Chapter 7

Degradation Monitoring of Photovoltaic Plants: Advanced GIS Applications

Miguel de Simón-Martín, Ana-María Diez-Suárez, Laura-Álvarez de Prado, Alberto González-Martínez, Álvaro de la Puente-Gil and Jorge Blanes-Peiró

Additional information is available at the end of the chapter

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Abstract

In order to evaluate a photovoltaic (PV) plant performance, payback time, profitability and environmental impact, an analysis must be made of plant maintenance needs, module and wiring degradation, mismatches and dust effects and PV cell defects and faults. Although a wide range of studies can be found that show the theory and laboratory testing of how these circumstances may affect PV production, very few studies in the field have covered or quantified real degradation effects and faults using a systematic procedure. The authors have therefore reviewed the conditions of PV plants operating in Southern Europe, examining the most frequently found faults and types of degradation, and they look at how novel technologies, such as geographic information system (GIS) applications, can help maintainers, owners, and promoters to supervise and locate damaged PV modules and monitor their evolution and impact on plant working conditions. GIS applications in this field allow the organization of a geo-referenced database of the system, locating and supervising the thirds of each PV cell in the power plant. With this information, investors and maintainers can exert increased control on the PV plant performance and conduct better preventive maintenance measures. The examples given demonstrate that these sorts of applications can be applied both to large PV plants and to domestic installations.

Keywords: photovoltaics, PV plants, PV faults, geographic information system, PV supervision, maintenance

1. Introduction

The operation and maintenance of a photovoltaic (PV) power plant is of extreme importance to guarantee its optimal performance. Effective maintenance involves at the least semi-automatic analysis and alerts. In this way, the maintenance operator is capable of making immediate decisions to solve safety problems and minimize power losses [1].

Moreover, monitoring is not just a regular recording of data but involves a more detailed analysis in order to prevent possible malfunctions associated with power and, in the end, economic losses.

Thus, the development of automatic supervision tools to help maintainers to carry out an effective supervision of the power plant and, what is more important, to monitor the evolution of the modules behavior in an easy and feasible way is of great interest in the industry. Furthermore, the detection of operating failures in a timely fashion through the evaluation of panels over time means that automated monitoring is, in fact, absolutely necessary. Such monitoring will lead to the early replacement of poorly performing components, preventive maintenance policies, and better management of plants.

For device manufacturers, performance evaluations of their products can be used as a benchmark of their quality manufacturing processes. On the other hand, researchers and R&D divisions from companies can take advantage of such evaluations, using that information to identify future needs in the industry and to test real working conditions. For PV plant promoters and owners, realistic performance data is essential for investment decision-making.

Although several techniques for the detection of real and/or potential failures in the PV field can be found in the literature [2–4], few of them attempt to detect anomalies such as power loss, module failure, or health and safety dangers until after they occur and the effects are felt. These techniques, moreover, do not address preventative maintenance strategies or effective economical programs for the replacement of components. In addition, these systems do not integrate geo-references that may help to improve the application of preventative maintenance strategies.

New methodologies are needed to locate and analyze performance and malfunction of plant components on a global scale. Despite the great value of analysis carried out in the laboratory, it can often be of little help when applied to the real operation of maintenance plans. Test conditions in a laboratory may allow for a complete analysis of PV components, but owners can ill afford to close an entire installation or part thereof for equivalent testing in the field. Besides, laboratory test conditions are unlikely to fully typify working conditions in a real field. As such, laboratory test results and, more importantly, any conclusions drawn from them are likely to be decontextualized. On the other hand, carrying out systematic procedural techniques in the field under changing environmental and climatic conditions is in no way easy.

Integrated geographic information system (GIS) platforms will allow test-related information to be comprehensively organized and geo-referenced, providing significant benefits. One such benefit is the fact that the impact of a single defective component on the overall

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performance of a plant can be analyzed. Predictive techniques can then be used to analyze deviations in the behavior of supposedly viable components and forecast possible outage in areas of the PV plant.

This chapter is organized into four further sections. First, a systematic review of the most common PV faults is undertaken. Then, the fundamentals of GIS and how they can be applied to PV maintenance and fault supervision are presented. In section three, the application of a GIS tool to both a large PV plant (100 kWp) and a domestic installation (9 kWp) is fully described and results of the implementation of both examples are shown. Finally, the last section includes the main conclusions and some future research directions.

2. Photovoltaic module defects and faults

Prior to going deeper into this topic, the term "failure" in the PV context must be properly defined. The bibliography defines a failure in a photovoltaic module as *an effect that degrades the module power output which is not reversed by normal operation or which, on the other hand, creates a safety issue.* Evidently, both of these effects can occur at the same time.

As such, degradation of wiring or modules, PV cell defects and malfunctions, dust, and mismatches can be considered to be failures of PV modules [5] and purely esthetic problems are not.

The following subsections describe briefly all potential PV module failures.

2.1. Delamination

This consists of the loss of adhesion between the glass, the encapsulation, the active layers, and the subsequent layers [6], which can cause loss of current (power) in the photovoltaic modules. Loss of adhesion may occur for various reasons. Large thin film modules and certain other types of modules sometimes contain an additional transparent conductive oxide (TCO) layer, which may lose adhesion with the adjacent glass layer [6]. If the loss of adhesion is due to contamination, perhaps from cleaning, or environmental factors, then delamination will often take place, followed by moisture entering and, in due course, corrosion. Delamination leads to reflection of light and a subsequent loss of power in the modules.

In most cases delamination can be detected by visual inspection, with the degree of layer detachment being quantified by use of a reflectometer. Some delaminations, however, cannot be identified in this way and so methods such as pulsed active thermography or lock-in thermography can be used, while smaller delaminations can be detected with ultrasound scanners and X-ray tomography. The latter methods are slow [7] but provide a much higher resolution.

2.2. Loss of adhesion in backsheet films

The multilayer composites that make up PV module backsheet films comprise three or more polymer layers. Outer layers provide resistance to weathering factors such as sunlight and humidity and are often made from fluoropolymers with polyvinyl fluoride (PVF), polyamide (PA), or polyethylene terephthalate (PET) [8] being popular choices.

Backsheet failures include yellowing, brittleness that leads to cracking, and delamination within the multilayer composite. Delamination and cracking allow water vapor and oxygen into the PV module and are considered to be the worst kind of failures within backsheets as they cause problems with isolation and subsequently can cause safety issues [9]. Water vapor critically affects degradation phenomena such as decomposition of the encapsulation, corrosion of the metal parts, and potential induced degradation (PID) of the PV modules. Such failures impact on the performance of a PV module and shorten its lifespan. Yellowing, on the other hand, has not been reported as having an influence on the electrical performance of modules.

2.3. Junction box faults and mechanical breakage

Junction boxes are attached to the back of modules and protect the connections to the external terminals. Bypass diodes in the junction boxes protect cells in a series when hot spots occur due to partial shadowing of the module [5]. The formation of moisture due to faulty adhesive can lead to wiring degradation that can be the cause of electrical arcing resulting in the potential for fire or threat to human life.

Mechanical breakages usually consist of cracks in the frame produced by poor handling or extreme winter snow loads.

2.4. Discoloration of the encapsulation material and bubble formation

Degradation of the encapsulation material (normally ethylene vinyl acetate or EVA) is an esthetic issue that does not usually affect the performance of a module. It can, however, lead to an average current loss of 0.5%/year or 0.8%/year for Si PV modules [10].

Rising temperatures, the photo-degradation of EVA by UV radiation, and the existence of molecular oxygen lead to the production of acetic acid and volatile gases, that are trapped within the module, and can produce delamination or the formation of bubbles [11].

The presence of acetic acid in a PV module is linked to several PV module failures due to its corrosive effects on cell metal, which may lead to an increased series resistance and hence losses in module performance [12, 13].

Some studies refer to discoloration as degradation rather than failure, as discoloration leads typically to lower performance but not necessarily to failure [6].

On the other hand, inappropriate temperatures or an excessively long lamination procedure [14] during the manufacturing of the photovoltaic module can cause bubbles of gas to be formed either as a direct or as an indirect consequence of melting and solidification processes (**Figure 1**). In **Figure 1(a)** an EVA discoloration can be appreciated while in **Figure 1(b)** we can observe an example of a bubble formed over a metal contact.

2.5. Cell cracks

PV cells are made of silicon so they are very brittle. Cell cracks are formed in different lengths and orientations in the substrate of the photovoltaic cells and often cannot be seen easily.

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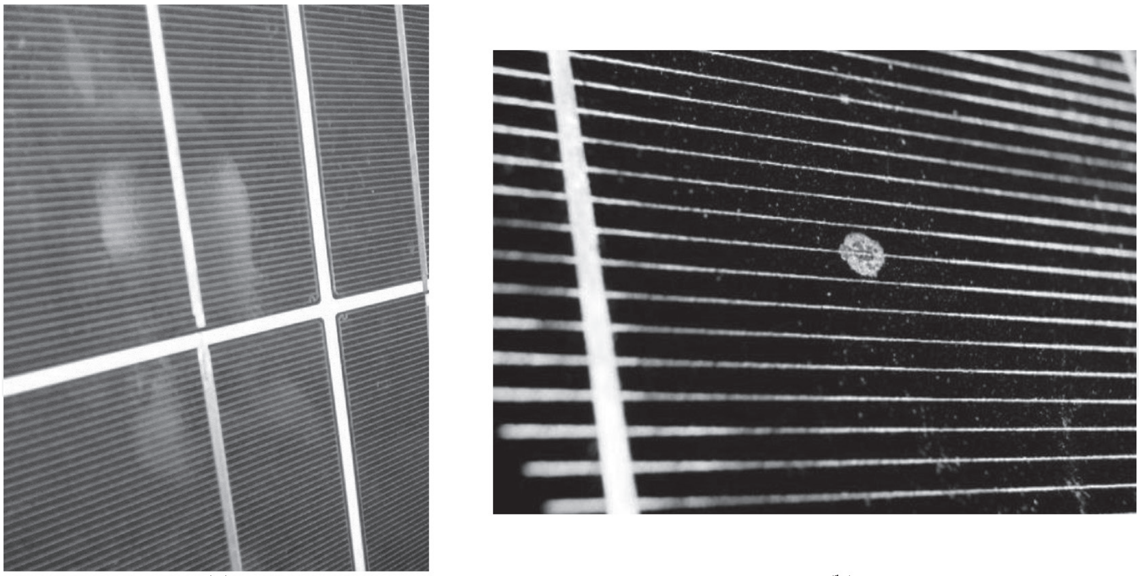

(a) (b)

Figure 1. Examples of (a) EVA discoloration and (b) bubble formation.

Figure 2 shows a clear example. Cell cracks may occur during or after production. Major sources of cell cracks are during packaging and transport or during the reloading of PV modules and installation in the field.

Small cell cracks show a great tendency to develop into larger, wider cracks during operation of the solar module due to mechanical stress [15] from wind or snow load and thermo-mechanical stress [16] from temperature variations due to changes in weather and intermittent cloud cover.

An inactive cell area of 8% or more is unacceptable. Apart from the risk of power loss there is also the chance of hot spots being formed. This can happen when a cracked cell has a localized

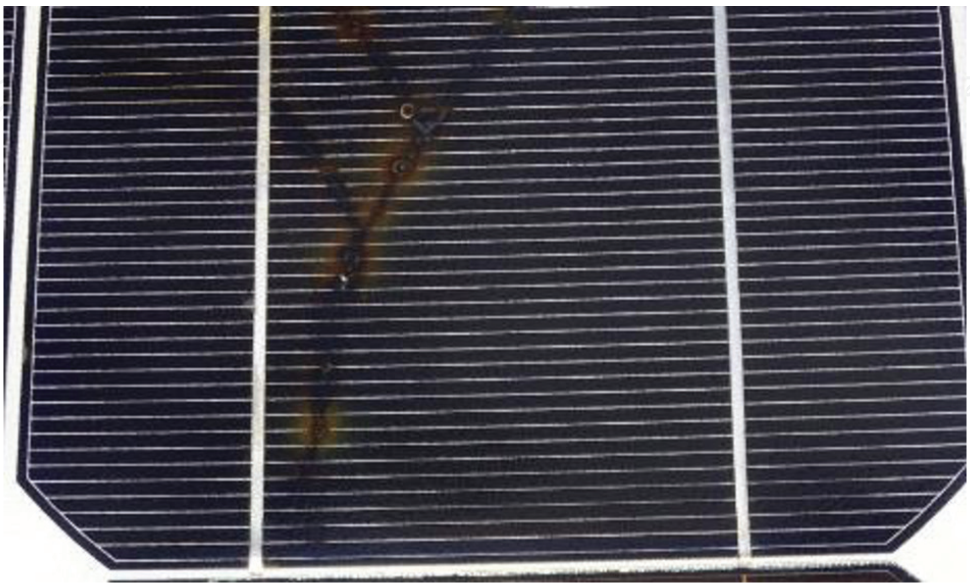

Figure 2. Example of cracks in a PV cell.

reverse current path in the still active cell part. The cell may reverse bias and the full current will be able to flow along the localized path as a consequence of the missing cell area. This can cause hot spots and subsequently burn marks [17].

2.6. Snail tracks

Snail tracks are discolorations of the silver fingers on solar cells. A significant example can be seen in **Figure 3**. The effect looks like a snail has passed across the front glass of the PV module. The discoloration takes place on cell cracks that are not visible at the edge of the solar cell. This typically happens between 3 months and 1 year after installation of the PV modules [18]. Discoloration speed is initially dependent on seasonal and environmental conditions, such that snail tracks seem to spread faster during summer months and in hot climates [5]. PV modules affected by snail tracks have been compared with reference modules under laboratory conditions [19] and results showed a 40% reduction in maximum power under standard conditions with a 25% lower yield than expected when measured over a 30-day period.

2.7. Hot spots and burn marks

A typical and very common failure in silicon PV modules is burn marks. This failure occurs due to part of the module becoming very hot and can be because of ribbon breakage, solder bond failure, or localized heating from reverse current flow or other hot spots [5]. Burn marks can produce power losses and serious safety problems. They are usually located on or closed to the metal contacts of the PV solar cells, such as it can be seen in **Figure 4**.

Hot spots are areas in a photovoltaic module that have very high operating temperatures when compared to surrounding areas. This may be due to interconnection failures, defects in the cell, dispersion of characteristics between modules of a generator and between cells of the same module connected in series, potential-induced polarization in modules manufactured with novel techniques, or when a cell generates less current than other cells connected in series as a consequence of intermittent cloud cover or partial shading [20]. As a consequence, the cell becomes polarized (the voltage between the terminals becomes negative) and starts to dissipate the power generated by the other serial cells in the form of heat.

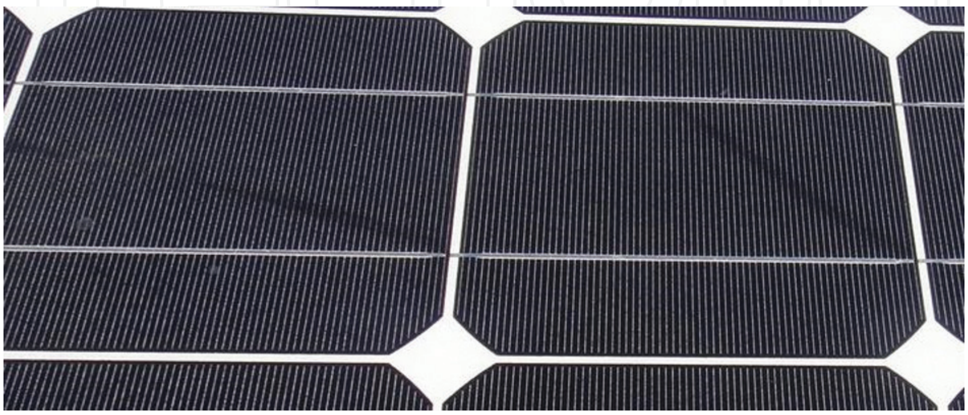

Figure 3. Example of a snail track over a PV cell.

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Recently, a new maximum power point tracking (MPPT) method was proposed to avoid the consequences of hot spots. It is based, firstly, on a bidirectional buck converter to control the operating point of each module and uses a boost converter to control the terminal voltage of each branch. Secondly, MPPT is modeled as an large-scale global optimization (LGSO), and a novel, multicontext, cooperatively coevolving particle swarm optimization (PSO) algorithm (CCPSO-m) is proposed to solve this large-scale problem [21].

2.8. Potential-induced degradation

Potential-induced degradation gives rise to power losses owing to the presence of eddy currents in the PV modules. Its effect can potentially reduce the power of the equipment [22].

The principal cause of these currents is reported to be voltage gaps between the ground and the module. In photovoltaic systems without a grounding system, this effect occurs when modules have a non-zero voltage, which is normally negative especially under high ambient humidity and/or temperatures and high voltage conditions [23].

2.9. Disconnected cells and string interconnected ribbons

Cell strings can become disconnected if string interconnected ribbons are weak, which may be caused by large deformations, by the quality of the welds during the production process, or by weak connections between the string and the ribbon. Small distances between cells can also contribute to interconnected ribbon breakage [5].

The consequences of this may be a broken cell interconnected ribbon and a subsequent decrease in maximum power point current [24] or a shunt by a cell interconnected ribbon and a subsequent decrease of open circuit voltage.

Figure 4. Example of a burn mark on a PV cell.

2.10. Defective bypass diode

Bypass diodes reduce the effects of intermittent cloud cover and partial shading on power generation by limiting reverse voltage potentials [5]. Power output is decreased significantly without bypass diodes and partial shading may cause local overheating, hot spots, and damage [25].

A new bypass system has been designed [26] allowing significant hot spot temperature reduction in both partial and full shading conditions. It relies on a series-connected power metal oxide semiconductor field effect transistor (MOSFET) that subtracts part of the reverse voltage from the shaded solar cell, thus acting as a voltage divider. The authors claim that it would be possible to cool up to 24°C with respect to the case in which standard bypass diodes are adopted.

2.11. Blue cells

This consists of the lightening of the dark blue tone of certain cells in the PV module. Some authors classify this as an esthetic defect, but others have noted that its appearance can cause a 17% yield loss under certain conditions [27].

3. Energy geographic information system applications

A geographic information system or GIS consists of a set of applications and programs that manage spatially referenced databases, which can be visualized through the use of maps [28]. It is a powerful and dynamic tool for the analysis of geographical and spatial data, which can also include non-spatial data.

A correctly implemented GIS tool provides comprehensive analysis of an area for any activity that entails a spatial component, meaning that GIS technology has wide application in resource management and can be an important tool in any decision-making task with a spatial element. GIS can thus be found applied to the development of solar atlas, resource location tools, and so on. Some authors have used GIS together with global positioning systems (GPS) and unmanned aerial vehicles (UAV) to propose efficient inspection and maintenance of PV plants [29].

3.1. Development of geographic information system tools for advanced photovoltaic plant supervision and management

The collection and compilation of a dataset of a number of PV power generation variables into a GIS tool for the easy visualization, location, and prediction of current problems in a PV power plant is of great worth. This involves the creation of a database and base map, and adequate procedures for systemizing data introduction and analysis, which in turn should lead to the simplification of the study of existing electrical and thermal defects.

Furthermore, the application of a GIS tool allows for the novel correlation of cell defects with not only power losses on the affected PV module but also with overall performance of the power plant.

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The complete PV power plant should first be introduced into the GIS software (ESRI ArcGIS) through aerial orto-photography before geometrical parameters are projected. The geographical position of the PV serial strings and limitation of plots can thus be set.

Furthermore, it is necessary to identify the exact position within the panel of any possible faults that may appear. For this reason, split installation of photovoltaic panels and the thirds of cells within each panel are taken into account. The maps have been geo-referenced by assigning them projected coordinates ETRS89 UTM 30 N.

PV modules are identified by their rack number and by a code that includes the serial string and the relative position of the string within the series.

A systematic procedure needs to be set up to identify the geographical position of a defect within a panel. A photovoltaic module is made up of 180 thirds of cells so the following nomenclature is suggested. Each cell in the panel can be split into 6 columns (A–F) and 10 rows (0–9). Each cell is, in turn, split into three thirds (X, Y, or Z). In this way, the position of a defect can be indicated in the third of the cell where it is located by an alphanumerical code (e.g., 4EY). **Figure 5** shows such an identifying code applied to a panel.

With the graphical part of the GIS tool delimited and the identification procedure for each PV cell established, a geo-referenced database or geo-database can be implemented. The geodatabase consists of a set of various kinds of geographical datasets in a common file system folder. From this a comprehensive information model can be created to represent and manage all the geographical information related to the power plant. This information model is realized as a series of tables storing entity classes, raster datasets, and attributes.

The model can be divided into three sorts of information: measurements of electrical variables, graphic information (pictures and thermographs), and defects and their description. **Figure 6** shows the schematic diagram of the relational database that has been created. According to

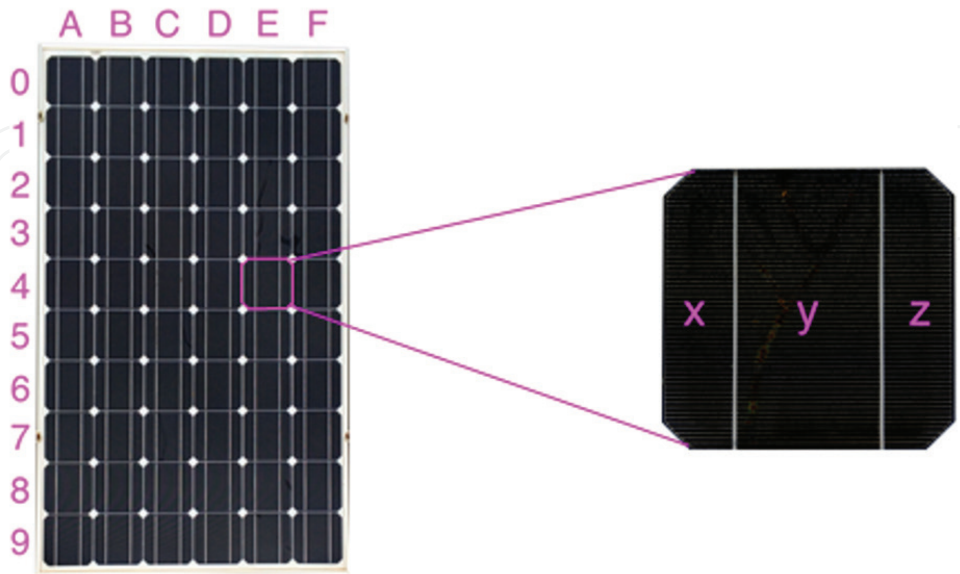

Figure 5. Adopted nomenclature for PV defect identification.

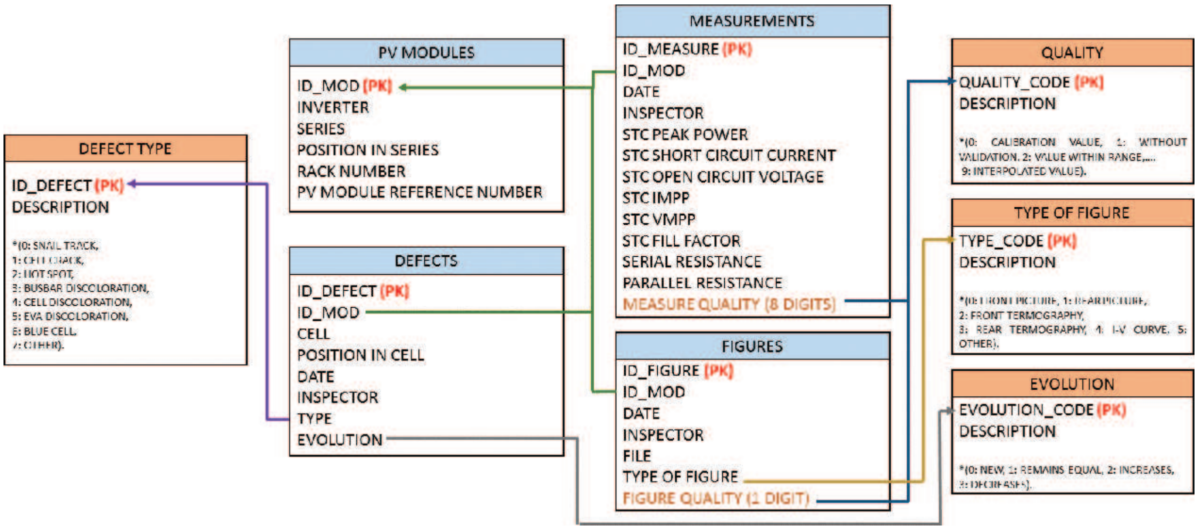

Figure 6. Schematic diagram of the database organization and relations.

the three sorts of information, the model has been organized into four main tables and four additional tables. The PV MODULES main table includes information related to a given PV module, such as its identifier code (ID_MOD) which is the primary key and uniquely identifies each record, the string series (SERIES), the inverter associated with the module (INVERTER), its relative position in the series (POSITION IN SERIES), its rack number (RACK NUMBER), and its manufacturing reference code (PV MODULE REFERENCE NUMBER).

The MEASUREMENTS main table includes the measured electrical variables that allow for analysis of the performance. Each measurement is assigned a unique identifier (ID_MEASURE) that relates each measurement record to the PV module using the ID_MOD. The date of the measurement (DATE) and the inspector who took the measurement (INSPECTOR) are also included. The installation date and factory settings of the module (FACTORY) can be included under the INSPECTOR setting. In order to assure an adequate analysis, the measurement quality (MEASURE QUALITY) is also included in the form of metadata, an eight-digit code described in the QUALITY auxiliary table. The quality code is a number between 0 and 9, that describes if the record is a calibration value (0), if the record has no validation (1), if the record has been checked for being in a suitable range (2), and so on. There is one digit for each measured electrical value.

The DEFECTS table records PV defects and faults. Each record shows the module affected (ID_MOD), the location code of the cell (CELL), which third of the cell is affected (POSITION IN CELL) along with the date (DATE), inspector recording the defect (INSPECTOR), type of defect (TYPE), and defect evolution within the module (EVOLUTION). The DEFECT TYPE auxiliary table records identifiers for the type of defect found in the form of a digit—0: snail track, 1: cell crack, 2: hot spot, 3: busbar discoloration, 4: cell discoloration, 5: EVA discoloration, 6: blue cell, and 7: other. The EVOLUTION field in the DEFECTS table is associated with the EVOLUTION auxiliary table. The following descriptors show the defect evolution in the PV module in this table—0: new defect or not detected before, 1: already detected but remains the same as the previous inspection, 2: has increased from the previous inspection, and 3: has decreased from the previous inspection.

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Finally, graphic information can also be included in the form of front and rear photographs and thermographs of each analyzed module. Furthermore, diagrams and figures can also be stored such as the I-V curve obtained by a PV curve tracer. This information is recorded in the FIGURES table, which includes hyperlinks to files (FILE), the type of graphic information (TYPE OF FIGURE), and its quality (FIGURE QUALITY). The type of figure is also related to the TYPE OF FIGURE auxiliary table. Figure quality is especially pertinent in the case of thermographs and consists of a one-digit code with the same description as is found in the previously described QUALITY auxiliary table.

As shown in **Figure 7**, pictures, thermographs, and I-V curves are spatially referenced and associated with each module. This is extremely useful as it means graphic information can be spatially related to the measured attributes in each panel. Furthermore, all graphic information is available both from the geo-database and through the GIS map.

Inspection entails the characterization of the performance of a PV module by measurement of its I-V curve within normal working conditions and its extrapolation to standardized standard test conditions (STC) conditions (cell temperature of 25°C, incident global irradiance of 1000 W/m^2, and air mass of 1.5).

There must be absolutely no shadow on the PV modules during this process, as it can cause irregular thermal areas leading to a misinterpretation of the results. Furthermore, windy conditions should be avoided as thermal exchange by convection may also cause a diffuse thermal image.

The most favorable conditions for taking quality, representative thermal images is when the panel is working at maximum power, which generally occurs at noon with clear sky conditions [30]. This means that thermographs should be taken only when there is a minimum of 700 W/m^2 of

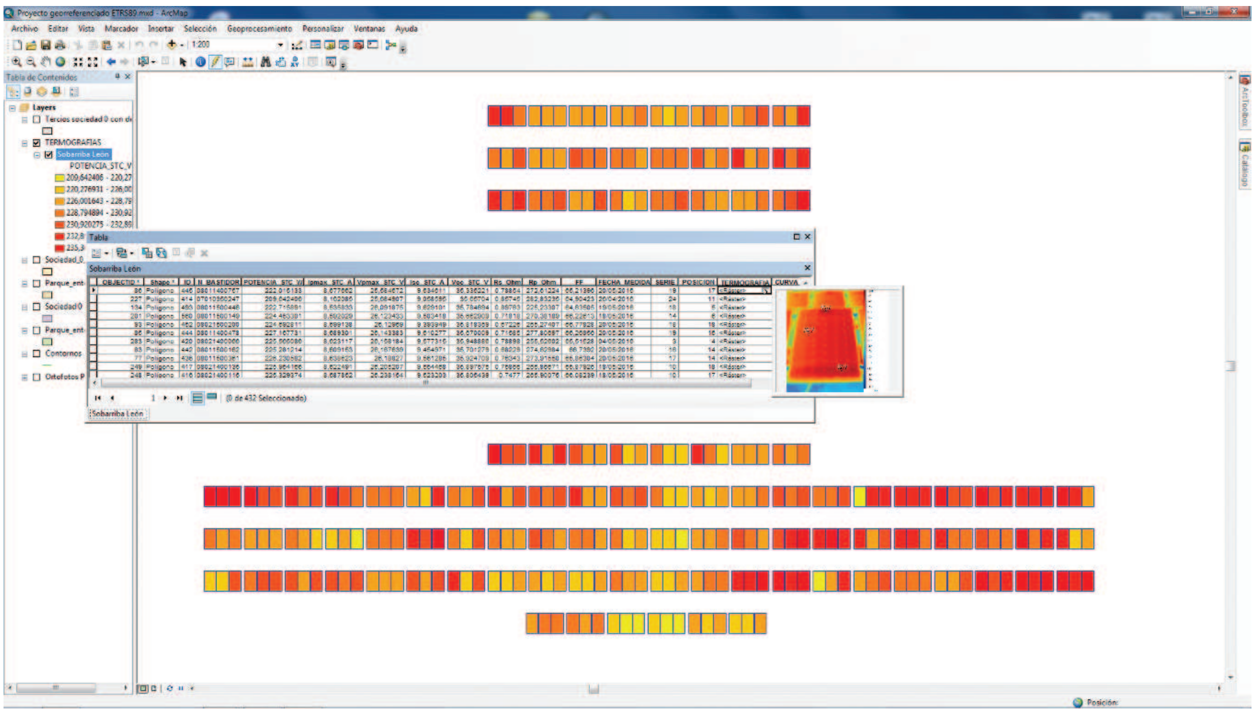

Figure 7. Instantaneous access to a PV module frontal thermography.

global irradiance on the horizontal surface. Furthermore, frontal and rear thermographs should be taken in order to minimize interference on the measurements due to reflections from the front of the PV module. However, special care needs to be taken when using rear thermographs for corrections, as temperatures may be higher due to a lack of thermal dissipation when compared to the front part [31].

Once the electrical measurements, fault detection, and graphic information have been obtained, all data can be compiled into a complete project constituting a GIS.

4. Examples

The GIS tool was applied to two case studies in Spain. The first was a fixed 108 kW peak power PV plant connected to the grid, which has been operating since mid-2008. The second was a fixed domestic 9 kW peak power PV plant installed on the rooftop of a family home. This installation has been in operation since the beginning of 2017.

4.1. Geographic information system applied to a 108 kWp PV power plant

The first case study is a commercial plant with 100 kW nominal power on the inverters and 108 kW peak power on the PV modules, operated by the Spanish company Sobarriba Leon 0. The PV modules are installed on fixed structures, pointing south, and inclined at 28 degrees to the horizontal. The PV field consists of 432 GFM 220-250 monocrystalline 250 Wp silicon modules manufactured by Wuxi Guofei Green Energy Source Co. Ltd. They are organized in 24 strings with 18 modules on each string. There are six electrical protection boxes for the strings in total. **Figure 8** shows all electrical parameters for each PV module, while **Figure 9** shows the PV faults log.

The effective application of the GIS tool allows the observation of all electrical parameters in a holistic way. As shown in **Figure 8(a)**, critical peak power performances can be easily detected among more than 400 PV modules. Other electrical parameters, such as fill factor, open circuit voltage, or short circuit current dispersion, can also be observed in the context of the facilities.

4.2. Geographic information system applied to a 9 kWp PV power plant

This is a home PV power plant operated by Himalaya Sol, a Spanish company. It consists of a fixed 9 kW peak power plant on the roof of a family home. It began operating in February 2017 and is made up of 36 GFM 220-250 monocrystalline silicon modules manufactured by Wuxi Guofei Green Energy Source Co. Ltd. The modules are fixed with a tilt of 32 degrees oriented to 6 degrees east and have a peak power of 250 W per unit. A P300 optimizer from Solar Edge is used to optimize power output given that the installation is affected by shadows due to the architectural configuration. The PV modules are arranged in 3 serial strings of 13, 13, and 10 modules, respectively.

Figure 10 shows all electrical parameters for each PV module, while **Figure 11** shows the PV faults log.

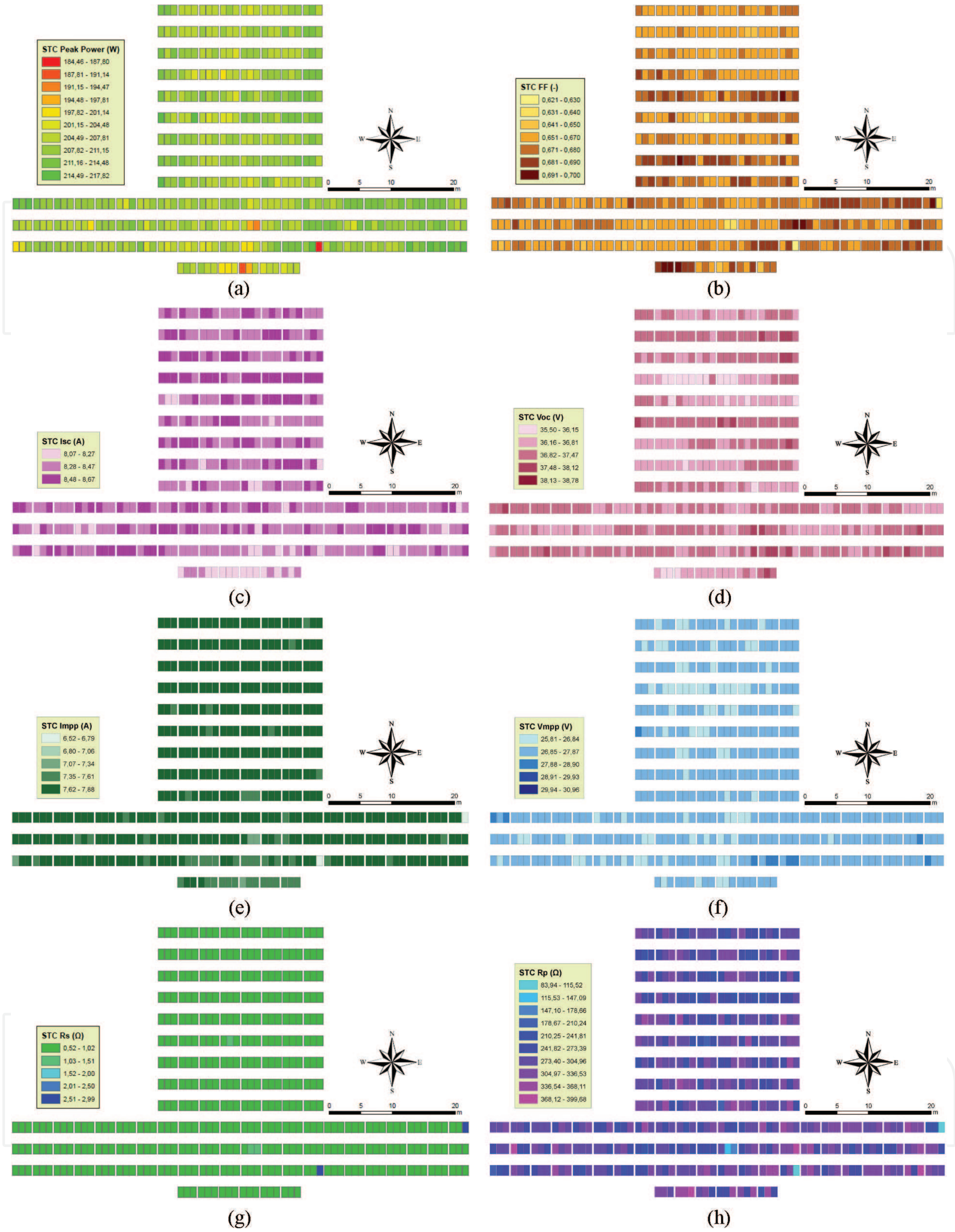

Figure 8. Electrical parameter distributions: (a) STC peak power, (b) STC fill factor (c) max. power voltage, (d) max. power current, (e) open circuit voltage, (f) short circuit current, (g) serial resistance, (h) parallel resistance (108 kWp PV plant).

Once again, it is considerably easier for staff to supervise and monitor the PV plant state. However, distribution of electrical parameters may be less significant as only 36 PV panels are included in this installation.

Results for the GIS implementation in the 9 kWp home power plant do not have much relevance as of the moment. Due to the fact that the installation only recently started working,

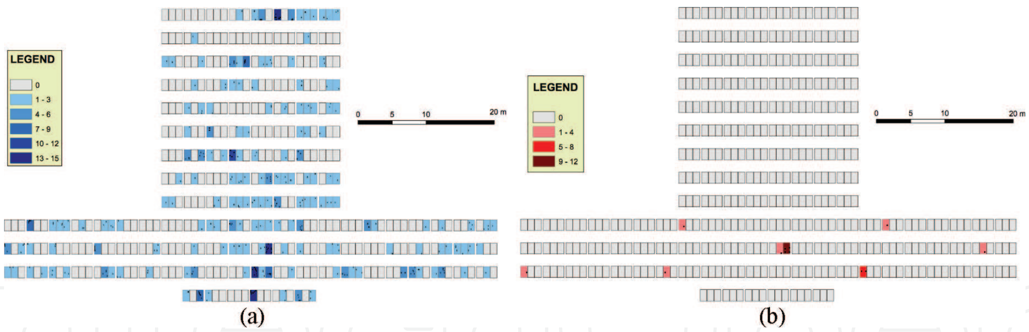

Figure 9. PV faults and defects in the 108 kWp PV plant: (a) snail tracks (b) hot spots and burn marks.

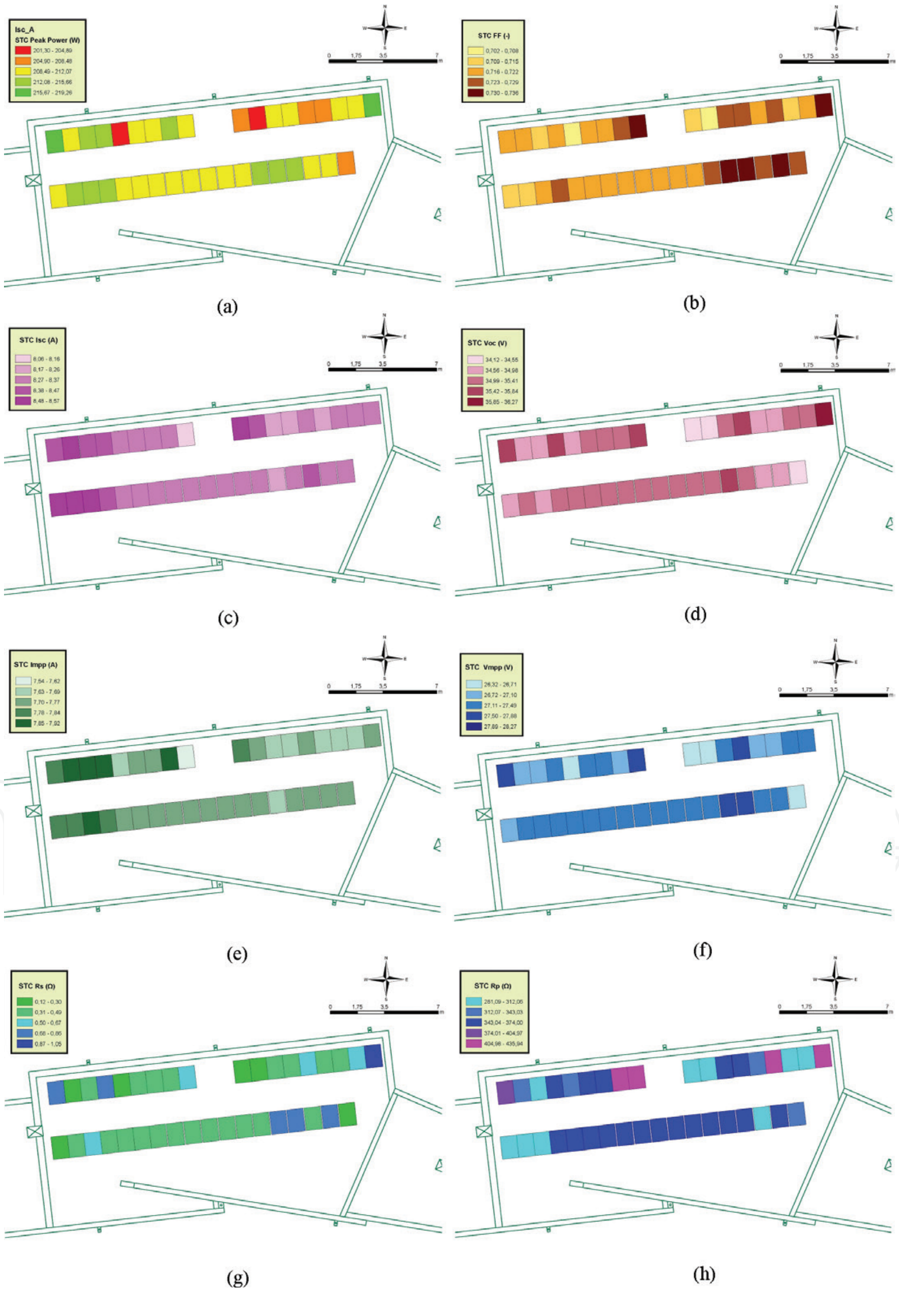

Figure 10. Electrical parameter distributions: (a) STC peak power, (b) STC fill factor (c) max. power voltage, (d) max. power current, (e) open circuit voltage, (f) short circuit current, (g) serial resistance, (h) parallel resistance (9 kWp PV plant).

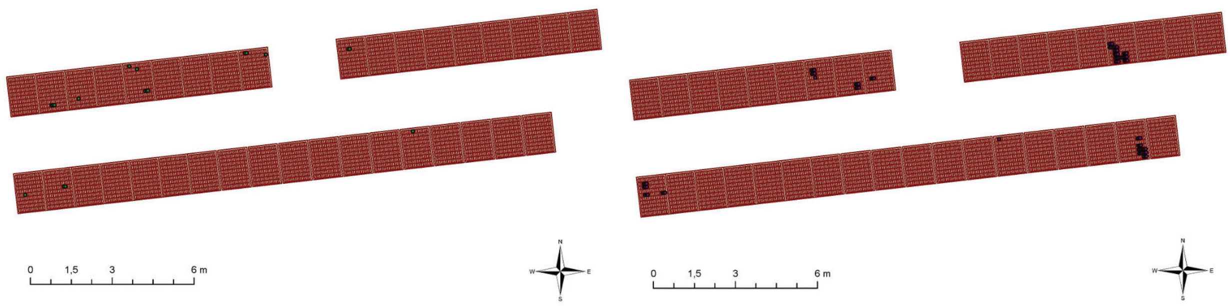

Figure 11. PV faults and defects in the 9 kWp PV plant: (a) snail tracks (b) cell discolorations.

almost no degradation has yet been observed. However, **Figure 11(a)** and **(b)** show some snail tracks and cell discoloration that might lead to the modules needing future maintenance. The distribution of these defects does not appear homogeneous and seems to be concentrated at string series extremes.

5. Conclusions

The GIS tool presented here has shown itself to be of great use when analyzing degradation effects on a PV field, the location of the most common PV defects, and their overall correlation with the plant. Although useful information was found in both case studies, the application of GIS to large plants seems to be more viable than for small installations.

The GIS tool is extremely useful for supervising the degradation of electrical parameters in a power plant and the evolution and distribution of defects in a PV field. Researchers and maintainers are encouraged to use it on their installations and compare results. We will continue to add periodical measurements and inspections to the geo-database and the real degradation effects of the PV field will then be completely analyzed. Such analysis will lead to more economical and effective maintenance and replacement strategies.

A systematic organization and analysis of measurements thanks to the implementation of GIS applications not only allows preliminary preventive maintenance actions to be carried out, such as replacing damaged PV modules, redistributing PV modules according to their performance, and developing specific supervision, cleaning, and maintenance procedures for modules affected by PV faults, but also makes feasible the supervision of the degradation of electrical parameters in the power plant and the evolution and distribution of defects in the PV field.

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Conflict of interest

The authors affirm that there are no conflicts of interest with regard to this research.

Author details

Miguel de Simón-Martín*, Ana-María Diez-Suárez, Laura-Álvarez de Prado, Alberto González-Martínez, Álvaro de la Puente-Gil and Jorge Blanes-Peiró

*Address all correspondence to: miguel.simon@unileon.es

Mines Engineering School, University of León, León, Spain

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