

Article

# A Relational Conceptual Model in GIS for the Management of Photovoltaic Systems

Fabio Piccinini \*, Roberto Pierdicca and Eva Savina Malinverni

Dipartimento di Ingegneria Civile Edile e dell'Architettura, Università Politecnica delle Marche, 60131 Ancona, Italy; r.pierdicca@staff.univpm.it (R.P.); e.s.malinverni@staff.univpm.it (E.S.M.)

\* Correspondence: f.piccinini@pm.univpm.it

Received: 31 March 2020; Accepted: 27 May 2020; Published: 3 June 2020



**Abstract:** The aim of this manuscript is to define an operational pipeline of work, from data acquisition to the report creation, for the smart management of PV plants. To achieve such an ambitious result, we exploit the implementation of a conceptual model, deployed through a relational database to retrieve any kind of information related to the PV plant. The motivation that drove this research is due to the increasing construction of PV plants. In fact, following European and international investments that heavily stimulated the use of clean energy, the need to maintain PV plants in their maximum efficiency for their whole lifecycle emerged, to bring about benefits from both the ecological and the economic points of view. While the research community focuses on finding new and automatic ways to detect faults automatically, few efforts have been made considering the so-called Operation and Maintenance (O&M). A relational conceptual model may facilitate the management of heterogeneous sources of information, which are common in complex PV plants. The purpose of the present study is to provide companies and insiders with a GIS-based tool to maintain the energy efficiency of a PV plant. Indeed, it is a common practice used by companies dealing with O&M of PV plants to create technical reports about the health status of the plants. This operation, made manually, is very time consuming and error prone. To overcome this latter drawback, this work attempts to encourage the use of GIS in the PV plants O&M, which proves to be efficient to deal with fault management and to assure a good level of energy production. The developed conceptual model, tested on two real case studies, proved to be complete, cost-effective and efficient to be replicated in other existing plants.

**Keywords:** photovoltaics; PV plants; PV faults; GIS; relational data base; operation and maintenance

## 1. Introduction

Renewable energy sources represent the main way to reduce fossil fuel usage and the consequent pollution; therefore, European and worldwide countries had heavily invested for stimulate the use of clean energy. As a result, the photovoltaic sector grew up both in terms of installed plants and energy produced. Following the European directives deriving from the Kyoto protocol, the quantity of energy produced from renewable sources in Italy has undergone, since the early years of 2000, an important increase—mainly due to the implementation of some incentive policies (called “Energy Account”) which have given a generous financial contribution for each kWh of energy generated by photovoltaic (PV) systems. As a consequence, in the last two decades, there was a considerable increase in installed PV power throughout the Italian territory. The Italian Energy Services Manager (Gestore dei Servizi Energetici, GSE, registered office in Viale Maresciallo Pilsudski, 92-00197 Roma) statistical report declares a total production of 22.654 GWh, demonstrating that PV power production represents an important source of energy for the country [1]. With the growing demand for a low consumption economy and thanks to technological advances, the production of PV energy has become one of the most important components in the production of clean and renewable energy [2,3].

Therefore, emerged the need to maintain these plants in their maximum efficiency during their whole lifecycle, to benefit from both the ecologic and the economic point of view [4]. Nevertheless, this work of maintaining the operational status of a PV plant at its best performances is not trivial and requires many efforts, both on-site and office. Although several techniques are nowadays available for the inspection of solar panels (most of them semi-automatic), the management is still based on handywork [5,6]. The operation and maintenance (O&M) of a PV power plant is of extreme importance to guarantee its optimal performance [7]. 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 (e.g., fire risk) and minimize power losses [8–10]. A strong contribution for a more reliable and affordable pipeline of O&M is represented by the adoption of Geographical Information Systems (GIS). A GIS allows a complete breakdown over any information that involves spatio-temporal components. It is well known, in fact, that GIS technology has a wide field of applications in the management of any kind of resource that can be described at geographical scale. Moreover, it represents an essential tool for the decision-making process, when heterogeneous data have to be managed in the same phenomena. As in many other fields—such as urban growth and population [11], Land Cover/Land Use applications [12], Cultural Heritage and Archaeology [13] and many more—GIS features have been widely adopted in the field of energy resources management [14], for instance to locate energy resources or to build a solar atlas. GIS tools can be exploited to analyze the spatial distribution of biomass resources, to optimize the location of biogas power plants [15], or to estimate with high precision the power potential of Concentrated Solar Energy (CSP) power plants [16].

While the research community is mainly focusing on uncovering new ways for the automatic detection of faults in PV plants [17], another important mission is to define a standard (or protocol) to manage the complex amount of information that comes from an active PV plant. Furthermore, in the field of photovoltaic energy, the application of GIS techniques might have an extreme importance, especially in the design, management, and supervision of large PV power plants. Indeed, the information about PV plants is generally not structured, and the owners of such systems need specific reports that provide information about the status of the system itself. In order to reduce these efforts and facilitate management, it is necessary to introduce an information system in the pipeline of PV plants management that is able to collect and organize the whole information about the solar power plants and their inspections results (such as modules total number, their size, number of cells, manufacturers and product names, effective power production, faults, spatio-temporal information, and maintenance operations carried out). As stated, the potential of the utilization of GIS based methodologies in the energy field seems to be of great interest in the near future.

This paper moves towards this direction, and contributes to define a work pipeline from data acquisition to the report creation, and it proposes a “standard” data structure for any system that permits automatic report creation and query; the purpose is to extend the GIS implementation in PV systems management, from the building location optimization, to the operation and maintenance topic as well. This approach is particularly valuable in large plants. Early fault detection avoids power plant performance loss and further damage on the PV plants. It is therefore very important to regularly carry out maintenance on the systems, both from an economic, ecological and safety point of view, as some of these failures can also pose a risk of fire or electric shock [18]. Indeed, it is a common practice used by companies dealing with O&M of PV plants, to create technical reports about the health status of the plants. This operation is, nowadays, made manually; this activity is very time consuming and error prone.

In the field of green energy resources management, the adoption of new strategies to carry out an effective supervision and monitoring in an easy and feasible way is of great interest in the industry. From the literature review, the use of GIS for such purposes emerged as becoming mandatory for the effective administration of PV plants. In fact, 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 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 [19]. Just to mention some related works, in [16] the authors present a GIS based technique to estimate PV production considering the shadowing effect; in another work [20] the GIS potential is exploited to create virtual dynamic maps of a power plant, including georeferenced thermal images. Moreover, other authors have used GIS together with Global Positioning Systems (GPS) and Unmanned Aerial Vehicles (UAV) to propose an efficient inspection and maintenance of PV power plants, where they also developed different functions to perform query and investigations over the effective state of conservation of PV plants [21].

GIS, as is well known, is able to manage different data coming from more sources, and permit to infer information by performing correlation among the same data. In [22], the designed tool has proven to be useful to analyze the effects of faults on a PV field and the most common PV defect locations and correlations. The study highlighted that such correlations are more reliable when applied to a huge PV plant, with respect to smaller ones. It is very interesting to note that the extensive use of GIS to perform forecasting and estimations for the optimization of landscape and urban resources emerged from the literature. For example, in [23], the study demonstrates that is possible to efficiently arrange solar power by understanding the amount of solar radiation, to figure out the land and roof suitability for solar power. The purpose was to achieve the promotion of the aggressive utilization of agricultural land and roofs that have not been used to grasp the efficient land and roofs for PV generation units. In other studies, geographical and morphological variables have been taken into account with the same purpose: identifying suitable locations for the construction of solar farms, as it requires detailed information and accurate planning. To this end, solar radiation [24], urban roofs information [25] and Digital Elevation Models [24] have been used for optimizing the installation of PV plants, considering inclination, orientation, morphology [26–29].

As evidence that GIS is probably a good solution to manage such a complex domain, the EU community have published the PVGIS [30], an open access system for accessing PV information all over Europe, including:

- PV potential for different technologies and configurations of grid connected and standalone systems.
- Solar radiation and temperature, as monthly averages or daily profiles.
- Full time series of hourly values of both solar radiation and PV performance.
- Typical Meteorological Year data for nine climatic variables.
- Maps, by country or region, of solar resource and PV potential ready to print.
- PVMAPS software includes all the estimation models used in PVGIS.

Following these trends, this work aims at stimulating the use of GIS in the PV plants O&M by organizing a Relational Database (DB), capable of collecting any information related to the PV plant itself. This different method, with the addition of spatial information, could bring forward innovative predictive and preventive maintenance systems in the future. This study aims to evaluate the potential of a specifically designed GIS tool in the location of PV faults and the analysis of faults' effects on PV power plants working in real operating conditions. The developed relational model is especially useful for companies dealing with fault management. We can thus summarize the main contributions of this article as:

1. Definition of a standard pipeline for the PV plants O&M within a GIS environment.
2. The definition of a conceptual model, for the management of heterogeneous information in a GIS environment, generalized for any PV Plant.
3. The adoption of an OPEN SOURCE GIS environment for the automatic production of reports, which can have a positive impact for companies dealing with PV plants management.

The reminder of the paper is organized as follows: after the aforementioned introduction section, the background section describes the data acquisition, together with the case studies chosen for this

work. Afterwards, the methodology section describes the conceptual data model, which looks to the management of heterogeneous data directly in GIS environment. The results section is aimed at demonstrating the potential of our approach, reporting specific analyses made to automatically create useful reports for the management of PV Plants. Finally, the main novelties, contributions, and future works are discussed in the last section.

## 2. Background

The creation of a relational database requires a tidy process of data organization, making any information linked to each other with a relational structure. In the case of PV plants, information is both qualitative and quantitative.

To build a database model with a good data connection and organization, and, finally, to test its functionality, data from two photovoltaic plants in Italy were used. The first was installed on the roof of an industrial shed in the province of Cuneo (Plant A) and the second was located in a countryside in the province of Pescara (Plant B). These data have been kindly provided by Solis s.p.a. and Flyengineering s.r.l. in anonymous form in respect of the privacy of the owners of the plants.

In this paragraph, we describe the way in which data have been collected and processed, and the main information that have been linked.

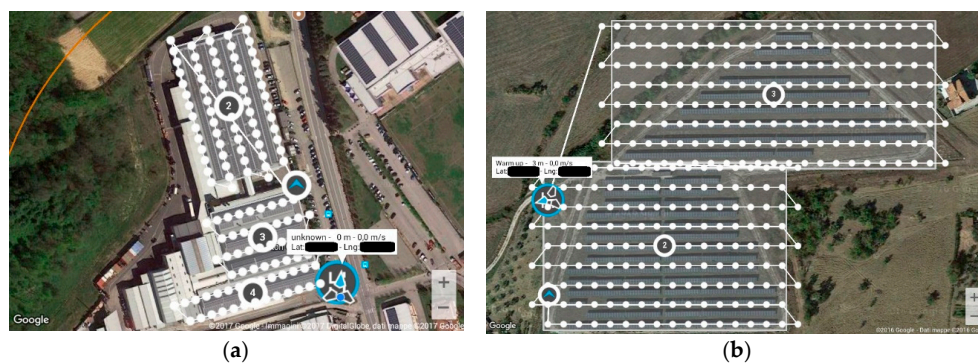
### 2.1. Data Collection

In this section, we describe the data usually collected for the management of PV plants. Once the input data have been properly processed, they are suitable to be managed in a GIS environment according to the proposed data structure. An example of manual report creation is reported in Section 2.2.2, to demonstrate the advantages of the proposed GIS solution.

#### 2.1.1. Aerial Data Collection: Digital Mapping.

Drones, or UAVs (Unmanned Aerial Vehicle), were initially used strictly for military purposes but nowadays, thanks to technological progress over the last 20 years and to their growing affordability, they are widely employed in many civil contexts. In fact, they can perform many tasks, especially depending on the tools that are mounted as payloads [31].

In the case of PV inspection, the use of a drone equipped with a thermal sensor can nowadays acquire the information quickly and especially provide an easy and safe way to check the plant in comparison to the work on the field [32]. In these two case studies, for the execution of the survey an “SR-SF6” has been used. It is a VTOL UAV, produced by Skyrobotic s.p.a., which has a total width of 1.2 m and a weight of 2 kg without payload. It can lift off a maximum total weight of 4.8 kg, and can fly in winds up to 12 m/s with gusts of 16 m/s. This UAV can fly both in manual and in automatic mode, following a flight plan designed and assigned via tablet, using Skyrobotic’s proprietary app, SkyDirector (see Figure 1) [33].



**Figure 1.** The flight plans designed using the SkyDirector app, for the aerial data acquisition. (a) and (b) depict the flight plans used for Plant A and Plant B, respectively.



In both cases, the flight was set at a 50m height from the ground, 40 m from the survey object, with 70% overlap and 60% side lap. The flight plan was then generated by the SkyDirector app according to the optics of the selected payload. To execute a photogrammetric survey to generate an orthophoto of the PV plant, a Sony DSC-QX100 has been used [34]—a digital camera with a resolution of 20 Mpx.

### 2.1.2. Ground Data Collection: Electrical Information.

Other data concerning photovoltaic systems are acquired from the ground in more traditional ways. This is the case, for example, with the I–V curve (current–voltage characteristic curve) tests, which are performed on individual modules or on the modules connected in series in a string. Using a special instrument called an I–V curve tester, current–voltage characteristics are measured under the operating conditions of temperature and irradiance, and corrected to standard test conditions. Afterwards, the final check consists of verifying if the supplied power falls within the tolerance declared by the manufacturer [35].

Another check that is carried out on photovoltaic systems is to calculate the performance ratio in terms of power. This key performance indicator highlights the overall effect of losses on the power generated in alternating current. These losses are due to the incomplete exploitation of solar radiation, the conversion efficiency of the inverter and component failures or inefficiencies [36,37].

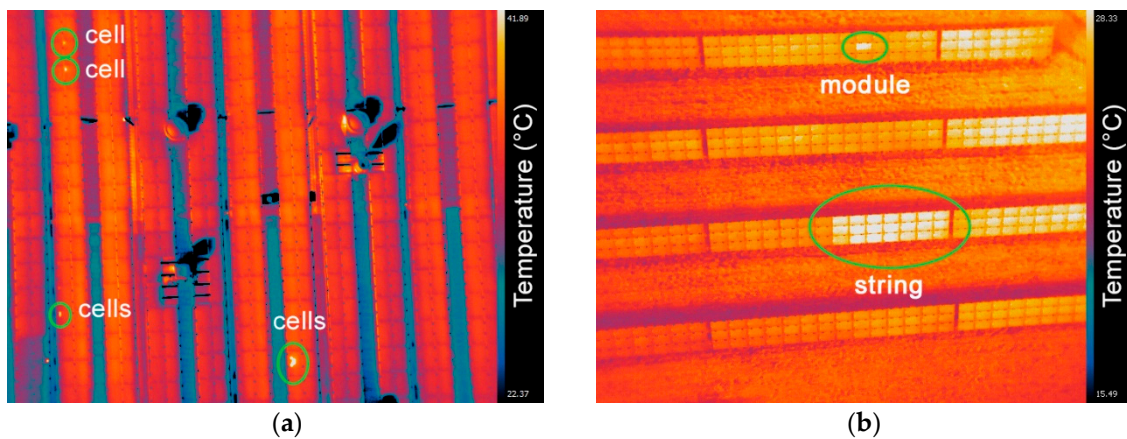
In order to test the database functionalities, the monthly and annual energy production data—which are not in our possession—have been hypothesized. These are usually measured for the entire plant and for individual inverters.

### 2.1.3. Aerial and Ground Thermal Inspection

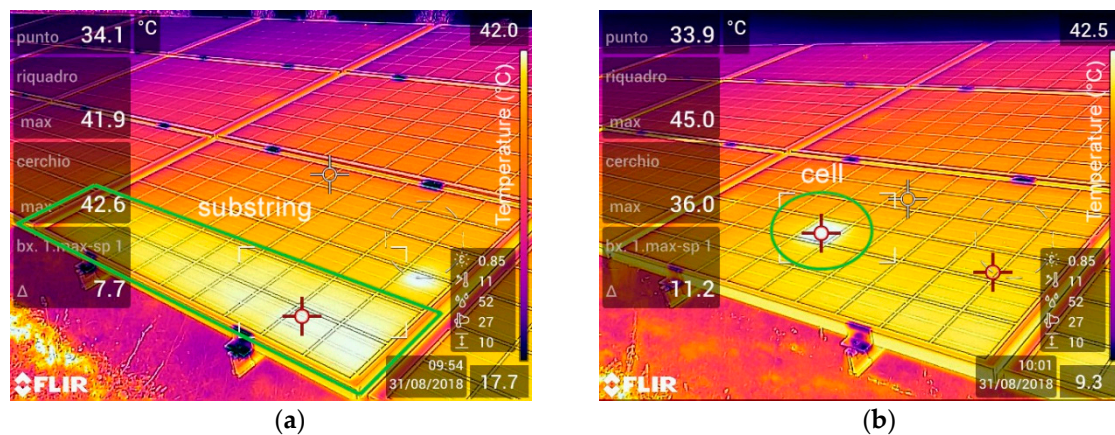
The life span of a photovoltaic system is dependent on that of its components. While the modules in the worst case give good performance for about 20 years with a common 0.5% annual degradation, unless they have critical issues, the lifetime of the inverters can vary widely depending on the climate of the installation site [3,38]. The major cause of damage to the inverters is the too-high temperature to which they are subjected in the absence of a good cooling system. For the modules, the main factors of performance loss are instead: light induced degradation, solder fatigue failure, silver grid finger delamination, bypass diode failure, delamination, cell cracks, corrosion, polymeric discoloration, ultraviolet degradation of the cell, polymeric mechanical failure, and potential induced degradation [39].

The aerial thermal inspections operations are usually performed by capturing infrared and visible images of the plants from drones in order to find and locate the overheated components compared to others of the same type. Overheating means that the component is broken or at least not working properly [31,32]. This information is fundamental to be included in a management system, to provide the producer with an agile tool to manage O&M procedure. For the first case study (Plant A), aerial thermal images have been collected with the same drone mentioned above, using a Flir Tau 2 640 thermal camera, with a resolution of  $640 \times 512$  pixels and a focal length of 13 mm [40]. It is recommended, for a good thermal inspection, to avoid the time periods in which parts of the system are shadowed. The best timeframe is usually at noon, when the PV plant is at the maximum power production conditions, if the sky is clear. Instead, for the second case study (Plant B), a Flir E75 [41] has been used from the ground to inspect individual modules that have shown abnormal overheating, or switchboards and inverters, more closely.

Figures 2 and 3 show data acquired from aerial and terrestrial thermal inspections, with visible examples of overheated components.



**Figure 2.** Thermal images collected from UAV. (a) Example of overheated cells, also called a hotspot, (Plant A), and (b) an example of an overheated module and string (Plant B).



**Figure 3.** Thermal images collected from ground level showing overheated elements (Plant B). (a) is an example of overheated substring probably due to a bypass diode fault, and (b) is an example of overheated cell, also called a hotspot.

## 2.2. Data Processing and Output

In this section, the typical workflow that is performed by the PV managers will be described. Indeed, after the acquisition of data, they have to be performed and organized to achieve a final report which comprises all the information described so far.

### 2.2.1. Plan and Orthophoto of the PV Plant

Firstly, an orthophoto of the PV plant was needed, so the photos acquired by the digital camera have been processed with an MVS (Multi-View Stereo) software.

The resulting orthophoto (Figure 4) was then imported into a CAD software in order to draw a scheme of the PV plant and define an identification system for the modules.



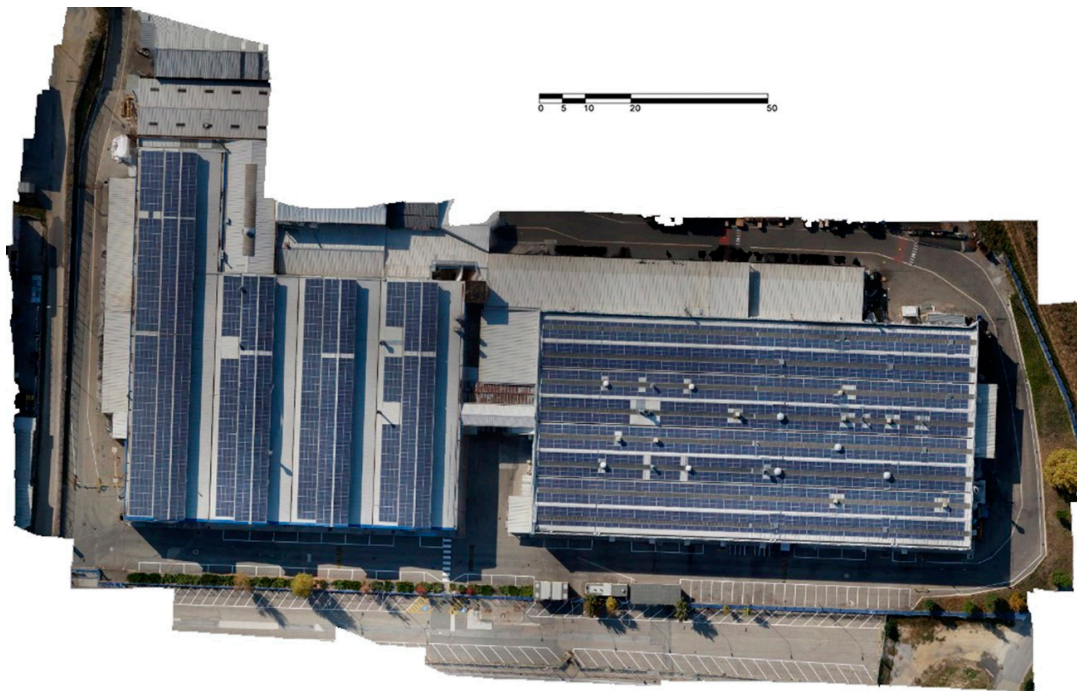


Figure 4. Orthophoto of the PV plant (Plant A).

### 2.2.2. Overheated Components Detection and Report Production

The thermal photos captured with the Flir Tau 2 640 are saved in “TMC” format. These files are readable by ThermoViewer that allows viewing the images in false colors, choosing among different color scales and configuring minimum and maximum temperatures to show [42,43]. Nevertheless, it takes an enormous amount of time and effort for the report production. In fact, in order to redact a classic inspection report, an expert technician must analyze the thermal images in sequence to identify the overheated components, using the flight plan as a help to understand which part of the plant is shown. Every overheated module, string and field must be noted on a map (Figure 5) and listed on a table, with an identification system and the indication of the thermal images in which they are visible.

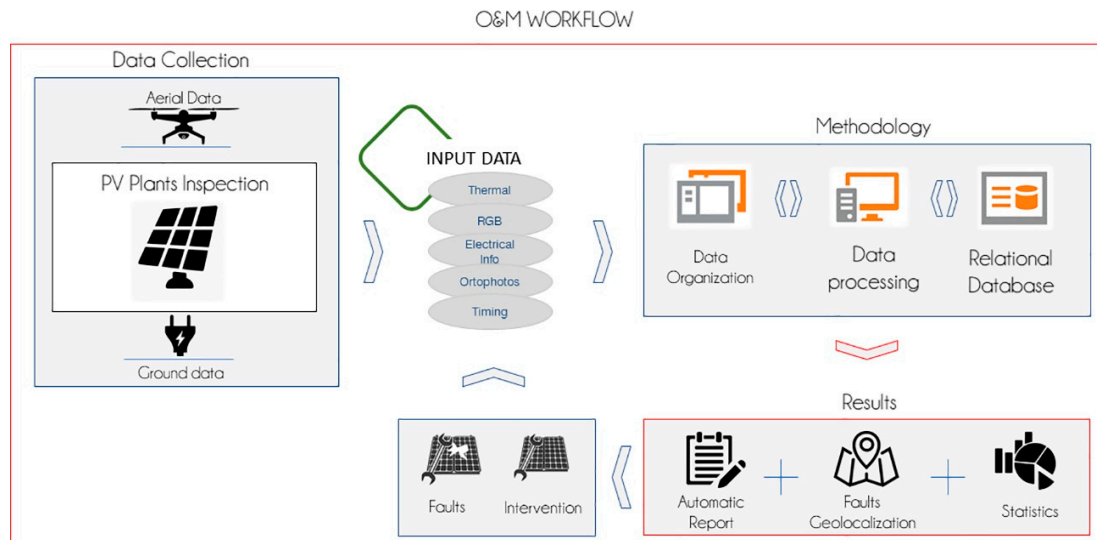


Figure 5. General plan of a portion of the second case study (Plant B), manually created by expert operator.

### 3. Methodology

In this section, the “conceptual model” developed will be described, which follows a data structure proposed for the management of PV plants; all data can be stored, allowing us to query and to generate automatic reports, overcoming the limitation of the procedure described in Section 2.2. An open source GIS, Quantum GIS (QGIS) [44], was used for this work.

The whole methodology described in the manuscript is summarized in Figure 6.



**Figure 6.** Workflow of the methodology adopted for the O&M in PV plants. The pipeline starts with the data acquisition from aerial and ground sources; such data are the input managed within the GIS solution, following the relational conceptual model. As a result, the user can extract all the information for a more efficient O&M. O&M is seamless, as data can be constantly updated.

#### 3.1. Main Components of a Photovoltaic Plant

A brief description of the main components of a PV Plant is worthwhile since, depending on the type of PV system, some specific components may be present or not; the main components, that are always present in photovoltaic systems, are listed and described in hierarchical order below.

- Cells are the fundamental elements of the modules; the main function is to convert the energy of solar radiation into electrical energy, in the form of direct electric current.
- Substrings are formed by cells electrically connected in series, in such a number as to reach the designed output voltage from the module.
- Modules are the basic products which compose a PV system. They consist of identical substrings electrically connected in parallel, in such numbers as to obtain the designed current intensity and nominal power at the output of the module.
- Strings are in turn formed by modules electrically connected in series in a number, chosen by the system designer, to reach the optimal inverters’ working voltage, without exceeding the maximum allowed.
- Arrays are composed of strings, connected in parallel and chosen by the system designer, so as not to exceed the maximum current intensity and power allowed in the inverter input.
- Switchboards are the electrical panels at the main junctions where all the wiring connecting the arrays to the inverters passes through.
- The inverters convert the direct current coming from the photovoltaic arrays into alternating current, allowing its use or distribution. They also have control functions.



This glossary, which does not have the ambition to cover all the terminology related to the PV sector, follows the nomenclature reported in the current European legislation [45]. This relational structure will also be present in the information system that has been developed.

### 3.2. Database Organization and Data Relations

The creation of a management system to be exploited in a GIS involves the creation of a Geodatabase where any information is related to a map; the consequent GIS model allows the managers of the PV plants to identify power losses caused by affected PV modules and to keep track of the overall performance of the power plant. The database implementation correlates the tables containing the previously described data with one-to-many connections in order to cross-reference the data and perform various types of analysis. Many of these tables contain georeferenced geometric vector data, which can be used to perform spatial analyses. In addition, GIS allows you to import geo-referenced raster data as satellite images or orthophotos.

To improve the readability and understanding of the database model, several tables have been grouped according to the different topics of the data stored in them.

The main group is the one about the plants and their components (Figure 7). It includes the tables: “status”, “owners”, “plants”, “inverters”, “switchboards”, “arrays”, “strings” and “modules”.

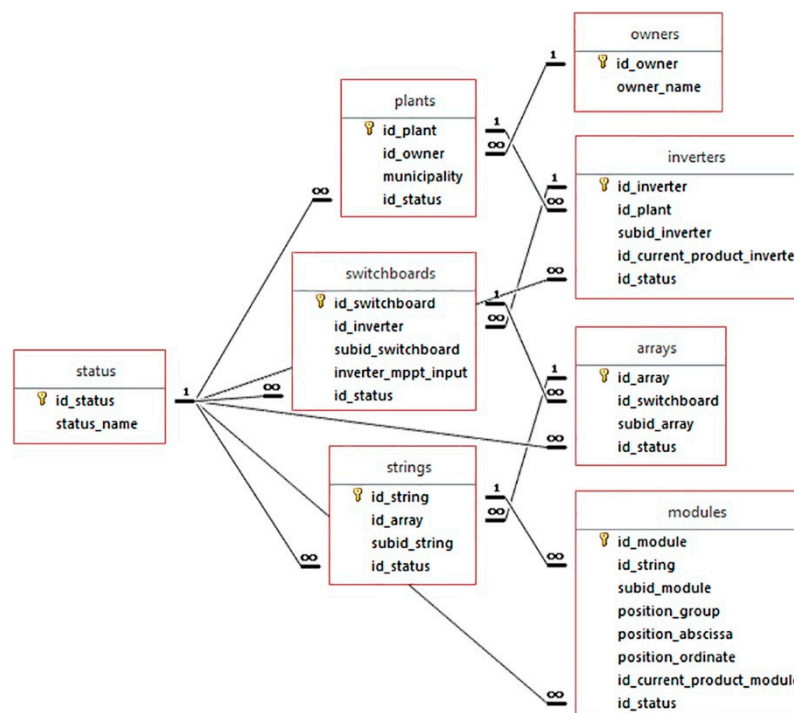


Figure 7. The main group of the conceptual model implemented into the relational database.

The components tables are linked as described above. Every record in these tables has its own unique ID and the ID of the superior element in the hierarchy, which it is linked to. The unique IDs are formed by the union of the superior element’s ID and the sub IDs (different for each component belonging to the same superior element) separated by a dash. In these tables and in the plants table, the “id\_status” field links the records with the “status” table, in order to indicate the status of the element.

The “status” table contains all the possible statuses of the plants and their components, defined by the fields “id\_status” and “status\_name”. For example, these statuses could be “on” or “off”, but others can also be added if necessary.

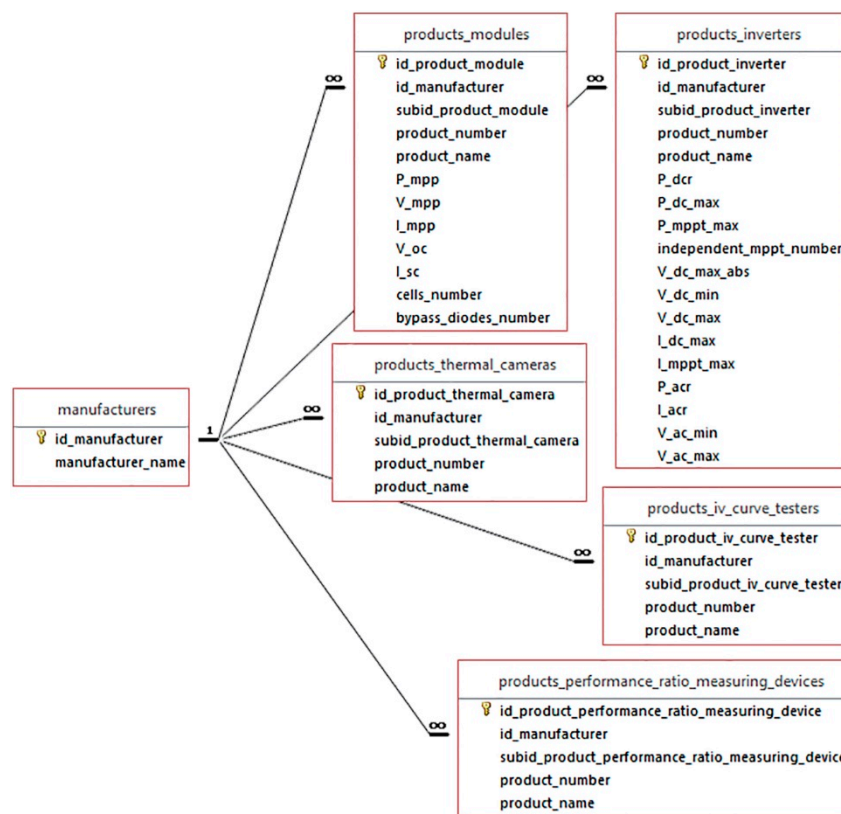
The “owners” table can be useful for plant management companies, in fact it could contain all the data about the various owners who can be linked to their plants inserting their IDs in the plants table.

The “plants” table also contains the “municipality” field to specify the administrative zone where the plant is located.

The “inverters” and “modules” tables include the “id\_current\_product\_inverter” and the “id\_current\_product\_module” fields, to indicate which commercial products of the “products\_inverters” and “products\_modules” tables are currently installed.

The “modules” table also includes the “position\_group”, “position\_abcissa” and “position\_ordinate” fields in order to locate the modules using a custom reference method based on the counting of the modules in the various groups.

The group about the products consists of the “manufacturers”, “product\_inverters”, “product\_modules”, “products\_thermal\_cameras”, “products\_iv\_curve\_testers” and “products\_performance\_ratio\_measuring\_devices” tables (Figure 8). It is useful to keep track of the commercial products that have been used to build the plants and to perform tests and inspections.



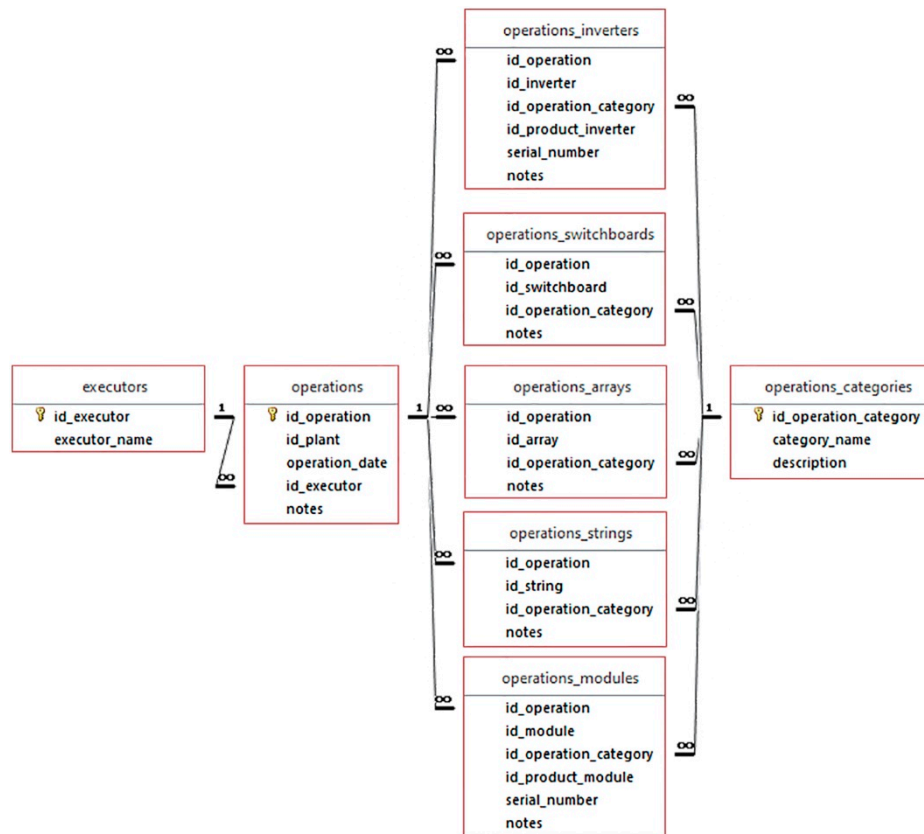
**Figure 8.** The products group of the conceptual model implemented into the relational database.

In the “manufacturers” table each record represents a company that produces components for PV construction, such as inverters or modules, or instruments used to perform tests or inspections on PV plants. It may be expanded with all company references, but, in this example, only the “manufacturer\_id” and “manufacturer\_name” fields are present.

All the product tables contain the commercial products identified by their IDs, formed by the union of the “id\_manufacturer” and their subID (different for each product of the same manufacturer). They also include the fields “product\_number” and “product\_name”.

The “products\_inverters” and “products\_modules” tables also contain the main technical specifications.

The group about the operations is useful to keep track of all the operations performed on the PV plants and their components. It includes the “executors”, “operations\_categories”, “operations”, “operations\_inverters”, “operations\_switchboards”, “operations\_arrays”, “operations\_strings” and “operations\_modules” (Figure 9).



**Figure 9.** The operations group of the conceptual model implemented into the relational database.

The “executors” table is also part of the “aerial thermal inspections”, “terrestrial thermal inspections”, “I-V curve tests” and “performance ratio checks” groups; in fact, each record represents a company executing operations, inspections, tests or checks. It may be expanded with all company references but, in this example, are only present the “id\_executor” and “executor\_name” fields.

The table “operations\_categories” is useful to indicate the various types of operation performed on the plants. It includes the fields “id\_operation\_category”, “category\_name” and “description”.

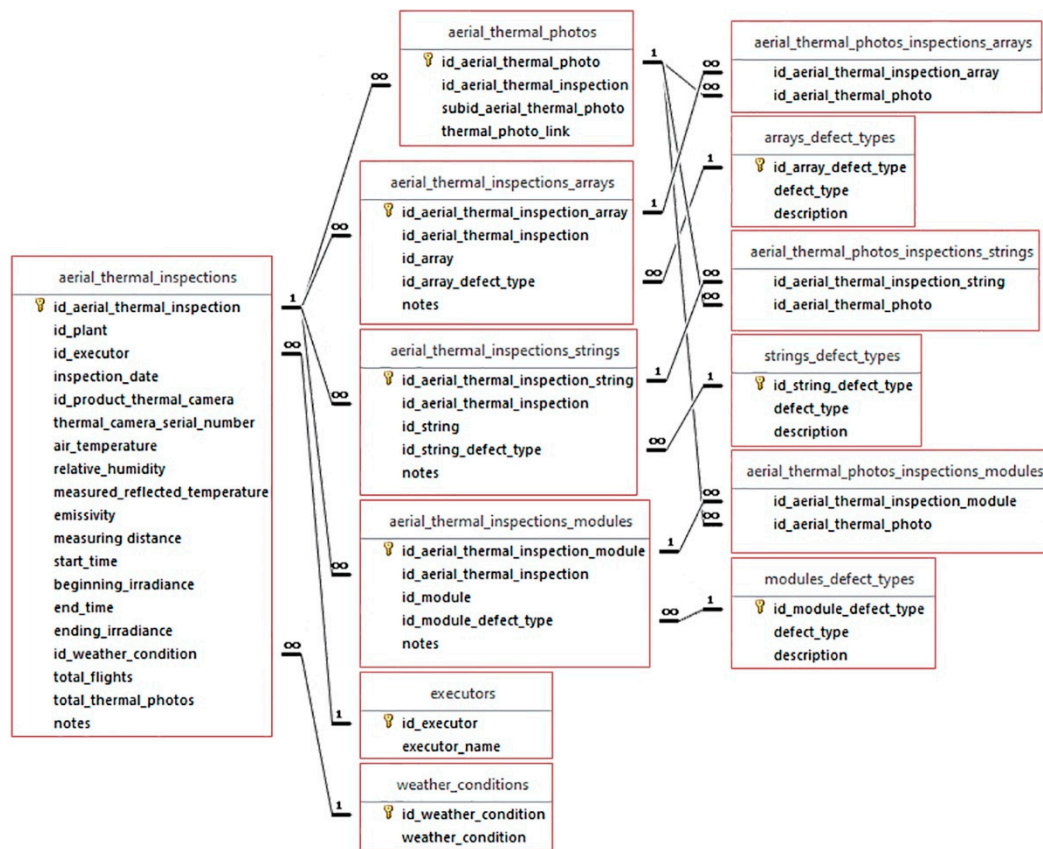
Every operation performed by an executing company on a PV plant is stored in the “operations” table and is defined by the fields “id\_operation”, “id\_plant”, “operation\_date”, “id\_executor” and “notes” (to annotate specific aspects about the operations).

Each record stored in the tables “operations\_inverters”, “operations\_fields”, “operations\_strings” and “operations\_modules” indicates on which components each operation had been performed. These tables include the fields “id\_operation”, the id of the specific component, “id\_operation\_category” and “notes” (to annotate specific aspects about single components in an operation).

The “operations\_inverters” and “operations\_modules” tables also include the “id\_product\_inverter” and “id\_product\_module”, other than the “serial\_number”, field to identify it uniquely.

The group about the aerial thermal inspections includes all the tables needed to store all the data from the aerial thermal inspections, such as “executors”, “weather\_conditions”, “aerial\_thermal\_inspections”, “aerial\_thermal\_photos”, “aerial\_thermal\_inspections\_arrays”, “aerial\_thermal\_photos\_inspections\_arrays”, “arrays\_defect\_types”, “aerial\_thermal\_inspections\_strings”,

“aerial\_thermal\_photos\_inspections\_strings”, “strings\_defect\_types”, “aerial\_thermal\_inspections\_modules”, “aerial\_thermal\_photos\_inspections\_modules” and “modules\_defect\_types” (Figure 10).



**Figure 10.** The aerial thermal inspections group of the conceptual model of the relational database.

The “executors” table is the same described above.

The “weather\_conditions” table contains the standard definitions for weather conditions and is also part of the “terrestrial thermal inspections”, “I-V curve tests” and “performance ratio checks” groups.

The “aerial\_thermal\_inspections” table provides general information about the inspection campaigns, such as the plant on which they are performed, the executor, the inspection date, the thermal camera that was used, the environmental conditions and any notes.

All the links to the thermal photos are stored in the “aerial\_thermal\_photos” table, defined by the fields “id\_aerial\_thermal\_photos”, “id\_aerial\_thermal\_inspection”, “subid\_aerial\_thermal\_photo” and “thermal\_photo\_link”.

Each record in the “aerial\_thermal\_inspections\_arrays”, “thermal\_inspections\_strings” and “thermal\_inspections\_modules” tables indicates if the relative component is totally, partially, or not overheated during an aerial thermal inspection campaign, thanks to the connection to the defect types table of the relative component. They also include the id field (formed by the union of the “id\_aerial\_thermal\_inspection” and the id of the relative component, also present in the tables) and “notes” (to annotate specific aspects about single components in an inspection).

The “aerial\_thermal\_photos\_inspections\_arrays”, “aerial\_thermal\_photos\_inspections\_strings” and “aerial\_thermal\_photos\_inspections\_modules” tables permit to link the results of the single components inspections with the multiple corresponding aerial thermal photos in which they are visible. Each record in these tables contains the two ids of the records to connect from the two tables.



The terrestrial thermal inspections group is similar to the one just described regarding aerial thermal inspections, with the difference that terrestrial thermal inspections are performed on individual modules, switchboards or inverters (Figure 11).

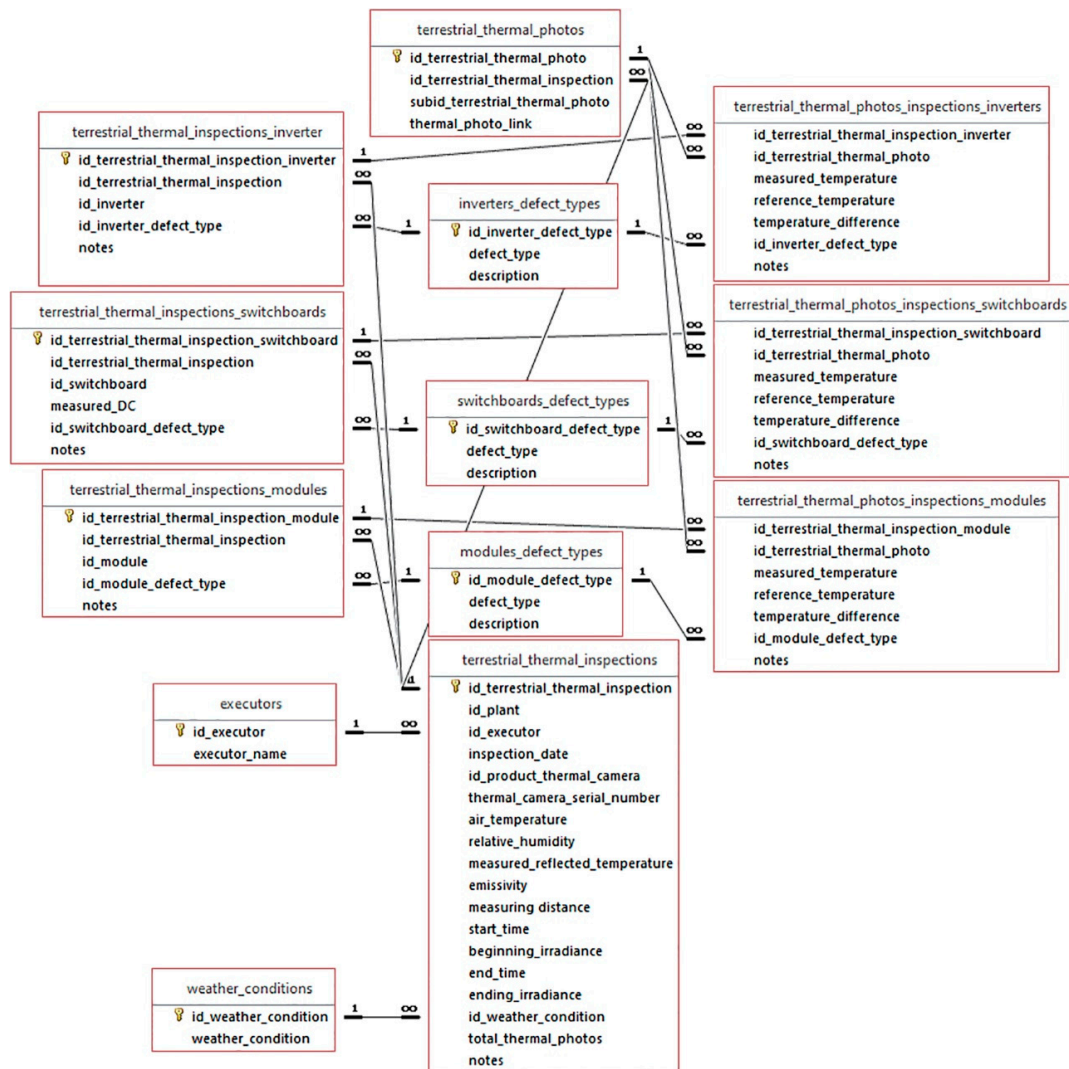


Figure 11. The terrestrial thermal inspections group of the relational database.

In contrast to aerial thermal inspections, thermal photographs of different sub-elements of the same component are acquired in terrestrial inspections.

In particular, in the tables that connect the inspections on the components with the multiple thermal photos of the various sub-elements, the measurements of the maximum temperature of the sub-element, the reference temperature and the temperature difference are stored. In addition, the connection with the defect type tables is also provided so that it can be specified for each photo of each sub-element.

In the “terrestrial\_thermal\_inspections\_switchboards” table there is also the field “measured\_DC” used to specify the direct current intensity measured in the switchboard during the inspection.

The group of the I–V curve tests includes all the tables necessary to contain the data of these tests that can be performed on strings or individual modules (Figure 12).

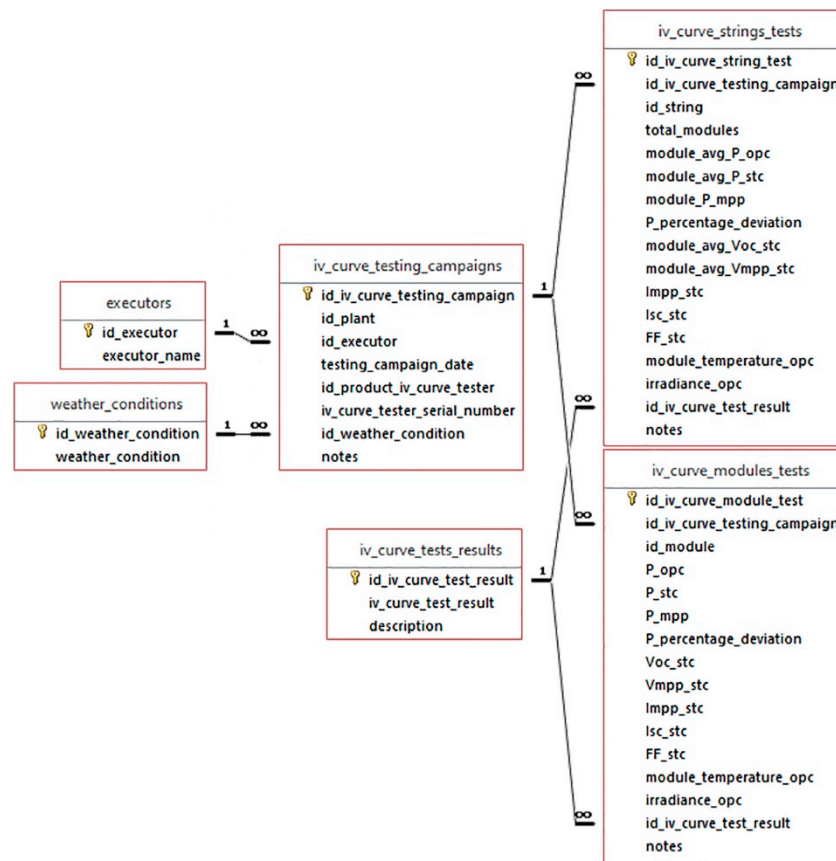


Figure 12. The IV curve tests group of the relational database.

The “executors” and “weather\_conditions” tables are the same described above.

The table “iv\_curve\_testing\_campaign” provides general information about the testing campaign, such as the plant on which it is performed, the executor, the date, the I–V curve tester used and any notes.

In the “iv\_curve\_strings\_tests” and “iv\_curve\_modules\_tests” tables are stored all the electrical measurements performed with the I–V curve tester, in compliance with the regulations [31]. These tables also provide the connection to the “iv\_curve\_tests\_results” table containing the possible results of the I–V curve tests.

The group of the performance ratio checks includes all the tables necessary to contain the data acquired during the checks performed on the inverters (Figure 13).

This group of tables is very similar to the one just described on the I–V curve tests. The only differences relate to the instrument, which is the performance ratio measuring device, and the electrical measurements performed—which are different, since they are in accordance with the regulations for the performance ratio tests [37].

The last group of tables is the one concerning energy production data (Figure 14).

The four tables in this group are able to store data on the energy produced monthly and annually and measured for whole plants and individual inverters. In each table is stored the energy produced, the rated power capacity and the specific energy produced, obtained by dividing the energy produced by the rated power capacity. All the tables of this database are stored in “SQLite” format files.

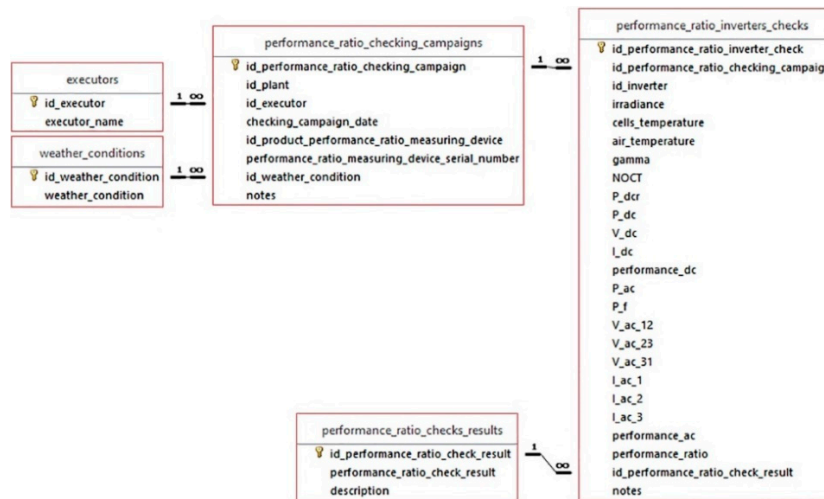


Figure 13. The performance ratio checks group of the relational database.

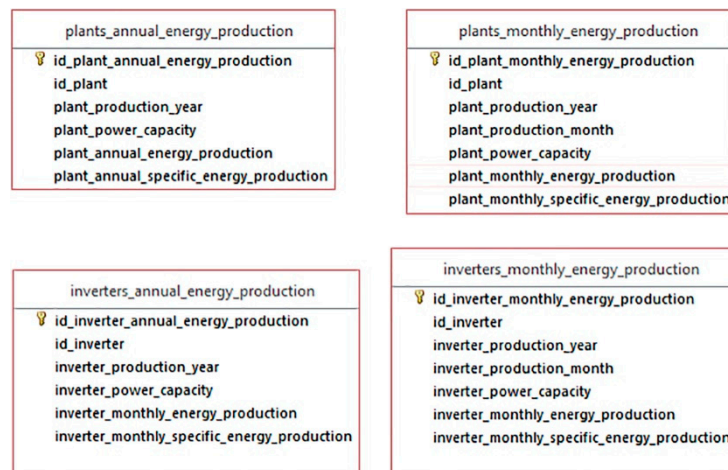


Figure 14. The energy production data group of the relational database.

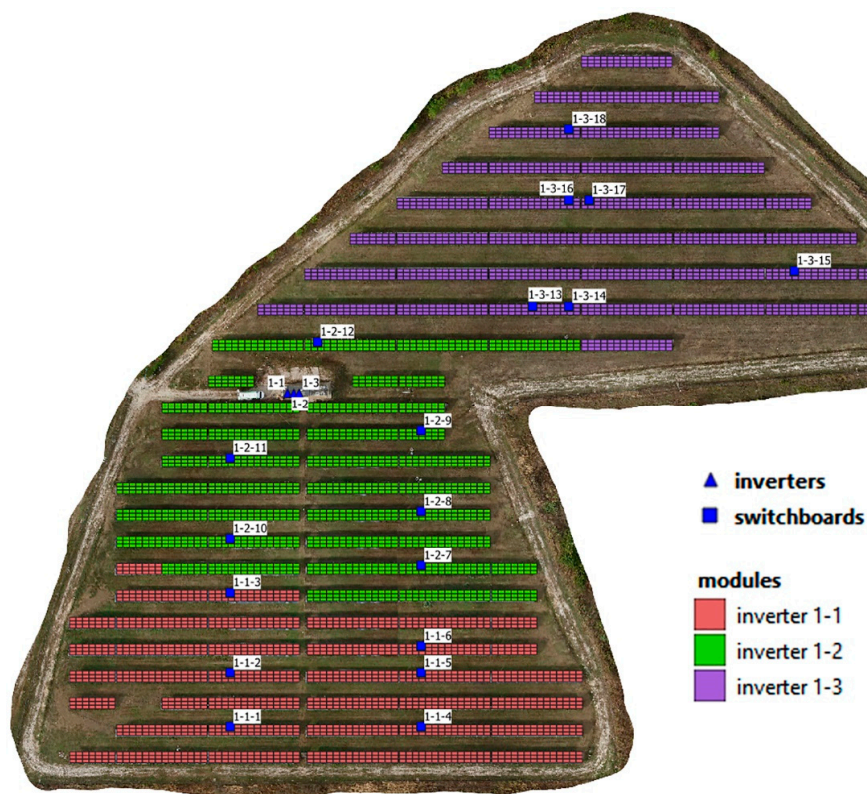
### 3.3. Database Vectorialization and Implementation

If a plant plan in vectorial format is not available, the first phase of building the database is to import the orthophoto of the plant in a CAD software in order to easily retrace and draw the plant’s geometries as closed polylines. Then these polylines have been imported in QGIS as polygons and topological corrected and validated. This process could also have been done directly in QGIS, but the use of CAD tools makes it much faster for regular and repetitive objects such a PV grids.

It is possible to take advantage of the relative positions, especially in case of newly collected data or information, thus incrementally populating the database. When a new inspection or test is performed, the involved geometries can be copied from the main tables.

## 4. Results

Results from the developed GIS-based system lie in the possibility of creating a complete, customizable and interactive map of photovoltaic systems, such as the one in Figure 15, that illustrates the positions of the inverters and switchboards and indicates which inverter the modules are connected to using different colors (Plant B).



**Figure 15.** The customized map of a PV system that illustrates the positions of the inverters and switchboards and indicates which inverter the modules are connected to using different colors. (Plant B).

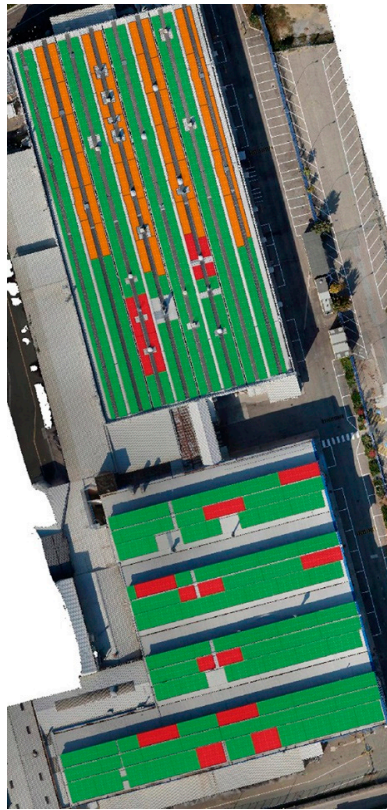
For the PV inspection, the thermal images have been collected according to the maintenance plans. The developed database archives the delivery inspection campaigns. It has been applied with success on the previously cited PV plant on the rooftop of an industrial building, in the province of Cuneo (Italy) (Plant A), proving that it can be easily queried, filtered and themed as desired, to represent the needed information in the best possible way. For example, to highlight overheated components resulting from a thermal inspection, as shown in Figure 16.

From the performed inspection (Plant A) it was found that the fault modules were 915 out of the 3156 installed overall—i.e., 28.99%—and in many cases, there were entire malfunctioning strings or arrays.

In QGIS, for selecting the necessary information from time to time, thematic reports could be drafted. A personalized report page could be generated for each selected geometry belonging to a specific layer, such as the ones from the inspection results, using the “atlas” function. Figure 17 shows a report generated by selecting the features in the “thermal\_inspections\_strings” table which are labeled as entirely overheated, through the “id\_string\_defect\_type” field, and generating an “atlas” page with: a map zoomed in to the specific geometry which the page is dedicated, and general orthophoto of the PV plant with the objective feature highlighted (Plant A). It could be easily personalized with all the useful information required from the database.

In this other example of map customization in Figure 18a, the spatial distribution of the results of the I–V curve tests, performed on the strings, is shown (Plant B). To generate this map, the features of the “iv\_curve\_strings\_tests” layer were colored by applying a green gradient, depending on the values contained in the “P\_percentage\_deviation” field, assigning a more intense green to the strings that passed the test better. In this case, all the strings had passed the test, otherwise the same could have been done with a red gradient to identify which strings had failed the test more severely than the others. Note that there are no I–V curve tests for strings that are not displayed.





**Figure 16.** The themed map of a PV system to highlight totally overheated strings (in red) and totally overheated arrays (in orange). (Plant A).

id\_thermal inspection:  
1

id\_string:  
1-18-4

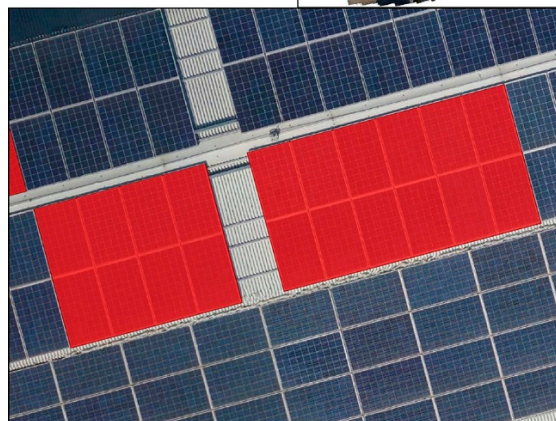
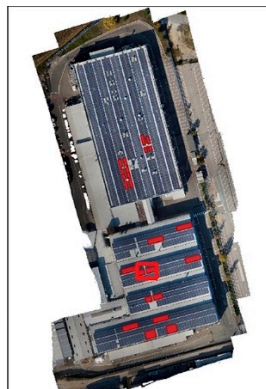
WGS84 UTM32N Coordinates:  
[redacted] m N; [redacted] m E

WGS84 Lat Long Coordinates:  
[redacted] N; [redacted] E

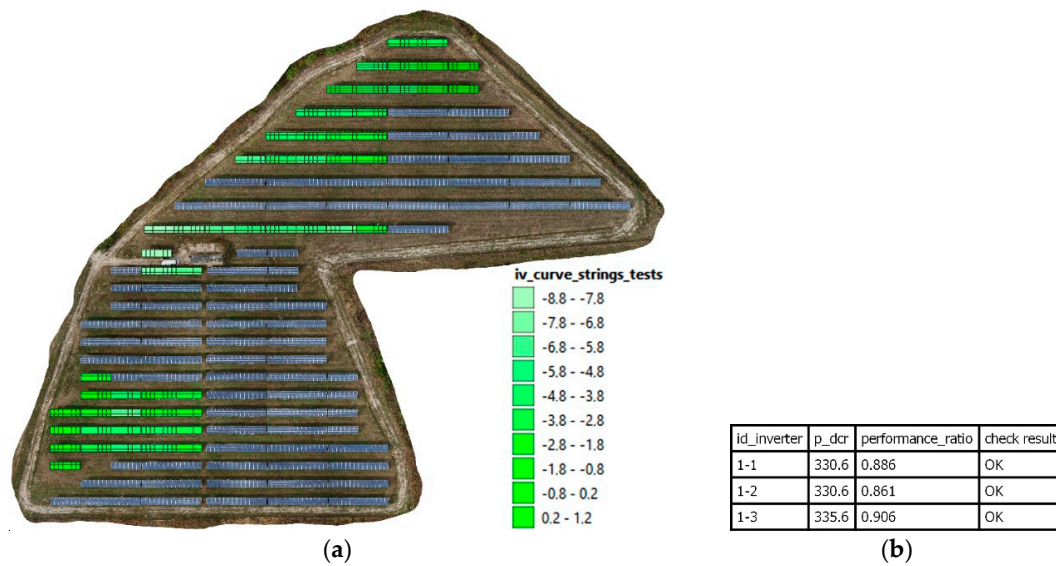
Overheating:  
Totally

Possible Failure:  
string cable damaged or disconnected

Notes:



**Figure 17.** Example of a report page generated using the atlas function of QGIS. (Plant A).



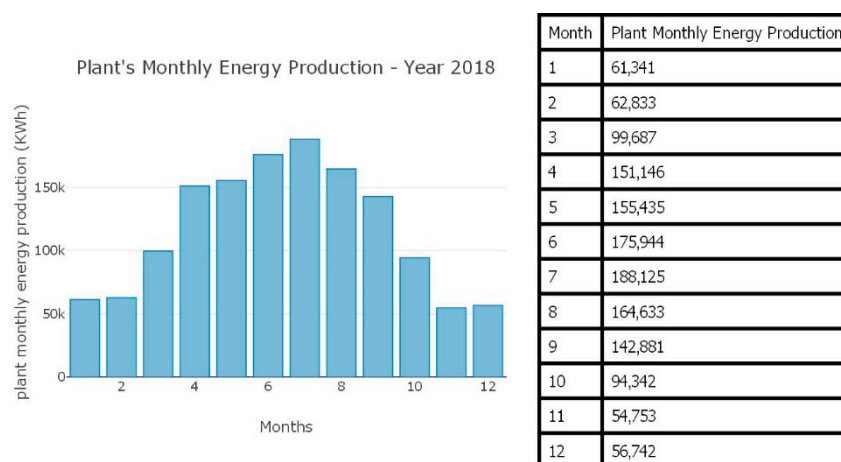
**Figure 18.** (Plant B) (a) The customized map of a PV system to show the results of the I–V curve tests. (b) The table with the results of the performance ratio check.

To create tables and graphs in QGIS report layouts, it is necessary to use the official plugin called “Data Plotly” [46].

In the example in Figure 18b, the data regarding the performance ratio check results (Plant B) have been simply extracted from the GIS in table form.

To generate this table, the “performance\_ratio\_inverters\_checks” layer features containing the “id\_performance\_ratio\_checking\_campaign” of the specific check campaign were selected.

The last example of a report obtainable from the GIS concerns the energy production data of the PV plant. In particular, Figure 19 shows a histogram related to the monthly energy production of the Plant B. This was generated by selecting the features of the “plants\_monthly\_energy\_production” layer with the value of the specific year in the “plant\_production\_year” field, setting the values of the “plant\_production\_month” field as the x-axis, and the values of the “plant\_monthly\_energy\_production” field as the y-axis.



**Figure 19.** The histogram and table with the monthly energy production data (Plant B).

### 5. Discussion and Conclusions

The developed relational conceptual model has potential applicability for the O&M of PV farms, since it facilitates the management of heterogeneous data in a unique database. It thus underpins

several advantages that are worth being discussed. First of all, the solution is open-source, whereas it is current practice to adopt black-box commercial solutions that are not designed to be adapted for every PV plant as our system is. Moreover, the developed relational database is a powerful instrument for PV plant management, thanks to the great possibilities of data analysis and the ease of the production of thematic reports, rather than conducting them manually or with other instruments such as CAD. The use of this maintenance system is especially useful for large power plants, where the management becomes very difficult using traditional methods.

Given that thermal inspections proved to be a very valid method for the health check, the proposed GIS management system will provide a full analysis of the faults evolution through time and space, allowing us to assess the impact of the faulty modules on the undamaged ones. Perhaps it could also help to study new innovative predictive and preventive maintenance systems in the future.

As described in this paper, overheated components detection requires the visual analysis of each individual thermal image by an operator, to manually identify thermal anomalies. However, new automatic fault detection systems, also using neural networks, are under development. This geo-database could be extremely useful to interconnect with these new systems for automatic storage and analysis of all the results provided.

As demonstrated by the two case studies presented, the system is even designed to handle electrical data, allowing us to keep track of the efficiency of the PV plant. By merging all data in a GIS solution, managers can plan maintenance over time. Data are georeferenced, so that there is not the need to re-draw the PV plant, since the information is georeferenced as well.

This study adds to the existing body of knowledge in the field of O&M for PV plants, since it is the first conceptual model proposed in the literature; its structure is publicly available, encouraging other researchers to build new knowledge on top of it.

Given the open source nature of the developed solution, this database model (available as Zip Archive in Supplementary Materials) can be expanded to store other types of data that were not initially planned to be included. For future works, an important task will be to collect more information from different PV plants and to attempt a predictive maintenance approach based on the collected data.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/1996-1073/13/11/2860/s1>, Zip Archive S1: Database conceptual model.

**Author Contributions:** The individual contributions of the single authors can be summarized as follows: Conceptualization and original draft preparation F.P.; methodology, supervision and validation E.S.M.; investigation and project administration R.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Acknowledgments:** The authors would like to thank FlyEngineering s.r.l. and Solis s.p.a. for providing data of the presented case studies.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Agrillo, A.; Surace, V.; Liberatore, P.; Benedetti, L. Solare Fotovoltaico—Rapporto Statistico. 2018. Available online: <https://www.gse.it> (accessed on 15 May 2020).
2. Li, X.; Yang, Q.; Lou, Z.; Yan, W. Deep Learning Based Module Defect Analysis for Large-Scale Photovoltaic Farms. *IEEE Trans. Energy Convers.* **2019**, *34*, 520–529. [[CrossRef](#)]
3. Gorjian, S.; Zadeh, B.N.; Eltrop, L.; Shamshiri, R.R.; Amanlou, Y. Solar photovoltaic power generation in Iran: Development, policies, and barriers. *Renew. Sustain. Energy Rev.* **2019**, *106*, 110–123. [[CrossRef](#)]
4. Ascencio-Vásquez, J.; Kaaya, I.; Brecl, K.; Weiss, K.; Topic, M. Global Climate Data Processing and Mapping of Degradation Mechanisms and Degradation Rates of PV Modules. *Energies* **2019**, *12*, 4749. [[CrossRef](#)]
5. Sharma, V.; Chandel, S.S. Performance and degradation analysis for long term reliability of solar photovoltaic systems: A review. *Renew. Sustain. Energy Rev.* **2013**, *27*, 753–767. [[CrossRef](#)]

6. Tsanakas, J.A.; Ha, L.; Buerhop, C. Faults and infrared thermographic diagnosis in operating c-Si photovoltaic modules: A review of research and future challenges. *Renew. Sustain. Energy Rev.* **2016**, *62*, 695–709. [[CrossRef](#)]
7. Grimaccia, F.; Leva, S.; Dolara, A.; Achaea, M. Survey on PV Modules' Common Faults after an O&M Flight Extensive Campaign over Different Plants in Italy. *IEEE J. Photovolt.* **2017**, *7*, 810–816.
8. Woyte, A.; Goy, S. Large grid-connected photovoltaic power plants: Best practices for the design and operation of large photovoltaic power plants. In *The Performance of Photovoltaic (PV) Systems: Modelling, Measurement and Assessment*; Elsevier Inc.: Amsterdam, The Netherlands, 2017; pp. 321–337.
9. Salient, S.; Chouder, A.; Guerriero, P.; Pavan, A.M.; Mellit, A.; Moeini, R.; Tricoli, P. Monitoring, diagnosis, and power forecasting for photovoltaic fields: A review. *Int. J. Photoenergy* **2017**, *2017*, 1356851.
10. Beránek, V.; Olšan, T.; Libra, M.; Poulek, V.; Sedláček, J.; Dang, M.Q.; Tyukhov, I. New Monitoring System for Photovoltaic Power Plants' Management. *Energies* **2018**, *11*, 2495. [[CrossRef](#)]
11. Bagan, H.; Yamagata, Y. Analysis of urban growth and estimating population density using satellite images of nighttime lights and land-use and population data. *Gisci. Remote Sens.* **2015**, *52*, 765–780. [[CrossRef](#)]
12. Abdullahi, S.; Pradhan, B.; Mansor, S.; Shariff, A.R.M. GIS-based modeling for the spatial measurement and evaluation of mixed land use development for a compact city. *Gisci. Remote Sens.* **2015**, *52*, 18–39. [[CrossRef](#)]
13. Malinverni, E.S.; Pierdicca, R.; Colosi, F.; Orazi, R. Dissemination in archaeology: A GIS-based StoryMap for Chan Chan. *J. Cult. Herit. Manag. Sustain. Dev.* **2019**, *9*, 500–519. [[CrossRef](#)]
14. Resch, B.; Sagl, G.; Törnros, T.; Bachmaier, A.; Eggers, J.B.; Herkel, S.; Narmsara, S.; Gündra, H. GIS-Based Planning and Modeling for Renewable Energy: Challenges and Future Research Avenues. *ISPRS Int. J. Geo-Inf.* **2014**, *3*, 662–692. [[CrossRef](#)]
15. Höhn, J.; Lehtonen, E.; Rasi, S.; Rintala, J. A Geographical Information System (GIS) based methodology for determination of potential biomasses and sites for biogas plants in southern Finland. *Appl. Energy* **2014**, *113*, 1–10. [[CrossRef](#)]
16. Gastli, A.; Charabi, Y. Solar electricity prospects in Oman using GIS-based solar radiation maps. *Renew. Sustain. Energy Rev.* **2010**, *14*, 790–797. [[CrossRef](#)]
17. Pierdicca, R.; Malinverni, E.S.; Piccinini, F.; Paolanti, M.; Felicetti, A.; Zingaretti, P. Deep convolutional neural network for automatic detection of damaged photovoltaic cells. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2018**, *42*, 893–900. [[CrossRef](#)]
18. Falvo, M.C.; Capparella, S. Safety issues in PV systems: Design choices for a secure fault detection and for preventing fire risk. *Case Stud. Fire Saf.* **2015**, *3*, 1–16. [[CrossRef](#)]
19. Kakumoto, Y.; Koyamatsu, Y.; Shiota, A.; Qudaih, Y.; Mitani, Y. Application of Geographic Information System to Power Distribution System Analysis. *Energy Procedia* **2016**, *100*, 360–365. [[CrossRef](#)]
20. de Simón-Martín, M.; Diez-Suárez, A.M.; de Prado, L.Á.; González-Martínez, A.; de la Puente-Gil, Á.; Blanes-Peiró, J. Degradation Monitoring of Photovoltaic Plants: Advanced GIS Applications. In *Solar Panels and Photovoltaic Materials*; IntechOpen: London, UK, 2018; p. 93.
21. de Simón-Martín, M.; Diez-Suárez, A.M.; Álvarez-de Prado, L.; González-Martínez, A.; de la Puente-Gil, Á.; Blanes-Peiró, J. Development of a GIS Tool for High Precision PV Degradation Monitoring and Supervision: Feasibility Analysis in Large and Small PV Plants. *Sustainability* **2017**, *9*, 965. [[CrossRef](#)]
22. Tsanakas, J.A.; Chrysostomou, D.; Botsaris, P.N.; Gasteratos, A. Fault diagnosis of photovoltaic modules through image processing and Canny edge detection on field thermographic measurements. *Int. J. Sustain. Energy* **2015**, *34*, 351–372. [[CrossRef](#)]
23. Shiota, A.; Fuchino, G.; Koyamatsu, Y.; Kakumoto, Y.; Tanoue, K.; Qudaih, Y.; Mitani, Y. Guide Construction of an Efficient Inspection, Maintenance and Asset Management of Photovoltaic Power Generation System Using GIS. *Energy Procedia* **2016**, *100*, 69–77. [[CrossRef](#)]
24. Shiota, A.; Koyamatsu, Y.; Fuji, K.; Mitani, Y.; Qudaih, Y. Development and Public Release of Solar Radiation Map for Effective Use of Solar Energy Based on GIS with Digital Surface Model. *IJOEE* **2015**, *3*, 169–173. [[CrossRef](#)]
25. Brumenm, M.; Lukac, N.; Zalik, B. Gis application for solar potential estimation on buildings roofs. In Proceedings of the IARIA WEB, Rome, Italy, 24–29 May 2015.
26. Verso, A.; Martin, A.; Amador, J.; Dominguez, J. GIS-based method to evaluate the photovoltaic potential in the urban environments: The particular case of Miraflores de la Sierra. *Sol. Energy* **2015**, *117*, 236–245. [[CrossRef](#)]



27. Victoria, M.; Andresen, G.B. Using validated reanalysis data to investigate the impact of the PV system configurations at high penetration levels in European countries. *Prog. Photovolt. Res. Appl.* **2019**, *27*, 576–592. [[CrossRef](#)]
28. Yousefi, H.; Hafeznia, H.; Yousefi-Sahzabi, A. Spatial Site Selection for Solar Power Plants Using a GIS-Based Boolean-Fuzzy Logic Model: A Case Study of Markazi Province, Iran. *Energies* **2018**, *11*, 1648. [[CrossRef](#)]
29. Noorollahi, E.; Fadai, D.; Akbarpour Shirazi, M.; Ghodsipour, S. Land Suitability Analysis for Solar Farms Exploitation Using GIS and Fuzzy Analytic Hierarchy Process (FAHP)—A Case Study of Iran. *Energies* **2016**, *9*, 643. [[CrossRef](#)]
30. Huld, T.; Müller, R.; Gambardella, A. A new solar radiation database for estimating PV performance in Europe and Africa. *Sol. Energy* **2012**, *86*, 1803–1815. [[CrossRef](#)]
31. Grimaccia, F.; Leva, S.; Niccolai, A. PV plant digital mapping for modules' defects detection by unmanned aerial vehicles. *IET Renew. Power Gener.* **2017**, *11*, 1221–1228. [[CrossRef](#)]
32. Xi, Z.; Lou, Z.; Sun, Y.; Li, X.; Yang, Q.; Yan, W. A Vision-Based Inspection Strategy for Large-Scale Photovoltaic Farms Using an Autonomous UAV. In Proceedings of the 17th International Symposium on Distributed Computing and Applications for Business Engineering and Science, DCABES, Wuxi, China, 19–23 October 2018.
33. Skyrobotic SR-SF6. Available online: [http://www.skyrobotic.com/wp-content/uploads/2015/09/Datasheet-SRSF6\\_Skyrobotic.pdf](http://www.skyrobotic.com/wp-content/uploads/2015/09/Datasheet-SRSF6_Skyrobotic.pdf) (accessed on 15 May 2020).
34. Sony QX100. Available online: <https://www.sony.co.uk/electronics/support/compact-cameras-dscqx-series/dsc-qx100/specifications> (accessed on 15 May 2020).
35. International Standard EN 60891. *Photovoltaic Devices. Procedures for Temperature and Irradiance Corrections to Measured I-V Characteristics*; International Electrotechnical Commission (IEC): Geneva, Switzerland, 2010.
36. Italiana, N.; Edizione, D.P.; Fascicolo, C. Regola tecnica di riferimento per la connessione di Utenti attivi e passivi alle reti AT ed MT delle imprese distributrici di energia elettrica C. E. I. 82-25. CEI 0-16, 0-21. 2008. Available online: <https://www.autorita.energia.it/allegati/docs/08/033-08argalla.pdf> (accessed on 15 May 2020).
37. IEC 61724-1 International Standard. Available online: [https://webstore.iec.ch/preview/info\\_iec61724-1%7Bed1.0%7Den.pdf](https://webstore.iec.ch/preview/info_iec61724-1%7Bed1.0%7Den.pdf) (accessed on 15 May 2020).
38. Sangwongwanich, A.; Yang, Y.; Sera, D.; Blaabjerg, F. Lifetime evaluation of grid-connected PV inverters considering panel degradation rates and installation sites. *IEEE Trans. Power Electron.* **2017**, *33*, 1225–1236. [[CrossRef](#)]
39. Lindig, S.; Kaaya, I.; Weiß, K.A.; Moser, D.; Topic, M. Review of statistical and analytical degradation models for photovoltaic modules and systems as well as related improvements. *IEEE J. Photovolt.* **2018**, *8*, 1773–1786. [[CrossRef](#)]
40. Flir Tau 2. Available online: [https://www.flir.com/globalassets/imported-assets/document/tau2\\_product\\_specification.pdf](https://www.flir.com/globalassets/imported-assets/document/tau2_product_specification.pdf) (accessed on 15 May 2020).
41. Flir E75. Available online: <https://flir.netx.net/file/asset/3910/original> (accessed on 15 May 2020).
42. ThermoViewer. Available online: <https://thermalcapture.com/thermoviewer/> (accessed on 15 May 2020).
43. ThermoViewer User Manual. Available online: <https://thermalcapture.com/wp-content/uploads/2018/01/ThermoViewer-UserManual.pdf> (accessed on 15 May 2020).
44. QGIS. Available online: <https://www.qgis.org/>, (accessed on 15 May 2020).
45. Jäger-Waldau, A. *PV Status Report 2019*; EUR 29938 EN; Publications Office of the European Union: Luxembourg, 2019.
46. Data Plotly. Available online: <https://plugins.qgis.org/plugins/DataPlotly/> (accessed on 15 May 2020).

