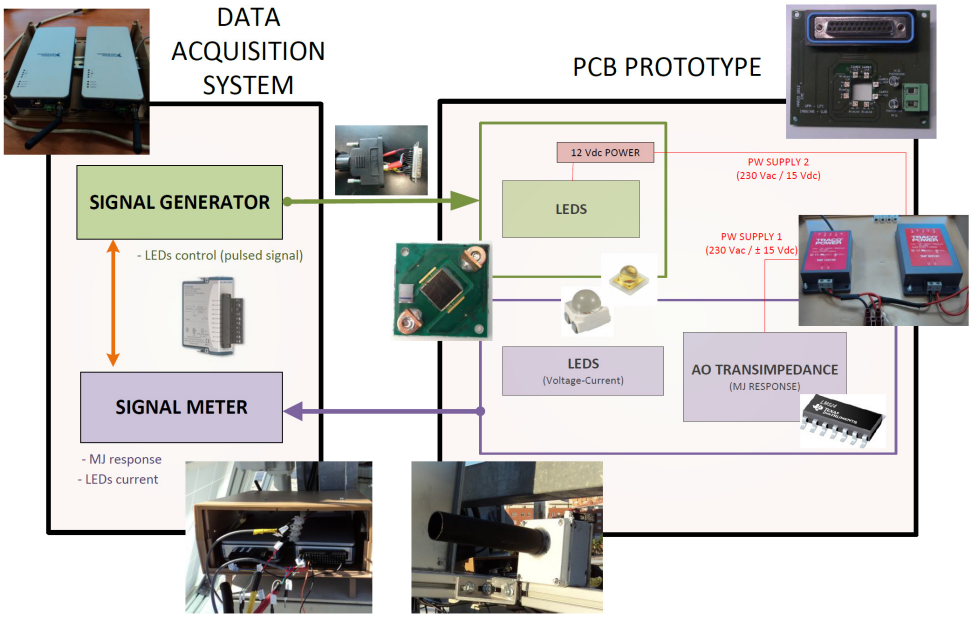

Figure 3.18. Block diagram of the LCA

Instead of using an oscilloscope like the previous results, an external acquisition system has been added, which is also responsible for the control signals that rules the LED operational states. It also measures and conditions the LCA output. It is important to define a proper sampling rate in order to

avoid aliasing effects. Although the Nyquist's theorem requires a sampling rate at least two times higher than the frequency of the signal, a rate higher than ten times has been chosen so the shape of the waveform can be accurately represented (Chugani, et al., 1998) (Travis & Kring, 2006).

For this preliminary test, the same steady income (halogen bulb) has been used for exciting the cell where in a first stage the modulated light from the blue LEDs has been applied and the result obtained seems to be consistent with the frequency applied.

The signal measured at the output appears to be clear enough once the effect of the inductance has been removed as figure 3.19 shows.

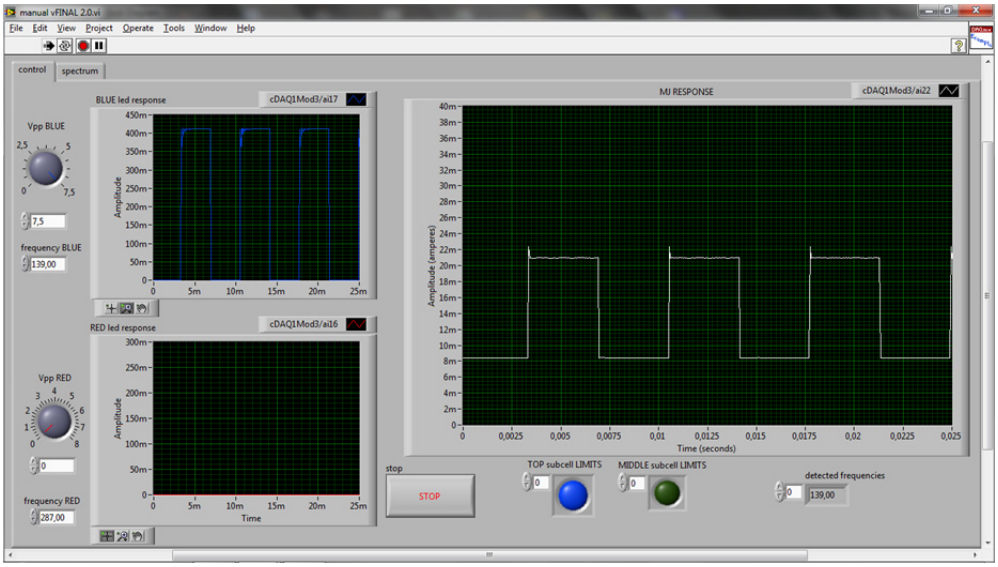

Figure 3.19. LCA output consistent with the blue LED frequency applied

The lowest photocurrent belongs to the intrinsic DC component of the MJ cell (short-circuit current), while there is no enough information to state the interpretation of the maximum level of the signal detected at the output.

According to the theory considered, it could mean that the amplitude of the blue LED has reached the limit imposed by the middle subcell, thus saturating

the output, but if the blue LEDs are powered at their maximum intensity it can be also an indication that the middle subcell current has still not been reached.

The only mechanism to detect this middle subcell current is by turning on the red LEDs and observing if there is a three level pulsed output as it was defined in the theory in Figure 3.9. From the examination of the experimental result obtained when both LEDs are on (see Figure 3.20), it can be assessed, in a first approximation, that the theory considered could be corroborated. In this case, according to the result, the top subcell seems to be limiting the MJ output.

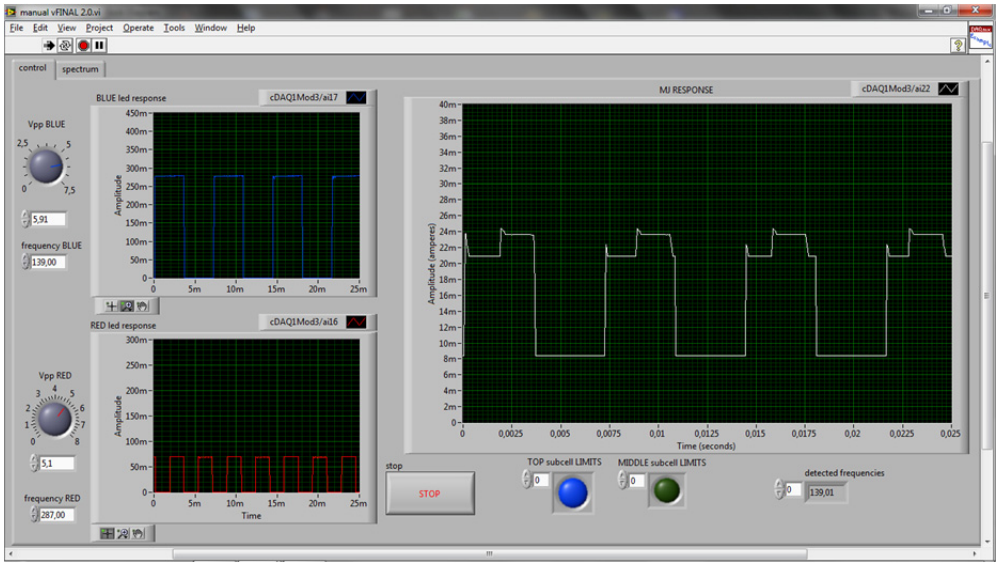

Figure 3.20. 3-level pulsed LCA output after both LEDs are ON

Nevertheless, although there is a coherent real background supporting the theory, the results from these indoor measurements cannot be fully validated due to some artifacts detected.

Bearing in mind that an artificial light source (halogen) has been used, in an initial attempt to measure the difference between the top and middle photocurrents, which is the additional application of the LCA device, an anomalous figure is obtained, because it corresponds to a mismatch ratio of

CM=0.4, so although in a normal real operational behavior the middle subcell generates more current than the top one, in this situation, this difference seems to be too large.

Moreover, if the experiment initially pointed at a top subcell limiting state, there should not be any signal measurable when applying just the red light, but the measures did not confirmed that hypothesis as Figure 3.21 shows.

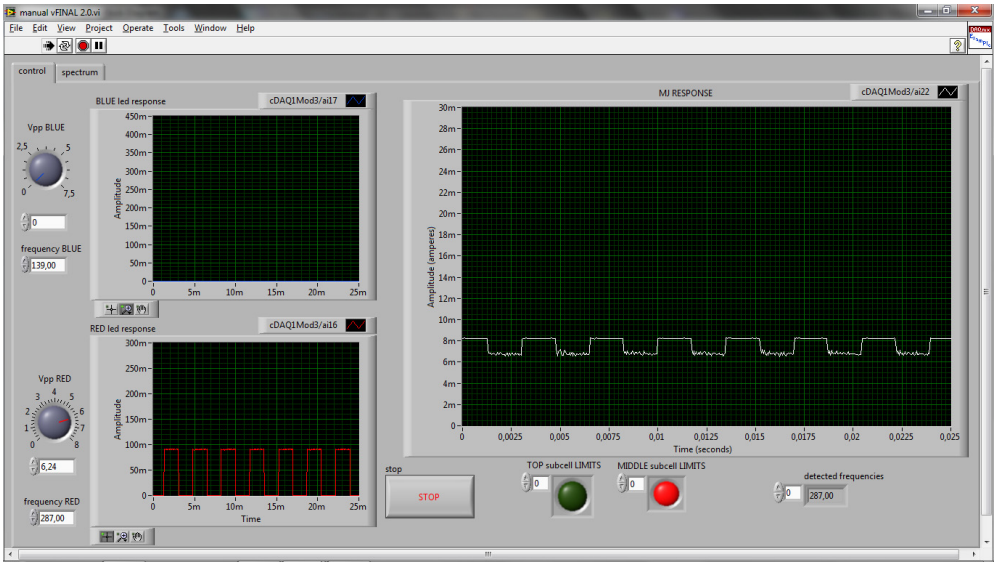

Figure 3.21. Artifact detected at the indoor experiments

The source of this uncertain artifact was found to have its origin in the light source used. An halogen lamp is a red-rich light, whose effect at the MJ cell could be translated into the top subcell limiting state previously identified, but the available data of the spectral distribution of the lamp gives no information beyond 1050 nm, although a decreasing trend is perceived, affecting mainly to the region where the bottom cell has its spectral response (see Figure 3.22)

Attending to the spectral characteristics of the red LED, it also partially reaches the bottom cell and therefore produces a slight overexcitement that, under a normal situation, will have no influence on the MJ detection capacity, but taking into account the spectral distribution of the lamp and the response

of the cell, the previous figure could be also explained as a situation where the bottom subcell may have a role in limiting the MJ device.

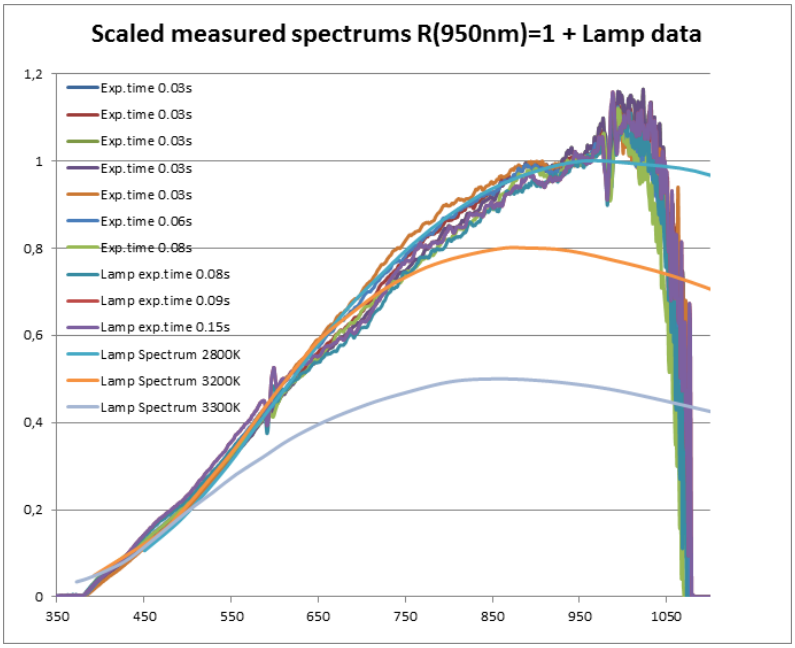

Figure 3.22. Spectral distribution of the halogen light used at the indoor experiments

Regardless the application of the lock-in theory and omitting the uncertainties and artifacts guessed, the indoor experiments have demonstrated that it is possible to detect the limiting subcell and to quantity the differences in top-mid photocurrents in a first approximation.

Despite all the theory exposed in the previous section, this first prototype was not designed for the physical implementation of the lock-in theory, because initially, it was intended to focus on the corroboration that it could be possible to detect a signal at the output of a MJ cell indicating which cell is limiting and the possibility to measure the differences in photogenerated current. A second development of the LCA will deal with that issue but not in this thesis.

3.4.3. Outdoor measurements

A provisional enclosure was designed to enable the LCA for outdoor measurements, where the aspects related to avoid or reduce light leakage and internal reflexions from the sunlight and the LEDs was emphasized, although this last issue is still under study. As a first step in the completion of the prototype, we have designed it for a MJ cell under 1 sun conditions.

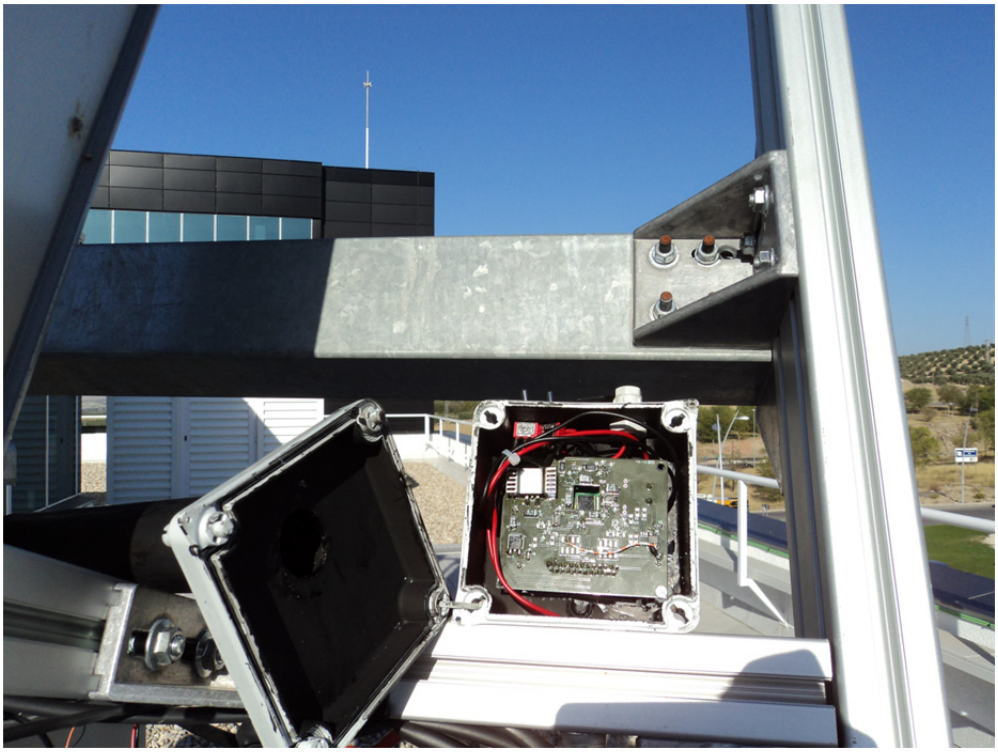

Figure 3.23. Handmade enclosure for the initial outdoor experiments

Regarding the mechanical design, the collimator tube is the main part, where two concepts have a mayor influence in the length and aperture diameter of the collimator. These are the opening angle and the slope angle, which are defined as follows:

$$\theta_O = \tan^{-1}\left(\frac{R}{L}\right) \tag{9}$$

$$\theta_s = \tan^{-1}\left(\frac{R - r}{L}\right) \tag{10}$$

In these equations, R stands for the radius of the aperture of the collimator, while L is the length of the tube and r is the radius of the receiver, the MJ in this setup.

Figure 3.24. First outdoor LCA prototype

Apart from imposing the minimum tracking accuracy of our system, the choice of these angles determines the quantity of circumsolar radiation and skylight scattering that enter the collimator too. These effects change the cell performance not only because they influence how much radiation reaches the cell, but they also produce spectral variations in the light received on the surface of the cell. The increase on skylight radiation results in the enhancement of short wavelengths and suppressions of long ones. Moreover, the

opening angle also influences the uniformity of illumination at the receiving area (Chai, 1976).

The slope angle should be between 1º and 2º, while the opening angle must be less than ±5º according to the recommendations of the WMO (World Meteorological Organization, 2008). The outdoor LCA prototype has been designed with and opening angle of ±4.4º, while the slope angle was 3º, based on the dimensions of the active area of the cell, not the physical one.

The tube was designed with no opening window with the aim to characterize the LCA device and diminish the distortion of the measurements that the transmission coefficient of the window may cause. Moreover, it was not mechanized optimally, so it is assumed that the measurements may contain certain level of error.

Regarding the software implementation for the generation and acquisition of the signals, the following steps have been followed:

1. - Measure the DC level, subtracting any possible offset appearing at the output that the operational amplifier (transimpedance OA) may cause.

2. – According to the current manufacturing process of MJ cells, most of the times, the blue LED is expected to limit the overall output of the MJ, so firstly the blue LEDs should be turned on increasing progressively their amplitude. Observe if the output frequency measured at the LCA corresponds to the Blue Led and if the amplitude follows the light increments or it gets saturated.

3. - Turn on the red LEDs at their maximum maintaining the blue ones on. If the waveform appears to have 3 levels we are presumably in a top subcell limiting state.

4. – To corroborate the previous state, turn the blue LEDs off. If only a DC signal appears at the output, it can be confirmed that the limiting subcell corresponds to the top layer.

This procedure is inversely applicable when the middle subcell is the dominant layer in the MJ device, but all this procedure is focused on a clear subcell limiting state. In those cases where it exists a current matching between the top and the middle subcell, the steps will not be so direct and there will appear other artifacts that should be carefully studied.

Focusing on the outdoor experiments carried out, it can be seen in the following sequence that the similarities with the indoor experiments are evident and they perfectly match the steps recommended previously.

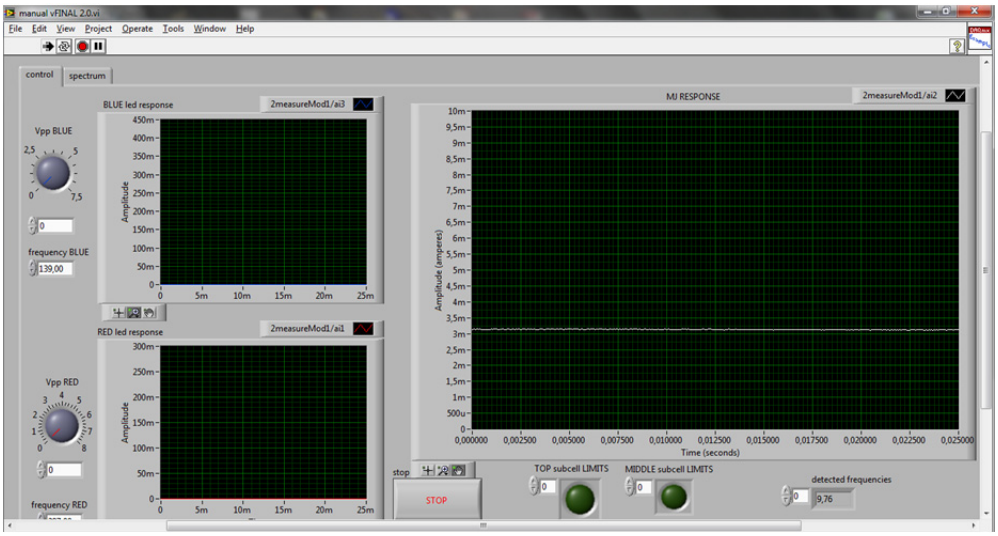

Figure 3.25. Step 1: DC level measurement

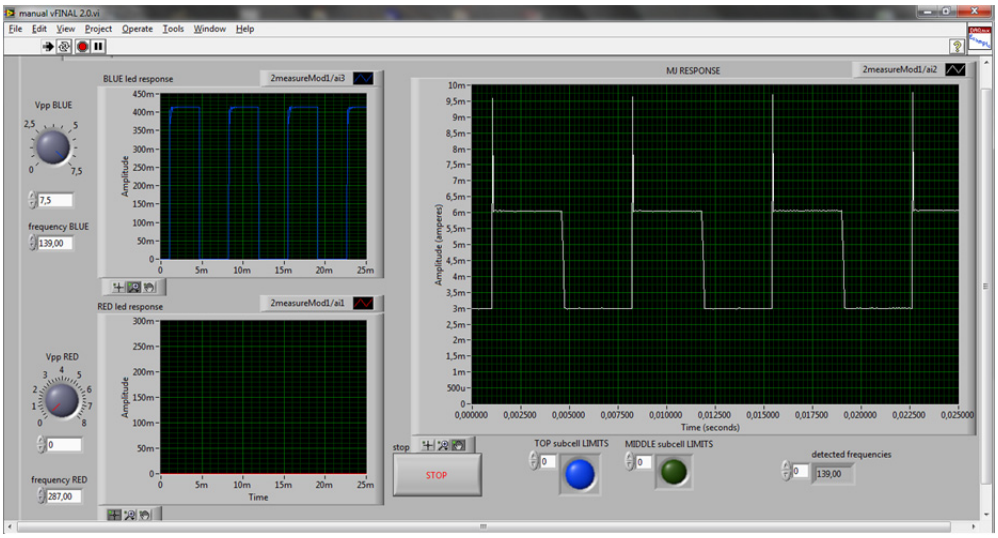

Figure 3.26. Step 2: Blue LED on (maximum power, saturated output)

In these figures it can be appreciated that there is a large gap between the top subcell photocurrent and the one generated by the middle subcell (around 3 mA). Unlike the indoor experiment, the reason is explained by the low levels of DNI measured and the high Air Mass existing at the moment of the experiment, because the data were taken at dusk. At that moment, most of the content of the sun's spectrum provides less short-wavelength radiation to be absorbed, so it is red shifted and thus, it is very likely that the top subcell is working in a really limiting state. The same effect has been observed at the dawn measurements.

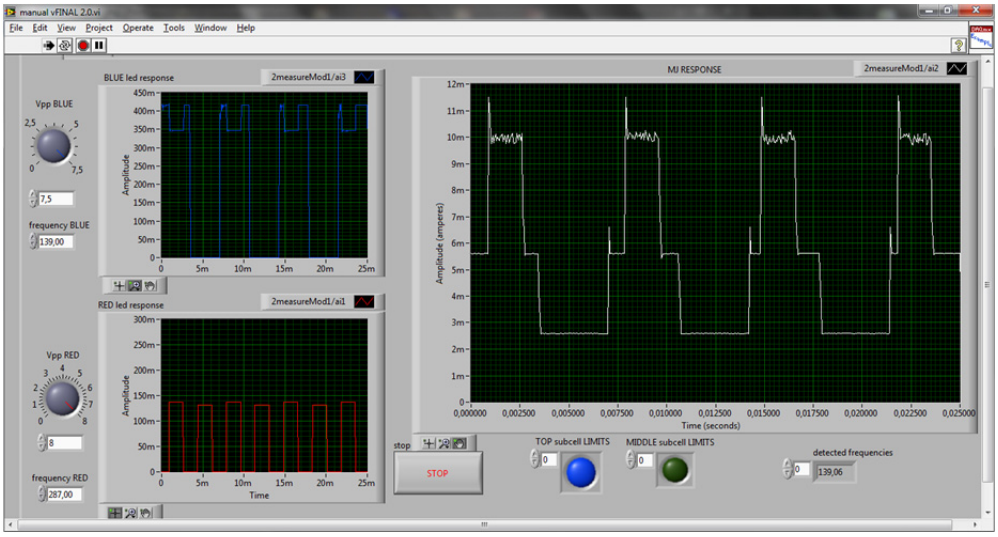

Figure 3.27. Step 3: Both LEDs on at their maximum power

Figures 3.28, corresponding to the step 4 of the procedure, corroborates that the limiting subcell is the top one.

The pre-designed current mismatching situation (CM<1) of the MJ under test and the period of time when the measurement campaign took place, forced a situation where there was always either a clear top-limiting subcell case, as shown in the previous sequence, or the gap between the current generated by the subcells was close to a matching state, but a clear middle subcell limitation state was not detected.

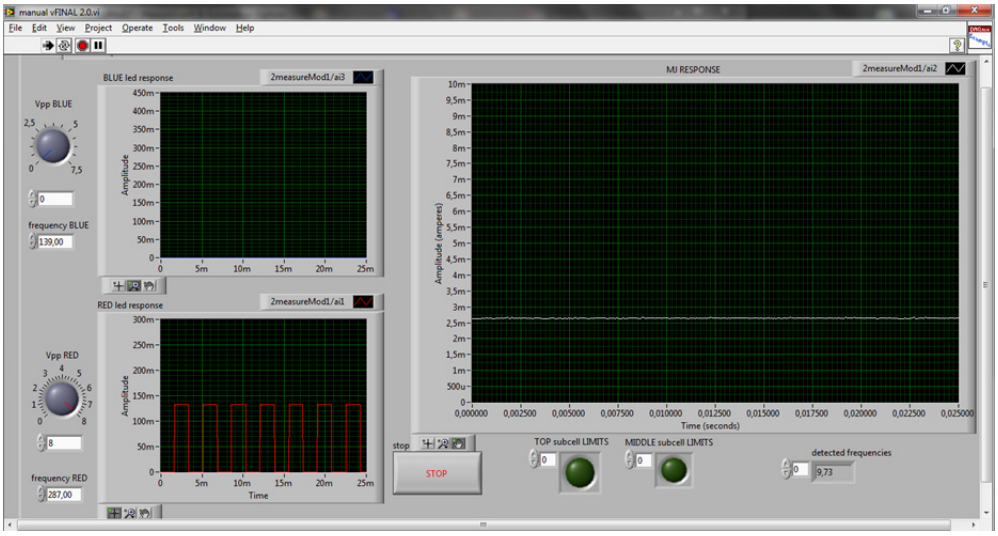

Figure 3.28. Step 4: Blue LEDs off maintaining Red ones on

For that purpose, the middle subcell was forced to decrease its output current by adding a shortpass filter that rejects most of the wavelengths contained in the spectral band where the middle layer is sensitive, so the content of red spectrum was diminished (see Table 3.8).

Transmission wavelength	400-630 nm
Rejection wavelength	675-850 nm
Average transmission	> 85%

Table 3.8. Main characteristics of the shortpass filter

The output measured was within the theoretical results expected (middle limiting state) and in accordance with the trend detected in the case of blue-limiting case. In figures 3.29 and 3.30, it can be clearly observed that the response of the MJ device follows the frequency of the pulsed red light, independently of whether the Red LED is on or both LEDs are emitting light.

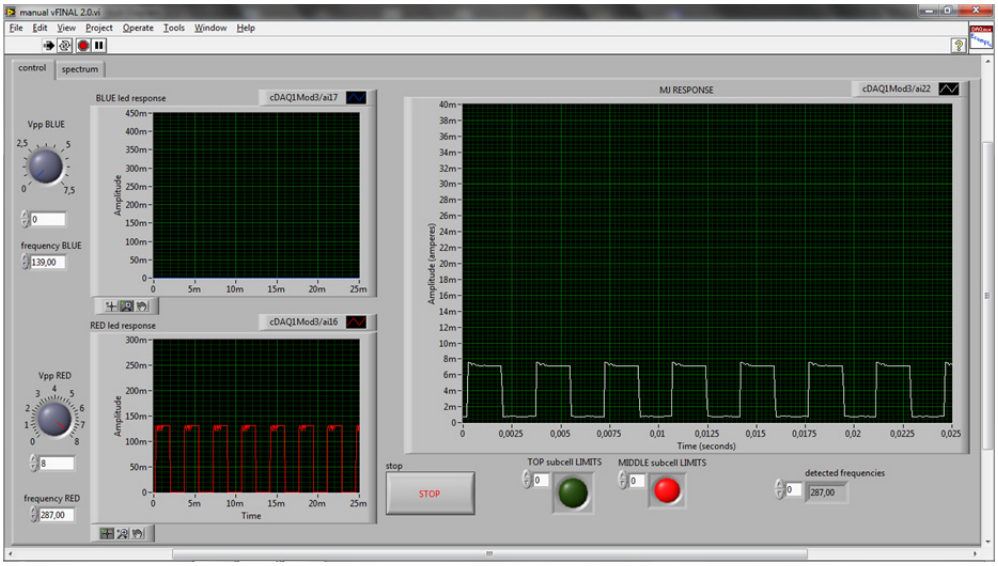

Figure 3.29. Middle subcell limiting case with Red LED on

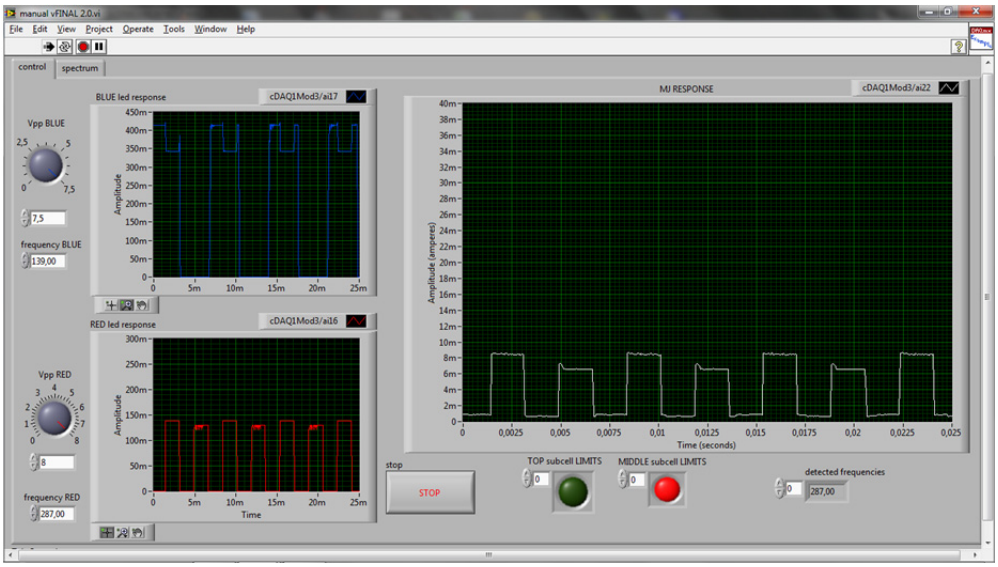

Figure 3.30. Confirmation of middle subcell limiting case with both LEDs on

Under the experiments carried out, and assuming possible sources of errors, the LCA seems to work properly in those states where there is either a clear top limiting state or the middle subcell conditions the output of the MJ.

Nevertheless, one of the uncertainties unsolved in this work deals with current matching states. In the next sequence, measured at the same period of time (10 minutes difference), it is observed that, when only either the Blue or Red LEDs are turned on alternately, the frequency measured at the output coincides with the pulsed frequency used for powering each LED set, so in a first attempt there is no current limiter state that can be identified.

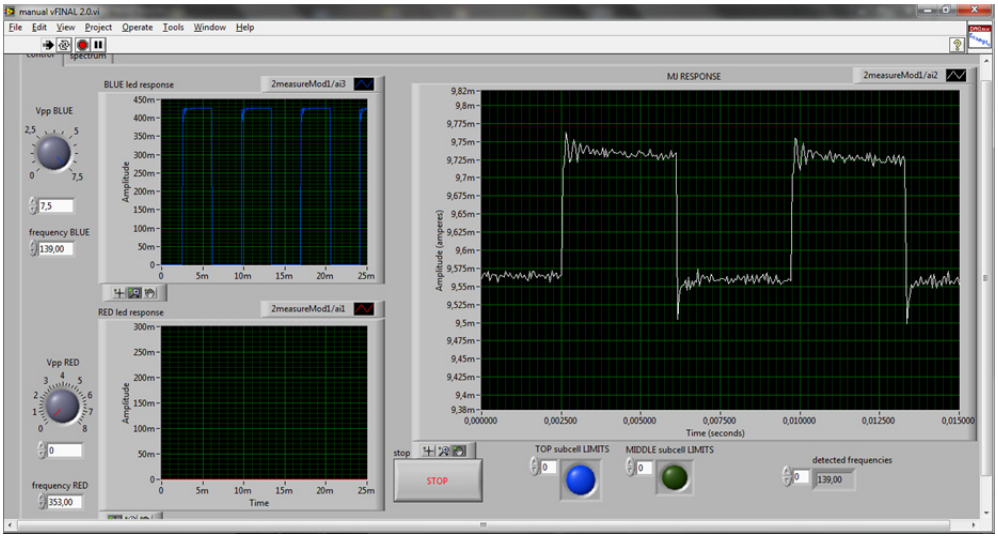

Figure 3.31. Current matching state. Blue LEDs ON

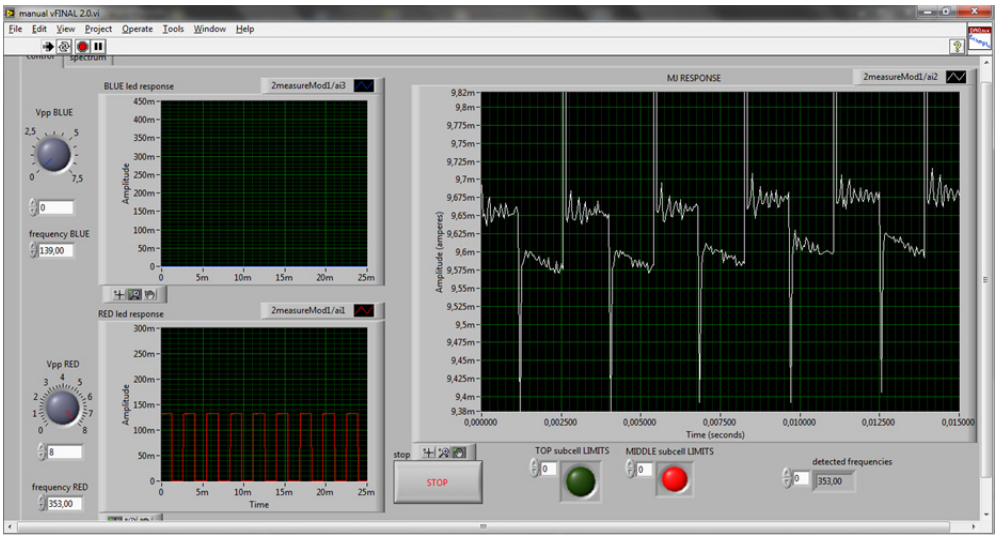

Figure 3.32. Current matching state. Red LEDs ON

When both LEDs are ON, the result measured (Figure 3.33) for a presumably current matching state, shows a certain similarity to the waveform theoretically defined in Figure 3.10, so it is very likely that the cell is operating in this a current matching state or close to it. Nevertheless, the output has the same frequency than the Blue LED one, and some small differences in current levels are still appreciable at the lowest level of the signal, then, the result appears to be incongruent.

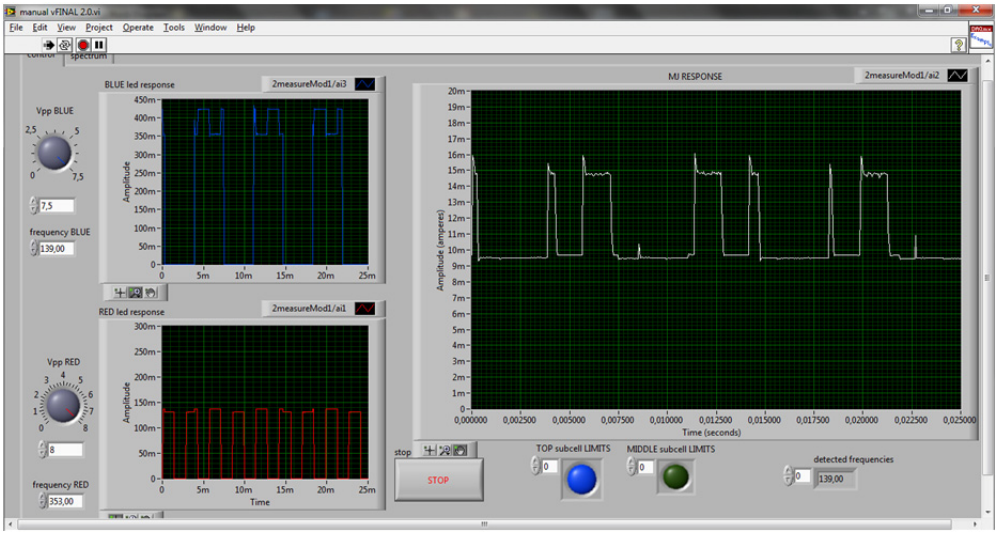

Figure 3.33. Current matching state. Blue and Red LEDs ON

Therefore, those current matching states, or nearly closed to, are not so easily detectable under the current development of the LCA, or at least, the existing uncertainties may complicate their detection.

Bearing in mind the errors that the mechanical enclosure may produce regarding the light leaks or the non-uniformities of the illumination due to internal reflexions and also recalling the viewing angle of the LEDs, which arrangement may produce non-homogeneities on the cell's surface, it is very likely that some non-idealities may appear in the subcell-limitation detection. According to some authors, current limitations that vary across the cell surface can be produced and the spatial non-uniformities mentioned can make the spectrum over the cell cause that the top and middle subcells limit the current in different parts of the cell simultaneously. In this situation, the statement

proposed in equation (3) should be modified, so the MJ current may not be the photocurrent of the least generating subcell. The previous equation should be modified according to the following expression (Dominguez, et al., 2013)

$$I_{SC\_MJ} = \alpha \cdot I_{L\_TOP} + \beta \cdot I_{L\_MID} \tag{11}$$

Focusing on the results regarding the capacity to measure the photocurrent generated by each subcell, the next table shows the differences encountered when the LCA measurements are compared to the calculated result from the application of equation 2 for the estimation of the photocurrent, where the the EQE of the cell was multiplied by the spectral data measured with a spectroradiometer located in the proximity.

Measurements		Calculated (EQE+spectrorariometer)			LCA Measurements		
		Top subcell (mA)	Middle subcell (mA)l	CM ratio	Top subcell (mA)	Middle subcell (mA)	CM ratio
Meas. 1	09:58	7.264	8.598	0.845	7.414	8.974	0.826
Meas. 2	10:16	7.966	8.892	0.896	8.039	9.174	0.876
Meas. 3	10:49	9.285	9.347	0.993	9.119	9.316	0.979
Meas. 4	11:01	9.409	9.390	1.002	9.279	9.204	1.008
Meas. 5	12:29	10.259	9.831	1.043	10.609	9.904	1.071
Meas. 6	12:46	10.167	9.839	1.033	10.309	9.809	1.051
Meas. 7	13:54	9.617	9.172	1.049	9.554	9.379	1.019
Meas. 8	14:00	9.388	8.912	1.053	9.584	9.552	1.003
Meas. 9	18:04	7.325	8.089	0.906	7.354	8.354	0.880
Meas. 10	19:08	2.980	5.020	0.594	2.704	5.774	0.468

Table 3.9. Measured and calculated comparison of the photocurrents

It can be observed that the results are relatively similar, so the LCA measurements seem to be valid enough in a first approximation, although there have been some nearly-close matching states, but the results were coherent with the simulations, despite the uncertainties mentioned previously.

Nevertheless, the comparison between the data calculated from the spectroradiometer and the ones measured with the LCA prototype have to be carefully studied. Firstly, the LCA was tested in a different location (200m), where the spectrum is expected not to change, with the exception that the adjoining buildings and facilities of the University could distort the radiation content, especially at dawn and dusk, which was one of the problems detected.

Secondly, the data obtained with the LCA may be overestimated, because the opening and slope angles of the prototype were not the optimum, so there was circumsolar content that may have been included in the measure, in addition to possible light leaks and internal reflexions produced by the handmade mechanized enclosure. At the moment the experiments were done, the spectroradiometer was measuring the spectral composition of the Global Normal Irradiation, and thus it should have included more spectral content beyond the DNI, that is the circumsolar radiation, so the overestimation of the MJ may have been compensated by the inherent excess value measured with the spectroradiometer. Obviously, in future prototypes, the circumsolar measurement should be avoided or at least controlled.

A different measurement round was used to compare the response of the LCA with the isotypes, assuming the same locational differences mentioned for the spectroradiometer. Neither the photocurrent produced by each isotype cell nor the current matching between the sensor and the LCA can be compared. The main reason is that the photocurrent densities will always be different because of the spectral response of the isotypes does not coincide with the SR of the MJ under test.

Isotype characteristics				
	TOP	MIDDLE	BOTTOM	CM
SR range (nm)	375-790	500-900	900-1700	0.935

Table 3.10. Spectral response of the isotype cells

A more appropriate comparison could be done when analyzing the CM at a certain measurement with regard to the current matching at standard conditions, so the spectral mismatch error can be defined (Dominguez, et al., 2013), or in other words, the trend regarding the spectral variations can be detected.

$$MM\,(E_1(\lambda), E_{AM1.5D}(\lambda)) = \frac{CM_{MEASUREMENT}}{CM_{AM1.5D}} \tag{12}$$

Despite the divergences of SR between the LCA and the isotypes cells, the variations in the content of the spectrum will produce approximately similar variations in both instruments, so if the CM trend is compared between them, it is expected to obtain similar results, as it can be observed in the following table.

Measurements	LCA		Isotype	
	CM	MM	CM	MM
Meas. 1	0.973	0.991	0.933	0.997
Meas. 2	0.979	0.997	0.936	1.001
Meas. 3	0.982	1.000	0.942	1.007
Meas. 4	1,008	1.027	0.946	1.012

Table 3.11. LCA and isotypes CM comparison

According to the previous result, and although the measurement round has to be extended, it can be assessed that the LCA corroborates the hypothesis planned in the theory.

3.4.4. Achievements to accomplish

Although the first prototype offers relevant information about the detection of the limiting subcell (either top or middle) and a good approximation of the

current photogenerated by each layer, there are some achievements that should be faced in future prototypes.

Regarding the mechanical issues, a detailed mechanized enclosure should be made, reducing the opening and slope angle and manufacturing the tube with anodized black material with the aim of avoiding internal reflections. In this aspect, the design of baffles inside the collimator tube should be included because their function is to shield the light coming from sources outside the field of view of the receiving area (MJ active area) and to reject internal reflections that may distort the measure (Scaduto, et al., 2006). The uniformity and homogeneity of the light reaching the cell has to be guaranteed to avoid the matching artifacts detected.

Nevertheless, in this study all the issues regarding the radiative recombination or luminescence effect that may occur within the cell's layers, when it is illuminated with the LEDs light, have been avoided (Lim, et al., 2013). These undesirable effects may distort the current mismatching states and its detection, together with falsifying the measurement of each subcell photocurrent. This effect is presumably produced only by the Blue LEDs and in the states, when they are individually turned on, but this is a statement that has to be empirically tested.

Additionally, humidity and moisture issues should be carefully studied in order to avoid electrical problems or wrong measurements. This is one of the main barriers that some current isotype spectral sensors encounter.

The electronics at the PCB have to be improved by trying to avoid the noise related issues, including, for that purpose, all the elements necessary for the lock-in implementation. It is also needed to remove the DC component and to avoid the offset of the Operational Amplifier used as a transimpedance. The stability of the measurement should be improved.

According to the measurement procedure and in order to give more representation to the experiments, an extensive capturing data campaign has to be made, first of all to corroborate if the cloud of data collected follows the same trend when they are interpolated, and also to gather all the possible real operational behavior. Also, all the uncertainties should be avoided when the comparison with the spectroradiometer and the isotype sensor is done.

The measurements carried out with this first prototype were done without voltage biasing the subcell under test. One of the reasons is justified under the lack of awareness of the limiting subcell, so unlike the EQE measurement procedure, where the current limiter subcell is established in advance, this information is unknown in the LCA, so there are some difficulties in establishing the V_{BIAS} according to the expression equation (1). Anyway, as it was exposed, the commercial MJ cells used in this theses have shown no significant differences at EQE measurements when $V_{BIAS} = 0$ or $V_{BIAS} = \Sigma V_{OC}^{j}$, and the artifact detected affecting the Ge bottom cell will not distort the measurements because the LCA is not designed for that subcell (Meusel, et al., 2003). Nevertheless, it is recommendable to check the previous statement with the realization of several experiments in this line.

Finally, it is necessary to identify the minimum DNI threshold below which the measurement could not be validated. In this sense, it is required to check the linearity of the cell under varying intensity levels because the EQE may vary (Bett, et al., 2007), although this issue will be more evident and critical if any optical stage is added.

Whenever the spectral response band remains approximately similar, the LCA can be rearranged to use solar cells from several manufacturers, thus becoming very versatile and easy to adapt. In this way, it will have similar spectral response as the CPV modules used in photovoltaic plants, so apart from indicating which is the limiting subcell of our device, it could be used to characterize the photocurrent produced by a commercial module. In this regard, other manufacturer's MJ cells should be tested.

The prototype has been applied to a MJ cell under 1 sun condition, so further designs should be modified to include a realistic concentration factor if it is intended to be used to characterize a CPV module, where the optic normally introduces spectral distortions, such as chromatic aberrations and transmission losses. If any concentrating stage is included, the replacement of the LEDs used must be taken under consideration as they will not develop enough light power to visibly excite each subcell of the MJ device. A solution could be done by means of lasers that are more powerful and delimit in a better way the spectral range of their light emission, but these lasers should be used carefully because they may cause nonlinearity problems in the subcells (Schönecker, et al., 1994) (Metzdorf, 1987)

Finally, the next generation of the LCA should be focused on the mechanism of measuring the bottom subcell as well as those MJ cells with 4-band that have been recently come up to the concentrating photovoltaic market (Dimroth, et al., 2014).

3.4.5. Short-term applicability of the LCA

Once the LCA is improved, the detection of the limiting subcell and the measurement of the top and middle photocurrents, thus the definition of the current matching ratio, can be used for several purposes.

First of all, it can be implemented for measuring the evolution of the CM ratio, or the MM, in a specific location under realistic data of irradiance, spectral content and temperature. This information will be useful for the prediction of the annual current output and, by extension, the energy collected at the location chosen, avoiding the uncertainties of simulations tools (Kinsey & Edmondson, 2009) and different spectral sensitivity regarding the use of isotype based instruments.

Under the energy prediction scenario, the information obtained by the LCA instrument will be useful for defining the proper current ratio that the MJ cell should have, by changing the bandgap of each layer, so it can be proposed a tuning on this ratio in order to maximize the energy harvested in a particular location (Victoria, et al., 2013)

Beyond the tuning of the current ratio within the materials band gaps composing the cell, but under the same concept of matching the local spectrum to the response of the cell, there are some MJ manufacturers that are developing adjustable spectrum lattice-matched multijunction solar cell architecture (Solar Junction, 2014), so the information collected from the LCA could be also useful for defining the proper bandgap tunability.

Additionally, it is well known that the optics of the CPV modules modify the spectral content reaching the MJ cell by causing chromatic aberration and changes in the homogeneity on the cell's surface. There are some CPV module prototypes with adjustable height concentrator, so a better, locally adapted correlation can be made regarding the spectral response of the MJ used and the sun spectrum available at a certain moment (Gerster, et al., 2013). The LCA

can offer valuable information regarding the spectral sensitivity of the cell under use and the spectrum content present at the moment.

3.5. References

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Chapter 4

Conclusions

4.1. Conclusions

This thesis offers a technical contribution and a progress in the knowledge concerning the photovoltaic field from two different perspectives and technological approaches regarding the photovoltaic energy conversion.

On the one hand, this thesis deals with a different overview and application of the consolidated and mature silicon based photovoltaics; and on the other hand, in order to contribute to the development of alternatives, it offers an instrumental solution applicable to the measures of the spectral influences of the sun on the Concentrator Photovoltaic technology

The main conclusion concerning the new economic trends of PV technology, under the extended self-consumption scenario, is based on the misconception that the profitability of a certain PV system is only dependent on the financial methodology applied and a proper design of the installation that yields to a higher energy production. The different approach proposed in this study concludes that the profitability of a system is also strongly dependent on a conscientious analysis of the consumption and PV generation profiles of the selected location, combined with the retail electricity prices applicable in each tariff period.

The milestones achieved in this new PV perspective are mentioned in the following lines.

- Traditional economic procedures applied to PV technology have been adapted in order to consider the influence of the hourly consumption profiles and the tariff periods of a certain user.

- The LCOE has been reviewed according to the assumptions made and the scenarios proposed for this specific location.

- Under the scenario proposed and assumed, a non-profitable grid-parity reality has been identified as a consequence of the mismatch between the consumption and generation profiles with questionable regulated electricity tariffs.

- Aerial pictures have been detected as a possible tool for calculating the PV potential of a certain location.

The second perspective addressed in this thesis deals with the Concentrator Photovoltaic, which it is introduced as a technological alternative regarding the flattering of the learning curve of Silicon based PV.

The works carried out in this thesis regarding the CPV, have dealt with the spectral selectivity and sensitivity of the MJ cells used in those systems. As a conclusion of the technological approach offered, the on-site measurement of the limiting subcell in Multijunction solar devices is possible, using easily implemented electronics and the same type of MJ cells used in commercial CPV modules.

The milestones achieved in this section are summarized below:

- The possibility and feasibility of detecting the limiting subcell (either top or middle) of a MJ solar device has been checked, without the use of isotype sensors or the procedures based on SR data and spectroradiometer measurements.

- The procedure proposed is also capable of measuring the photocurrent developed by a MJ cell and the gap existing until the other subcell reaches its limiting condition, thus measuring the photocurrent generated by both the top and middle subcells.

- The methodology for the implementation of this device to the measurement of all the three layers composing a MJ solar cell, or even the new 4-juntion cells available recently, has been defined.

4.2. Results from the study

One of the main results obtained in this work is related to the theoretical application and adaptation of an economic procedure for the proper grid-parity verification, depending on the generation and consumption singularities of the location chosen.

Furthermore, the most tangible result from this work has been the creation of a prototype for measuring the currents generated by the top and middle subcells in a MJ solar device.

The theoretical and technical contributions of this thesis have been supported by the publication and diffusion of the following documents.

4.2.1. Peer-Reviewed International papers

1).-D.L. Talavera, J. de la Casa, E.Muñoz-Cerón, G.Almonacid. *Grid parity and self-consumption with photovoltaic systems under the present regulatory framework in Spain: the case of the University of Jaén Campus.* Renewable and Sustainable Energy Reviews. Volume 33, Pages 752-771. Elsevier Ltd. May 2014. ISSN: 1364-0321

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4.3. Recommendations for future research

In this work, two independent future lines can be identified according to the topics addressed in the document.

The recommendations for traditional flat-PV are based on the search of new approaches or applications, because a technological revolution is unlikely to be found due to the maturity of the silicon PV systems and the flattering of its learning curve. The possible future lines of research, partially appeared as a consequence of this thesis, are listed below.

- Study of the economic impact of the integration of renewable energies regarding the redistribution of the fixed costs of the electrical system.

- Study of the technical impact and limits of the integration of renewable energies within the electrical grid.

- Development of a software tool for the automatic definition of the photovoltaic potential of a specific location based only on the proper treatment of commercial satellite photography.

- Development of a photovoltaic stand-alone and grid-connected mixed system with the proper intelligent electronics for the control of the

inverter and the battery regulator, which is permanently in communication with the instant retail prices of the electricity market. This mixed system should have the capacity of deciding when it is more profitable to consume the PV self-generated electricity, instantaneously or from the batteries, or if the consumption from the grid is economically better, depending on the comparisons of the hourly electricity prices and the LCOE of the system.

The identification of future works regarding the LCA device has been collected in its corresponding section of achievements to accomplish, but it can be summarized in the following recommendations:

- Manufacturing of a second generation of the prototype where the non-homogeneity and non-uniformity problems are solved, together with the improvement of the measurement procedure and the increment of the number of experimental tests.

- Inclusion of the concentrating optic stages for a better detection and comparison with real commercial CPV modules, regarding the issues concerning the uniformity and homogeneity of the light that the optic causes on the cell's surface.

- Development of a new version of LCA where the ability of measuring the bottom subcell or even the recently developed 4 junction solar cells, is included.

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Introducción

II.1. Contextualización

La energía solar fotovoltaica (FV) basada en la célula de Si cristalino posee una gran madurez tecnológica fruto de un largo periodo de investigación y un cúmulo de años de experiencia; favorecida a su vez por las diferentes modalidades de planes de expansión y apoyo promovidos por numerosos países. Por todo ello, en los últimos años, hemos asistido a un crecimiento exponencial de la potencia fotovoltaica instalada especialmente en España y algunos países Europeos (International Energy Agency, 2013) (Martinez de Alegría Mancisidor, et al., 2009).

Sin particularizar en los pormenores burocráticos o económicos de este crecimiento en instalaciones fotovoltaicas, en la actualidad, el verdadero punto de inflexión en la continuidad del desarrollo de esta tecnología se produce debido a que se está llegando a cotas de eficiencia de conversión energética muy próximas a su límite máximo teórico. Éste límite teórico para el Silicio es relativamente bajo, en torno al 31% (Shockley & Queisser, 1961), y hoy se fabrican ya células en laboratorio que alcanzan eficiencias del 25%, que se traducen en eficiencias de un 22,9% cuando se confecciona un módulo, por lo que nos encontramos muy próximos a su límite teórico (Green, et al., 2014) (Landsberg & Markvart, 2003). Por lo tanto, no parece que con esta tecnología se puedan conseguir ya grandes avances en eficiencia y por consiguiente, el mecanismo más factible de reducción de costes se basa principalmente en la mejora de los procesos de fabricación. Otra aplicación alternativa o enfoque,

procede del autoconsumo de la electricidad generada mediante los módulos FV dentro de la propia red del usuario. De hecho, esta es la solución más prometedora para la integración de la fotovoltaica en las redes de generación eléctrica y es por ello por lo que se encuentra en línea con los planes y directivas de energías renovables tanto a nivel europeo como nacional (European Comission, 2009) (Ministry of Industry, Tourism and Trade, 2010).

A pesar de que la paridad de red es una realidad consolidada, se recomienda llevar a cabo un análisis de rentabilidad pormenorizado con el objetivo de manifestar la factibilidad de la instalación de un sistema FV bajo unos perfiles de consumo específicos sujetos a unas tarifas eléctricas determinadas.

Más allá de estos nuevos enfoques, existen otras tecnologías para el aprovechamiento del efecto FV que si bien, en la actualidad, ofrecen peores resultados de eficiencia y/o coste, y por tanto tienen un menor nivel de desarrollo tecnológico y comercial, ofrecen por el contrario unas características y especificaciones teóricas que permiten predecir unos mejores comportamientos de eficiencia y/o coste a medio plazo.

Entre los caminos que se siguen hay dos ideas contrapuestas: una que persigue el abaratamiento del dispositivo a costa de lograr menores eficiencias (tecnologías de película delgada) y otra, por el contrario, va dirigida a desarrollar dispositivos muy eficientes aunque su coste sea elevado.

Bajo la segunda premisa mencionada, se encuentras las células multiunión (MJ), que poseen varias capas de materiales compuestos que permiten límites teóricos de eficiencia más elevados que las células de silicio (Yamaguchi, et al., 2008) (Baur, et al., 2007).

Compañías como Sharp, Soitec, Spectrolab, Amonix, Solar Junction, y laboratorios como Sandia, NREL, el Instituto Fraunhofer, o el Instituto de Energía Solar de la UPM, han desarrollado células de varias uniones las cuales han llegado a registrar eficiencias cercanas o superiores al 40% (Green, et al., 2014).

Las células de alta eficiencia, junto con elementos ópticos avanzados, para reducir la superficie necesaria de célula, constituyen los sistemas de Alta Concentración Solar Fotovoltaica (HCPV). La concentración solar se ha utilizado ampliamente a lo largo de la historia y ya en los años 80 se comenzó a

aplicar en los sistemas FV con la finalidad de reducir costes. España es uno de los países pioneros en el desarrollo de los sistemas FV de concentración, gracias fundamentalmente a los trabajos del instituto de Energía Solar de la UPM durante las pasadas décadas (Sala & Luque, 2007). Sin embargo, la relativamente baja eficiencia de las células existentes en esos años no permitió que esta idea diera los frutos esperados y la concentración no alcanzó la madurez tecnológica adecuada para plantear usos comerciales.

La aparición en la última década de las células multiunión significa un nuevo impulso en este ámbito de la investigación, aunque aún es necesario ahondar en sus características de funcionamiento. Uno de los aspectos todavía no bien conocidos ni explicados adecuadamente es la sensibilidad de estas células MJ al espectro solar incidente (Martí & Luque, 2004) (Kinsey & Edmondson, 2009).

El espectro solar varía a lo largo del día y también depende de las características ambientales del entorno, de la óptica del concentrador, así como de la precisión del seguimiento. El efecto más inmediato de la variación del espectro solar en el comportamiento de la célula MJ, es la limitación en intensidad en alguna de sus uniones, que reduce la corriente total que genera. Este fenómeno hace que la cantidad de energía entregada por una célula esté fuertemente condicionada a las características del espectro. Por lo tanto, la adaptación al espectro es un punto crucial en el diseño de las células MJ para conseguir rendimientos elevados.

Un campo amplio para la investigación está relacionado con la propuesta de soluciones técnicas para la medida del espectro o mejora de las técnicas ya existentes en la literatura FV de cara al análisis de la respuesta espectral de células MJ (Metzdorf, 1987) (Adelhelm & Bücher, 1998) (Meusel, et al., 2003).

Bajo esta contextualización, queda justificada la continuidad en avanzar tecnológicamente con el objetivo de afianzar la electricidad solar como una alternativa real a las fuentes de energía convencionales tanto a nivel de eficiencia como de costes de producción (Hegedus & Luque, 2011) (Cristobal López, 2012).

Por tanto, parece adecuado seguir fomentando la gran capacidad y tradición investigadora en este sector (Unión Española Fotovoltaica, Noviembre 2013) e

invertir conocimiento para reducir el coste de la electricidad solar mediante el efecto FV a través de la búsqueda de alternativas.

II.1.1. Relevancia de la propuesta

Teniendo en cuenta la breve contextualización anteriormente descrita, esta propuesta de tesis pretende lograr los siguientes hitos, los cuales pueden agruparse en las categorías que se describen a continuación:

- Científico y tecnológico: El análisis y caracterización a sol real de una célula fotovoltaica MJ, en términos de su respuesta espectral, nos permitirá por un lado, profundizar en el conocimiento de las características de operación en condiciones ambientales estándar y por otro lado, los resultados y conclusiones extraídos de la relación corriente-espectro de dicho estudio posibilitarán la estimación de la producción eléctrica de sistemas con esta tecnología incipiente. En relación al concepto de autoconsumo, el interés técnico está dirigido al desarrollo de las herramientas adecuadas para un diseño e implantación masivas de la integración FV en un contexto urbano actual.

- Socioeconómico y de transferencia tecnológica: Los resultados previos serán de utilidad tanto a los fabricantes de célula multiunión como a los diseñadores de los elementos ópticos, ya que podrán proponer modificaciones en los diseños CPV con el objetivo de fomentar una reducción de costes o un aumento de la eficiencia.

II.2. Objetivos de la investigación

La realización de la tesis pretende la consecución de dos objetivos principales que se corresponden con los diferentes enfoques acometidos en la presente investigación.

En primer lugar, el objetivo relacionado con la tendencia económica de la tecnología FV, es la adaptación de herramientas de simulación energéticas y económicas para satisfacer los requisitos de la teoría de autoconsumo, de cara a

realizar una contribución a la valoración de la rentabilidad de la paridad de red.

En relación al enfoque con respecto a CPV y su dependencia espectral, el segundo objetivo de la tesis recae en el análisis de la relación existente entre las longitudes de onda del espectro solar y la respuesta de una célula solar multiunión. Especialmente, este objetivo estará centrado en la detección de la subcélula limitante de un dispositivo MJ bajo condiciones de exterior reales. Dentro de este mismo propósito, se confeccionará un dispositivo de medida espectral con el ánimo de correlacionar la respuesta de células MJ comerciales con medidas in-situ realistas.

II.3. Hipótesis

En la actualidad, la tecnología fotovoltaica se presenta como una energía alternativa preparada para competir con otras fuentes tradicionales de energía. En cualquier caso, su curva de aprendizaje cada vez más plana muestra una realidad donde se estima necesario buscar otras aplicaciones alternativas. En este sentido, los asuntos relacionados con la rentabilidad del mecanismo del autoconsumo eléctrico, así como del cumplimiento de la paridad de red son una de las tendencias más estudiadas.

Adicionalmente, en el entorno de la tecnología FV, la concentración fotovoltaica parece posicionarse como una alternativa prometedoras capaz de ofrecer un incremento notable en el aumento de la eficiencia del sistema, así como de reducción de los costes de generación eléctrica en un plazo de tiempo corto y medio respectivamente.

Existe una sólida base experimental que permite ser optimista en cuanto al desarrollo de nuevas células solares diseñadas específicamente para trabajar en condiciones de alta concentración y con anchos de banda espectrales más amplios que permitan capturar de forma más eficiente los fotones procedentes del Sol.

Sin embargo, la complejidad de casar los planteamientos teóricos, las medidas experimentales y la dispersión de algunos parámetros, dificultan la correlación entre las medidas experimentales con el funcionamiento de los

dispositivos MJ bajo estudio; especialmente, todos los campos de la investigación relacionados con la dependencia espectral de cada una de las uniones que confeccionan una célula solar MJ.

A la luz de estos dos escenarios, se plantean diferentes hipótesis. Por un lado, la primera de ellas se basa en el desarrollo de las herramientas apropiadas para la simulación que permitan una evaluación de la rentabilidad de la paridad de red para un caso específico, mientras que la hipótesis técnica basada en los sistemas CPV consiste en la capacidad de adaptar y medir experimentalmente la relación existente entre el espectro solar y la salida en corriente de una célula MJ.

II.4. Distribución de la tesis

Una vez expuesta la contextualización y la relevancia de la propuesta de tesis, así como establecidos sus objetivos y las hipótesis de partida, se va a proceder a realizar una breve descripción de la distribución de la tesis que se presenta en este documento.

La paralización tecnológica de los sistemas tradicionales FV, combinado con su gran nivel de madurez alcanzada, provocan que este mercado deba buscar otras alternativas de crecimiento que vayan más allá de la búsqueda de mecanismos de aumento de su eficiencia de conversión energética. Obviamente, estas nuevas tendencias requerirán de innovaciones tecnológicas, pero la mayor parte de ellas relacionadas con campos de la ingeniería adyacentes, como pueden ser los sistemas de gestión energética o la implementación de las denominadas redes inteligentes.

Bajo estas premisas, hoy en día la aplicación más innovadora para la FV está relacionada con la integración dentro de las redes de generación eléctrica así como su correlación con los hábitos de consumo de electricidad de los usuarios finales. El autoconsumo de la electricidad generada mediante paneles FV está considerada como una solución factible en línea con los planes y directivas de energías renovables tanto a nivel europeo como nacional (European Comission, 2009) (Ministry of Industry, Tourism and Trade, 2010).

La comparación del precio normalizado de producir una unidad de electricidad FV, con los precios de las tarifas eléctricas requerirán un análisis combinado en términos de energía y económicos, porque, a pesar de que la paridad de red es una realidad debido a los costes unitarios de FV y a los altos niveles de radiación existentes en España, existen algunos casos específicos donde el grado de rentabilidad dependerá tanto del perfil de consumo del usuario como de la tarifa eléctrica que le sea aplicable.

Adicionalmente a este análisis, en el capítulo 2 también se pone de manifiesto que la penetración en el mercado de esta alternativa es totalmente dependiente de las políticas y marcos regulatorios establecidos por los correspondientes gobiernos, de este modo, los mecanismos de apoyo serán críticos para un despliegue adecuado y sostenible de la tecnología. Se presenta por tanto, un breve repaso de la evolución temporal de los impedimentos y limitaciones legales al respecto.

Posterior a esta exposición, una nueva sección de la tesis estará dedicada a una de las alternativas en investigación más prometedoras en relación a la tecnología fotovoltaica en su propósito de aumentar los niveles de eficiencia de conversión, esto es, la concentración fotovoltaica. A pesar de haber sido ampliamente abordada en la literatura científica, la dependencia espectral de las células multiunión, la estandarización y creación de procedimientos de medida así como la implementación de herramientas instrumentales aún son un campo de la investigación pendiente de cubrir.

Una vez se ha hecho una revisión del estado del arte en lo que a niveles de eficiencia y estandarización respecta, así como el análisis de los dispositivos y herramientas disponibles para la medida de la respuesta espectral, se propone la implementación de un dispositivo para le medida in-situ de la subcélula limitante en los dispositivos solares multiunión. Este dispositivo es capaz de detectar, teórica y experimentalmente, cual es la unión limitante así como cuantificar la fotocorriente generada por ambas células, superior e intermedia.

Finalmente, una vez expuestas estas dos contribuciones en el campo de la tecnología FV, se describen las conclusiones relativas a estas dos líneas de investigación abordadas en este manuscrito, incluyendo de igual modo aquellos hitos no alcanzados así como sugiriendo posibles líneas para futuras investigaciones a la luz de los resultados obtenidos.

A modo de resumen, mencionar que los resultados obtenidos es este trabajo son por un lado fruto de la aplicación y adaptación de un procedimiento económico para la verificación de la paridad de red y por otro lado, se presenta un resultado más tangible relacionado con la creación de un prototipo para medir las corrientes generadas por las subcélulas superior e intermedia de un dispositivo solar MJ.

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Conclusiones

III.1. Conclusiones

Esta tesis supone una contribución técnica así como un progreso en el conocimiento relacionado con el ámbito fotovoltaico desde dos perspectivas y enfoques tecnológicos diferentes en relación a la conversión energética FV.

Por un lado, esta tesis trata una visión y aplicación distintas de la ya existentes en la madura y consolidada tecnología FV basada en el Silicio, mientras que por otro lado, con el ánimo de contribuir al desarrollo de alternativas, ofrece una solución instrumental aplicable a las medidas de las influencias espectrales del sol en la tecnología fotovoltaica de concentración.

La principal conclusión en relación a las nuevas tendencias económicas de los sistemas FV, bajo el extendido escenario del modelo de autoconsumo, se basa en la malinterpretación de que la rentabilidad de una cierta planta FV es exclusivamente dependiente de la metodología y parámetros financieros aplicados, así como de un diseño adecuado para obtener productividad energética mayor. Los diferentes enfoques propuestos en este estudio concluyen que la rentabilidad de un sistema FV es también fuertemente dependiente de un análisis meticuloso de los perfiles de generación FV y los perfiles de consumo del lugar seleccionado, así como de la tarifa eléctrica aplicable en cada periodo tarifario definido.

Los hitos alcanzados en esta nueva perspectiva se mencionan a continuación:

- Se han adaptado los procedimientos que tradicionalmente se aplicaban para los estudios económicos fotovoltaicos, con el objetivo de considerar la influencia de los perfiles horarios de consumo y los periodos tarifarios.

- Se ha revisado el valor de LCOE para la tecnología fotovoltaica bajo las suposiciones y escenarios planteados.

- Basado en el escenario propuesto, se ha detectado un caso donde la paridad de red no resulta rentable como consecuencia del desajuste entre los perfiles de consumo y generación junto a una tarifa eléctrica regulada cuestionable.

- Se han detectado las fotografías aéreas como una posible herramienta capaz de calcular el potencial fotovoltaico de una localización específica.

La segunda perspectiva abordada en esta tesis versa sobre la concentración fotovoltaica, que se presenta como una alternativa tecnológica como consecuencia de la cada vez más plana curva de aprendizaje de la tecnología fotovoltaica basada en el silicio.

Los trabajos llevados a cabo en esta tesis en relación a la CPV tratan sobre la selectividad espectral y sensibilidad de las células MJ usadas en estos sistemas. Como conclusión de la aportación tecnológica ofrecida, mencionar que es posible la medida in-situ de la subcélula limitante en los dispositivos solares multiunión, mediante la implementación de componentes electrónicos sencillos y usando células del mismo tipo que las que conforman los módulos CPV comerciales.

Los hitos alcanzados en esta sección son expuestos en las siguientes líneas:

- Se ha comprobado la posibilidad y factibilidad de detectar la subcélula limitante (bien sea la superior o la intermedia) de un dispositivo solar multiunión sin la necesidad de usar sensores formados por células isotype o procedimientos de medida basados en los datos de respuesta espectral de la célula y medidas de espectroradiómetro.

- El procedimiento propuesto también es capaz de medir la fotocorriente generada por una célula MJ así como la diferencia existente (en términos

de corriente) hasta que la siguiente subcélula alcanza su condición limitante, midiendo de este modo la corriente generada por ambas subcélulas, la superior y la intermedia.

- Se ha definido la metodología para la implementación de este dispositivo de cara a la posible medida de las tres uniones que conforman una célula solar MJ comercial, o incluso de las células de 4 uniones que recientemente se han desarrollado.

III.2. Resultados del estudio

Uno de los principales resultados obtenidos en este trabajo está relacionado con la aplicación y la adaptación de un procedimiento económico para una verificación adecuada de la paridad de red, dependiendo de las singularidades de consumo y generación de la ubicación escogida.

Además, el resultado más tangible de este trabajo ha sido la creación de un prototipo para la medida de las corrientes generadas por las subcélulas superior e intermedia de un dispositivo solar multiunión.

Las contribuciones teóricas y técnicas de esta tesis han sido avaladas por la publicación y difusión de los resultados en los siguientes documentos.

III.2.1. Artículos internacionales revisados por pares.

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3).-D.L. Talavera, E.Muñoz-Cerón, J. de la Casa, M.J.Ortega, G.Almonacid. *Energy and economic analysis for large-scale integration of small photovoltaic systems in buildings: The case of a public location in Southern Spain.* Renewable and Sustainable Energy Reviews. Volumen 15, Número 9, Páginas 4310-4319. Elsevier Ltd, December 2011. ISSN: 1364-0321

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III.2.2. Contribuciones a congresos internacionales

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2).- D.L.Talavera, E.Muñoz-Cerón, J. de la Casa, M.J.Ortega, G.Almonacid. *Economic and cost analysis of Photovoltaic Grid-Connected systems in*

Buildings: The case of the University of Jaen Campus. 26th European Photovoltaic Solar Energy Conference and Exhibition. Sesión: 6CV.1.17. Páginas: 4565-4568. Hamburgo (Alemania). Septiembre2011. ISBN: 3-936338-27-2

3).- J. de la Casa, G.Almonacid, E.Muñoz-Cerón, M.A.Rubio Paramio, D.L. Talavera, M.J.Ortega, A.Martínez Ruíz, P.G.Vidal, P.Pérez Higueras, J.Gallego, M.J. del Jesús, J.Aguilera. *UNIVERSOL project. Final Results.* 26th European Photovoltaic Solar Energy Conference and Exhibition. Sesión: 5BV.1.2. Páginas: 4068 - 4072. Hamburgo (Alemania). Septiembre 2011. ISBN: 3-936338-27-2

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III.2.3. Otras contribuciones

1).- P.J.Pérez-Higueras, G.Almonacid, P.Gómez, E.Muñoz, I.Luque-Heredia, P.Banda, P.Valera and M.Cabrerizo. *Propuesta de un marco regulatorio para la Concentración Fotovoltaica en España (2010-2020). (Proposal of a regulatory framework for Concentration Photovoltaics in Spain (2010-2020).* Jaén, Spain. February 2010. Promoted by: ASIF and ISFOC. Coordinado por: Centro de Estudios Avanzados en Energía y Medio Ambiente de la Universidad de Jaén. ISBN: 978-84-692-9987-6

2).- J.Aguilera, G.Almonacid, L.Hontoria, E. Muñoz, G.Nofuentes, P.J. Pérez Higueras, J.Terrados, P.G.Vidal. The CPV Challenge (Part I): Achieving Grid Parity. First Conferences Ltd. London, UK. March, 2009. ISBN: 978-0-9562426-0

3).- Director de proyectos fin de Máster de la titulación: Máster en Energías Renovables de la Universidad de Jaén "Integración de sistemas Fotovoltaicos en una urbanización. Un análisis del concepto de generación eléctrica distribuida y autoconsumo" (Septiembre 2012)

4).- Co-Director de un proyecto final de carrera de la titulación de Ingeniería Técnica Industrial con especialización en Electrónica Industrial. Universidad de Jaén. "Diseño de un sistema de monitorización". (Septiembre 2009)

III.3. Recomendaciones para futuras investigaciones

En este trabajo se han identificado dos líneas futuras de investigación con carácter independiente conforme a la temática tratada en este manuscrito.

Las recomendaciones para la tecnología de panel plano se basan en la búsqueda de nuevos enfoques o aplicaciones debido a que es poco probable que aparezca una revolución tecnológica como consecuencia de la madurez de los sistemas FV basados en el Silicio y de una curva de aprendizaje cada vez más plana. Las posibles líneas futuras de investigación sugeridas a la luz de esta tesis se enumeran a continuación.

- Estudio del impacto económico de la integración de energías renovables respecto a la redistribución de los costes fijos del sistema.

- Estudio del impacto técnico así como de las limitaciones de la integración de energías renovables en el sistema eléctrico.

- Desarrollo de una herramienta software para la definición automática del potencial fotovoltaico de una ubicación específica basada solamente en un tratamiento apropiado de fotografía por satélite comercial.

- Desarrollo de un sistema FV mixto (autónomo – conectado a red) con su correspondiente electrónica para el control simultáneo del inversor y del regulador de la batería, y que esté en permanente comunicación con los precios instantáneos de la luz existentes en el mercado eléctrico. Este sistema mixto deberá tener la capacidad de decisión para discernir aquellos momentos en los que sea más rentable consumir la electricidad autogenerada con FV, instantánea o procedente de las baterías, o por el contrario si es más rentable consumir directamente de la red basándose en la comparación del LCOE del sistema FV y los precios horarios del mercado eléctrico.

La identificación de futuros trabajos en relación al LCA han sido sugeridos en el correspondiente apartado de logros por cumplir, pero a continuación se resumen las recomendaciones más destacables.

- Fabricación de un prototipo de segunda generación donde se solventes los problemas detectados respecto a la falta de homogeneidad y uniformidad, así como la mejora del procedimiento de medida y el incremento del número de ensayos experimentales.

- Inclusión de etapas ópticas de concentración para una mejor detección y comparación con módulos CPV comerciales, en relación a los aspectos de uniformidad y homogeneidad que la óptica causa en la superficie de las células.

- Desarrollo de una nueva versión del LCA con capacidad de medida de la subcélula inferior o incluso de las recientemente desarrolladas células de 4 uniones.