# Operating Experience of Photovoltaic Systems installed at the University of Jaen

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***Abstract*—** Photovoltaic systems have showed themselves to be one of the most promising applications for dealing with the solar electricity generation. This way, the photovoltaic market has drastically changed. The annual growth rates of worldwide photovoltaic production increased. The use of photovoltaic for electricity generation purposes has recorded one of the largest increases in the field of renewable energies, and this trend is expected to continue in the coming years. The University of Jaén (Spain) is a pioneering public organism in the field of grid-connected PV systems, as it proves the milestones developed by its IDEA research group in the last decades. The University of Jaén has installed several integrated photovoltaic systems in buildings and these systems work properly. Currently, the university produces some of the electrical energy consumed and has provided this institution with infrastructures for the research and development of photovoltaic solar energy

***Keywords*—** Building Integration, Grid-Connected, Design, Photovoltaic potential.

## I. Introduction

PHOTOVOLTAIC solar energy is a clean renewable energy with a great potential, easy to install and to maintain, highly reliable and long-lasting. In last years, this kind of energy has experienced an outstanding and rapid growth due to the recent environmental commitments submitted by the developed countries and their comparative advantage. PV systems have special characteristics that provide some added value as systems of power generation. In fact, the rise of PV as a formula to obtain electricity is one of the highest registered in the field of the renewable energies and this tendency is expected to continue in the next years. As a consequence, a soaring number of new PV components and devices, mainly arrays and inverters, are coming on to the PV market [1]. Although PV systems -particularly grid-connected photovoltaic systems- have had a technological breakthrough, efforts are still required in research, technological development and innovation (R&D&I) and they must be achieved mainly by improving the different parts of the systems.

Photovoltaic systems have showed themselves to be one of the most promising applications for dealing with the solar electricity generation. This way, the photovoltaic market has drastically changed. The annual growth rates of worldwide photovoltaic production increased. At the same time, a significant change has been observed in the last years, when the growth in installed power is related mainly to relatively high scale centralized system.

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 [1] [2] [12] [14] [15] [17]. The new Spanish feed-in tariff regime, through the development and application of the Royal Decree 1578/2008, tries to recognize the advantages of the PV systems integrated in buildings, either on façades or on top of roofs, due to their advantages as a distributed source of energy, the lack of increase of the territory occupation and their contribution to the social diffusion of the renewable energies [3]. This favourable social and economical environment settles the opportune foundation for the creation of a socially sustainable energy project.

Such a significant increase in the number of photovoltaic installations is due to two main causes. In one hand, to the remarkable increase of support plans, programs and actions that several administrations have started/established with the clear aim of promoting and developing this kind of photovoltaic systems. In the other hand, to the great technological progress that has taken place in this kind of systems and, particularly, in grid connected PV systems [13][16].

However, the electrical energy generated by photovoltaic systems represents only a few of the Europe total electricity generation. Therefore, if the objective is to achieve that photovoltaic solar energy plays a important role within new energetic system, making all the possible efforts to achieve this objective is a basic requirement. That way, photovoltaic energy-supporting economical actions and programmes should be increased and those research and development programs focused on solving out the improvable aspects of photovoltaic systems should be encouraged.

The University of Jaén is a pioneering public organism in the field of grid-connected PV systems, as it proves the milestones developed by the IDEA research group in the last two decades. The initial research and development of this kind of systems made by the IDEA group was manifested in 1995, during the design and implementation of the "Photovoltaic Pergola", which was a 2 kWp gridc onnected system in the terrace of the Engineering College [4] [5]. At the same time, a deep analysis was carried out in the "Condestable project", which was an attempt of integration of renewable energy sources in the Historical center of Jaen (Spain) [6] [7]. In 2001, it was inaugurated the UNIVER Project, a 200 kWp installation which was the largest PV system integrated in a public area in Europe. Its design and installation meant a great advance in areas such as the electric protection on PV systems [8] [9].

Nowadays, the performance analysis of a two-axis tracker ("El Girasol") and the previous studies that are being carried out for the installation of several Concentrator Photovoltaic systems.

To facilitate photovoltaic technology diffusion, the researchers of the University of Jaen have to considered the development of those concepts providing methods for photovoltaic systems design which are more similar to those methods used in other fields of engineering in general and electrical engineering in particular. This fact implies a new approach of photovoltaic systems engineering. An approach that facilitates the use of these systems to experts from other fields which are not familiar with the so particular concepts and procedures used in the analysis and design of photovoltaic systems.

## II. PHOTOVOLTAIC SYSTEMS INSTALLED AT THE UNIVERSITY OF JAEN

### *A. Pérgola Fotovoltaica*

The *"Pérgola Fotovoltaica"* is a 2 kWp grid-connected photovoltaic system integrated at terrace of a old building of the Engineering College. The system was installed in 1995 and was dismantled in 2005 because the building was demolished. The system was one of the first building-integrated made in Spain

Fig. 1 Pérgola Fotovoltaica

The generator is made up by 23 photovoltaic modules Isofotón I-88 with a 15.45 A current at maximum power point. This generator is divided into four series-connected subgenerator, three of which are made up by 6 series-connected modules; meanwhile the fourth one only has five modules. Subgenerators orientations are 6º, 21º, 36º and 51º East respectively, and all of them show the same tilt, 15º.

Fig. 2 Old building of the Engineering College of the University of Jaén

### B. *The Univer Project*

The Univer Project consists of the installation of a grid-connected photovoltaic system, with a total power of 200 kWp, in Jaen University Campus (Figure 3). We can find four subgenerators with a similar configuration, changing only the generator power, and three different architectural solutions: Two subgenerators which are part of the University parking covers and two subgenerator embedded in the building where the Transformation Center and the inverters are located. The system is made up by two subsystems based on 60 kW-inverters and twenty four subsystems with 2 kW-inverters.

Fig. 3 University Campus

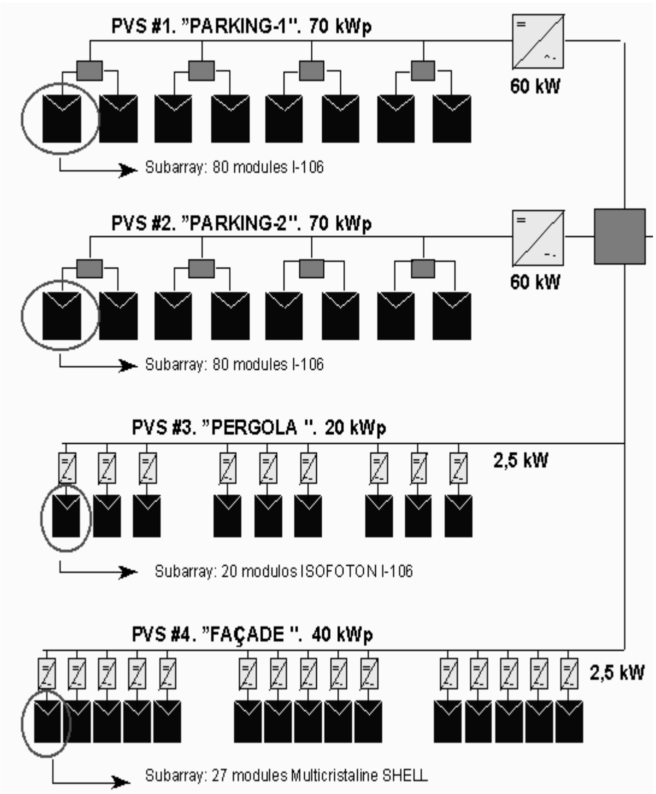


Fig. 4 General Layout

Photovoltaic System 1 "Parking 1"

System "Parking 1" is integrated in one of the parking covers at the University Campus. It consists of a photovoltaic generator with 68 kWp nominal power and a 60 kW triphase inverter. The photovoltaic generator consists of 640 modules of model ISOFOTON I-106, 80 modules series connected each one, and 8 parallel arrays. For the integration of the photovoltaic generator, we use the existing parking covers at this University Campus, which are totally free of shadows and with a 30º southeast orientation and tilted 7,5º.(see Figure 5).

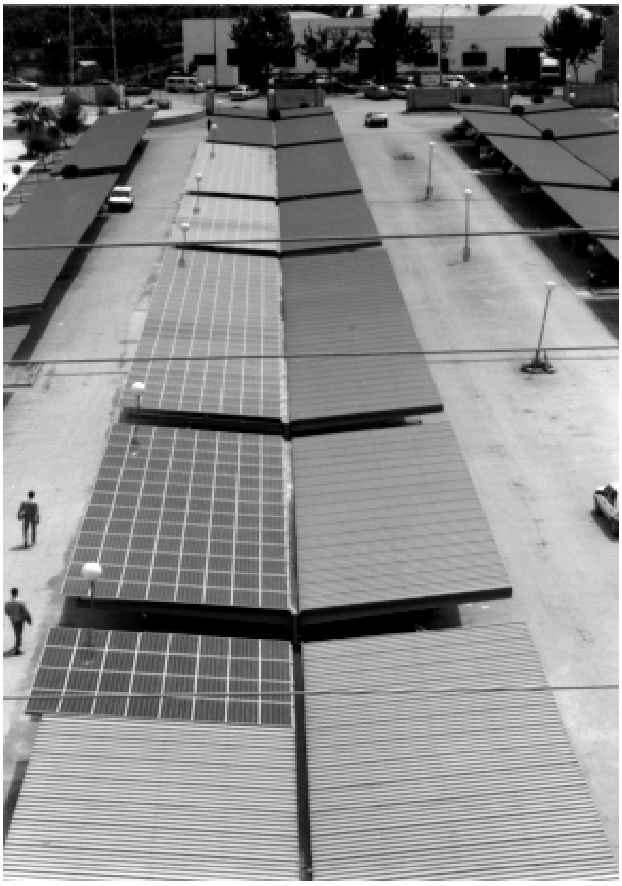

Fig. 5. Photography of 'Parking' system

Photovoltaic System 2 "Parking 2"

It has the same design, modules and power conditioning unit as PV system 1. It is located in a parking canopy parallel to PV system 1, in the same parking area, as shown in figure 2. The original roofing was easily removed and the existing support structure was used to accommodate the PV modules

System "Parking 2" is the same as "Parking 1", and it is located in a parallel cover in the same parking

Photovoltaic System 3 "Pergola".

This PV generator is integrated in the Connection and Control Building of the project [10] [11]. In this building are located the inverters, the data acquisition system and the safety and protection systems. The PV system consists in a photovoltaic generator with a 20 kWp of nominal power, made up by 9 subgenerators (2 kWp) and string oriented inverters.

One of the aims of this integration is to get an area of shadows that improves the environment climatic conditions, very necessary in this part of Spain, and at the same time, it can be useful for students (see Figure 6).

Fig. 6. Photography of 'Pergola' system

Photovoltaic System 4 "Façade".

This PV generator is integrated in the south façade of the building, which is located close to the Connection and Control Building. It consists of 15 subgnerators with a total of 40 kWp PV polycrystalline modules and a 40 kW string oriented inverter (see Figure7).

Fig. 7. Photography of 'Façade' system

With the aim of keeping people protection, the Univer Project includes passive and active measures that avoid direct contacts with the active system parts (earth grids and an permanent insulation controller to detect the earth faults of the generators). This is one of the most outstanding aspects of the Project, and it has also been the most studied because of the high number of students at this Campus. The studies carried out about the installation safety and protection have been developed from two points of view: on the one hand, from the installation itself, and on the other one, from people safety. In this sense, it is important to point out the lack of a legal regulation related to such aspects in this type of installations in Spain.

In general, the risks that can affect an electric installation are due to overvoltages and overcurrents, although in our particular case, and because of the phovoltaic system working, we will only be affected by overvoltages as a consequence of the eventual presence of atmospheric discharges, induced inductions, etc. In this sense, the installation includes voltage limiters that reduce it to a value under the insulation level required to the equipment. These limiters are placed at the inverter input and output, at the DC junction general board, and at the junction boxes of the different generators arrays. As for people protection, the installation includes the necessary elements to avoid possible direct and indirect contacts. In this sense, there are three levels of protection: floating system, insulation control and earth connections

The main organizations that collaborated on the Univer Project were:

• University of Jaén (project co-ordinator): the project was developed by the research group, Grupo IDEA, comprising architects and lecturers from the Electronics and Electrical Engineering Departments. One of the main fields of research of the Group is the photovoltaic solar energy one and the integration of photovoltaic (PV) generators in buildings.
• Instituto de Energía Solar: R+D Centre at Madrid Polytechnic University. Responsible for quality control and are the technical advice for the engineering system.
• Newcastle Photovoltaic Applications Centre: R+D Centre of Northumbria University. The centre has wide experience with these systems and evaluation the project results.
• Isofotón, S.A.: manufacturer of the photovoltaic modules. Supplied the modules and was the technical advisor for the photovoltaic generators.
• Solar Jiennense: installer of renewable energy systems. It was responsible for the electrical installation and the technical assessment of the civil works and the supporting structures.

### *C. "El Girasol" PV System*

*El Girasol* (The Sunflower) is a 9.6 kWp grid-connected photovoltaic system .The installation, located at the University of Jaen Campus, is made up by three main systems:

- a dual axis tracker,

- a generator, divided in three 3.2 kW photovoltaic subsystems which are connected to the grid through single-phase inverters
- a monitoring system.

The Sun-Tracker is a pedestal type one with a single foundation plate, on which a mechanical transmission block for azimuth and elevation control is set. The Photovoltaic Generator has a total power of 9,600 Wp and it is made up of 48 polycrystalline silicon photovoltaic modules. All of them produce a 200 Wp maximum power at standard test conditions, and have been made by Kyocera (model KC200GHT-2). In order to connect the Photovoltaic Generator to the grid, we have used a DC/AC converter made up of three single-phase inverters, model Ingecon Sun model by Ingeteam Company, with a nominal power of 3.3 kW. Each inverter feeds energy into a different phase, so the whole performs like a three-phase system.

Fig. 8 El Girasol PV system

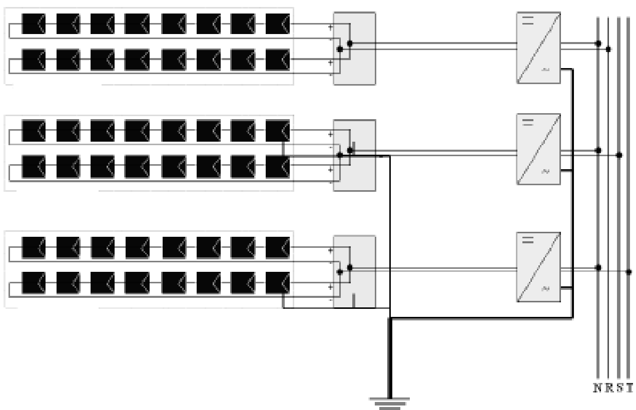


Figure 9. Electrical diagram of the system

## III. CONSUMPTION - GENERATION RATIO

The systems have been designed to generate around 10 % of the total Campus energy requirements. The PV generation coincides in peak hours to the University electric demand, so most of this energy will be self-consumed.

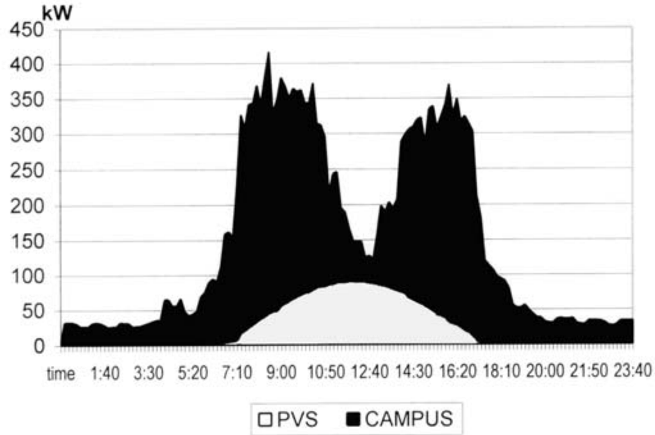


Figure 10.- Campus consumption and PV generation.

The figure 10 shows the university energy consumption in a typical day (black area). We have overlapped the energy generated by the photovoltaic systems in the same day. As can be seen, most of the energy is self-consumed.

## IV. MEASUREMENT SYSTEM

The grid connected PV installations of Jaen University are fully monitored to assess the potential of PV technology and performance of this kind of system. The monitoring system was designed according to the European Guidelines and IEC 61724 [18], [19].

This system is permanently in direct communication with the PV system inverters and the different measurement sensors. It consists of a data acquisition system, based on datalogger with a multiplexing card of 20 channels and two global purpose cards. The datalogger is connected to a computer and the measured data is recorded every ten minutes.

The monitoring parameters for each PV system are: the ambient temperature Ta (ºC), the in-plane irradiance Gi (W/m2), the array voltage VDC (V), the array current IDC(A) and the output inverter power PAC(W).

This monitoring system is connected to a computer. That computer is provided with a software that retrieves the interest data being acquired and save them in the proper format. The following figure shows the telemonitoring system structure:

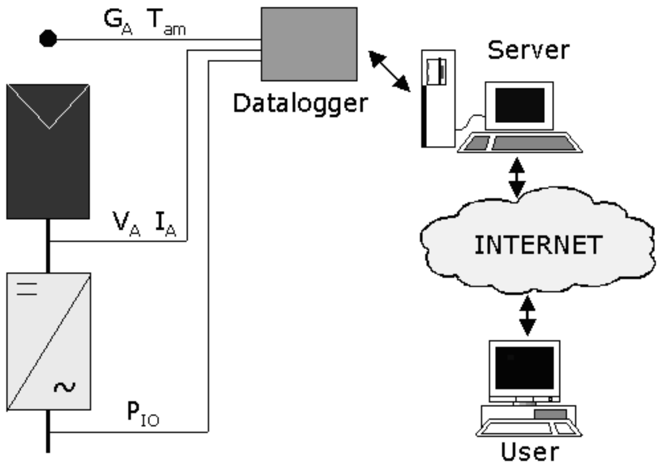


Figure 11. Telemomotoring system structure.

## V. Parameters for performance analysis of grid connected PV systems

Several standard performance parameters for describing grid connected PV system behavior have been established by the international Energy Agency (IEA) and are described in the IEC standard 611724 [18] and extended and improved by *Ingeniuersschule Burgdorf, ISB* [19].

Three most appropriate performance indicators may be used to define the overall grid connected PV system performance with respect to the energy production, solar resources, and overall effect of system loss are: the final PV system yield $Y_f$ and the performance ratio (PR).

The final PV system yield $Y_f$ is the net energy output delivered to the grid $E_{AC}$ divided by the nominal PV generator power *P**. It represents the number of hours that the PV generator needs to operate at its rated power to provide the same energy. The final yield normalizes the energy produced with respect to the system size; consequently, it is a convenient way to compare the PV system output of differing size. It is expressed in hour per year kWh/kWp year.

$$Y_f = \frac{E_{AC}}{P^*} \quad (1)$$

The parameter more used is the so-called Performance Ratio (PR), which is a dimensionless quantity that indicates the overall effect of losses (due to inverter inefficiency and cell temperature, losses in wiring and protection diodes, poor module at low irradiance, partial shading, and module mismatch, etc.) on the rated output. It is defined as the ratio of AC energy ($E_{AC}$) delivered to the grid to the energy production of an ideal loss-less PV system with 25ºC cell temperature and the same solar irradiation. It is given by:

$$PR = \frac{E_{AC}}{\frac{E_{G_i}}{G^*} P^*} \quad (2)$$

PR values are useful for determining if the system is operating as expected and identifying the occurrence of problems due to different system components faults/failure, nevertheless it can not identify the cause.

## VI. Operating Experience

The system 1 of the UNIVER project was started up in August 1999. The other systems were started up in March 2001. In next paragraph, data related to year 2005 operation are submitted. We are chosen this year because the system behaved normally and as expected for this type of system, without evidence of any remarkable anomaly.

*“El Girasol”* was connected to the grid on 2007, and data related to this first year operation are submitted in next paragraph.

For year 2005, ‘Parking’ system had been measured an annual irradiation of 1596 kWh / $m^2$ and this system had been injected into the network 83459 kWh, which implied a performance (PR) of 69% and a productivity of 1105 kWh / kWp. ‘Pergola’ system, had been measured an annual irradiation of 1664 kWh / $m^2$ and this system had been injected into the network 2823 kWh, which implied a performance (PR) of 72% and a productivity of 1198 kWh / kWp. ‘Façade’ system had been measured an annual irradiation of 1177 kWh / $m^2$ and this system had been injected into the network 2630 kWh, which implied a performance (PR) of 74% and a productivity of 877 kWh / kWp.

During the first year operation of system *“El Girasol”*, the global irradiation over horizontal surface in this period of time goes up to H(0)=1,720 kWh/$m^2$ and the estimated irradiation over the PV generator was H(S) = 2,827 kWh/$m^2$. If the PV generator surface is $S_G$ = 67.72 m2, the estimated solar energy received in this last year of operation was $E_{GS}$=191,444 kWh. From the monitoring systems of the inverters, the DC energy generated was $E_{DC}$= 20,698 kWh, so the efficiency of the inverters was 94.8%, the efficiency of the PV generator was 10.8% and the global efficiency of the system for this year was 0.2%. And finally the global performance ratio of the system was 72%. The energy injected to the grid was 20,538 kWh. This means a system yield of 2,139 kWh/kWp·year (The productivity is calculated dividing the 20,538 kWh injected to the grid by the 9.6 kWp of the generator nominal power at standards conditions).

Related to the system *“El girasol”* behaviour during this first year of operation, we would like to highlight the following: 1.- The high operation reliability during this period, with no outstanding incidents and minimal maintenance needs. 2.- The high system efficiency, which involves a good system design and installation have been carried out, that right components have been selected and a suitable tracking program has been carried out. 3.- "*El Girasol*" shows 49% yield increase when compared to a fixed and ideally faced one. In order to obtain this information, it has been supposed that in Jaen, a fixed installation with a 30º lean and headed South, would get an average annual productivity of 1.435 kWh/kWpeak·year in the best setting expected

| System | Year | PR | Final Yield kWh/kWp year |
|---|---|---|---|
| Parking | 2005 | 73 % | 1.191 |
| Pérgola | 2005 | 72 % | 1.254 |
| Fachada | 2005 | 73 % | 954 |
| Girasol | 2007 | 72 % | 2.139 |

Table I. Performance ratio and final yield

## VII. Analysis of System Losses in System "Parking 1".

System losses can be classified in four different groups:

a.- Losses due to temperature.
b.- Losses in generator.
c.- Losses due to a decrease in insulation system.
d.- Losses in inverter
e.- Other losses.

a.- Losses due to temperature (L cap). They appear because cells presents temperatures higher than 25ºC and reach 8,4%

b.- Losses in generator (L gen). Theoretical peak power in generator is 68 kWp, but the measurements carried out show that the actual STC power is only 62 kWp. This causes a decrease in the power generated of about an 8,2 %. Here are also included those losses due to mismatch and wiring.

c.- Losses due to a decrease in insulation system (L ais). The people safety system of the Univer PV plant is based on the use of a Permanent Insulation Control (PIC) device that is able to detect insulation decreases in floating system. When this failure takes place, the PV field is shortcircuited and connected to the ground. In some cold and wet mornings, the PIC device has detected a high decrease of the insulation resistance (about 5 kOhms) of the PV system, when the usual value of this resistance varies between 40 kOhms and 700 kOhms, according to the environmental conditions. This problem is mainly due to the existence of condensation drops in the connection boxes of modules. Losses directly related to this failure add up 0,6%, .

d.- Losses in inverter (L inv). The measurements made in the inverter (60 kW) during this year have resulted in an average efficiency of 88 %.

e.- Other losses (L var). This group includes all the other losses of the system, some examples are those caused by a wrong MPP tracking or partial shadows ongenerator. The value is 9,7%.

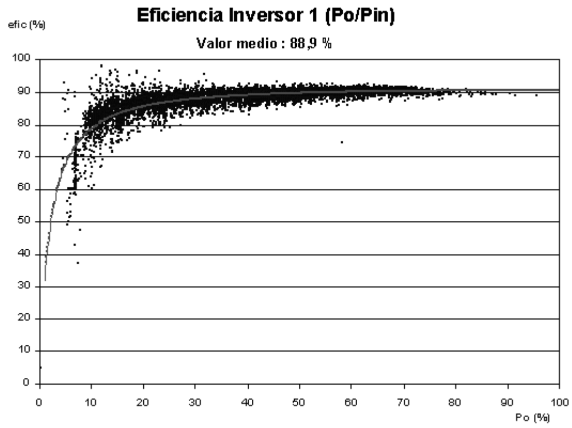


Figure 12.- Efficiency of Inverter 1

## VIII. Conclusion and Future Acction

The University of Jaén has installed several integrated photovoltaic systems in buildings and these systems work properly.

Two innovative aspects have been developed:

• Design and implementation of a successful protection and safety system destined to PV system built in crowded places.

• Other of the most valuable aspects of systems are the architectonical integration and the possibilities of being replicated in other regional places.

Currently, the researchers of the University are experts in the field of photovoltaic systems connected to the grid, the university produces some of the electrical energy consumed and has provided this institution with infrastructures for the research and development of photovoltaic solar energy

Furthermore, these systems have created emblematic elements that help the spreading of photovoltaic solar energy. Specially, The Girasol and Façade generator create a great visual impact for not only the 15,000 University students but also regional population. One evidence of this fact is that the image of these generators appears in mass media when news related to the university research studies or renewable energies arise.

Recently, the University has proposed an ambitious project, the so-called UNIVERSOL project, where the necessary tasks will be carried out in order to evaluate the "photovoltaic potential" of the Campus of the University. This project is the previous step to convert this Campus in a big public area which combines the PV electricity generation with the common uses of a university place, in other words, to create a mixed space where the generation of knowledge can be combined with the electricity generation

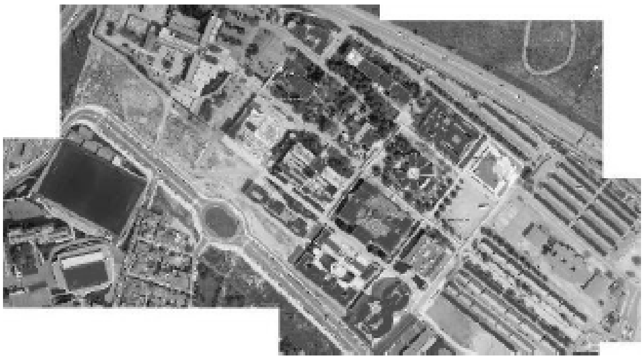

Fig. 13 Potential PV areas University Campus

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