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Ener3DMap-SolarWeb roofs: A geospatial web-based platform to compute photovoltaic potential

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ABSTRACT

The effective exploitation and management of renewable energies requires knowledge not only of the energy intensity at the exploitation site but also of the influence of the geometry of the site and its surroundings. For this reason, the efficient processing and interpretation of combined geospatial and energy data is a key issue. This paper presents the development of a web-based tool for the automatic computation of photovoltaic potential on rooftops and on parcels without buildings. The tool called Ener3DMap-SolarWeb Roofs is based on Leaflet and supports WMS, GeoJSON, GeoCSV and KML formats, among others. With these data formats, base maps, geometric data from the rooftops automatically computed from LiDAR and imagery data with self-developed processing algorithms, cadastral data and a solar radiation model are integrated in the tool. These different types of data, the high level of automation and the different scales for which energy data is calculated (hourly, monthly and annually) are the main contributions of the presented tool compared to other existing solutions. The capacities of the tool are tested through its application to analyze the solar potential of rooftops with different shapes and for different solar panel configurations. The accuracy of the results is ensured through the integration of a validated methodology for the computation of geometry and a validated solar radiation model, PVGIS.

1. Introduction

A commitment to change the global energy model is a necessary reality in today's world. In fact, the transition from fossil fuel-based systems to renewable alternatives based on sustainable practices has already been initiated in promising ways [1]. To meet global climate targets for reducing greenhouse gas emissions, energy efficiency and sustainability, one of the keys is to avoid energy losses by producing energy close to its consumption [2], i.e., in homes and industries. In this sense, photovoltaic (PV) energy is one of the most versatile and appropriate renewable energies since (i) it can be installed in urban environments directly on building rooftops and in dedicated plots in urban and rural environments [3,4] and (ii) the orientation of the solar panels can be modified to obtain higher energy peaks (South orientation) or more constant production (East-West orientation) [5]. Due to the modular nature of PV panels, they can be directly integrated on buildings, allowing individual or shared self-consumption [6], contributing to electricity cost savings. Even though PV technology has become cheaper in recent years, it has still not expanded as would be expected. One of the main reasons is that citizens and entrepreneurs are unaware of the potential and capability to generate energy from the sun on their buildings or the amortization schedule of such technology [7].

The other reason for the slow incorporation of PV technology in the energy mix is that efficient installation and management of solar energy resources requires a knowledge of the energy potential in different time periods, of the technology and of the economic indices [8]. There are different data sources that facilitate an understanding of the incoming solar radiation on a surface [9], but the design of PV installations requires knowing the solar potential at the installation position, improving the scale [10].

The need for geo-referencing all the data involved makes geographical databases the optimal support for the energy analysis, in a similar approach as that used for land use change and fire assessment [11,12]. Solar analysis has also been performed using geographical databases, with different scales and levels of computation, as reviewed in Ref. [13].

This study develops a web-based tool for the computation of the solar energy potential on building rooftops and on parcels without buildings. The strengths of the tool lie in its high automation level, as the roof geometry is automatically provided without user data input, its online nature, removing the need to install software, and its ease of use. The

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List of abbreviations

2D	2 Dimensions
3D	3 Dimensions
API	Application Programming Interface
DLG	Digital Line Graphic
DOM	Digital Orthophoto Map
DSM	Digital Surface Model
GeoJSON	Geometry Javascript Object Notation
GeoCSV	Geometry Comma-Separated Values
GIS	Geographic Information System
JSON	Javascript Object Notation
KML:	Keyhole Markup Language
LiDAR	Light Detection And Ranging
PNOA	Plan National de Ortofotografía Aérea (Spanish Plan of Aerial Orthophotography)
PHP	Hypertext PreProcessor
PS	Peak Sun
PV	PhotoVoltaic
PVGIS	PhotoVoltaic Geographic Information Model
SDI	Spatial Data Infrastructure
WMS	Web Mapping Service

Units

kWh	kilowatt-hour
kWh/year	kilowatt-hour per year
kB	kilobyte
m^2	square meters
MB	Megabyte
s	seconds
W	Watts

automatic incorporation of geometric data from existing rooftops is achieved with the application of the methodology published in Ref. [14], in which LiDAR data and aerial orthophotographies are processed to compute tilt angle and orientation, useable area and building position (latitude and longitude).

To guarantee the replicability of the methodology developed, the input sources were selected such that they are available in most countries, as explained in Ref. [14]. In the case of geospatial and geometrical data, its applicability was ensured by the use of data sources following the INSPIRE directive [15].

The paper is organized as follows: Section 2 outlines all necessary layers and input data for the design of PV installations on rooftops, as well as the methodology followed to compute geometric roof data from LiDAR data, and the design and implementation of the web tool; Section 3 describes the operation of the web tool; Section 4 presents the validation tests, both experimental and theoretical. Finally, Section 5 summarizes the main conclusions.

1.1. State of the art among the scientific community

The need to understand the process of computing rooftop solar potential has led to the development of different solutions that combine geometry with solar irradiation data. Geographic Information Systems (GIS) have been widely used for the resolution of the renewable energy siting problem, as discussed in publications on offshore and inland wind energy [16,17], geothermal energy [18], hydraulic and marine energies [19,20] and bioenergy [21]. In the particular case of solar energy, several GIS tools have been developed by the scientific community to solve the siting problem for different applications, from solar farms [22, 23] to the integration of solar panels in building envelopes [24–26].

Spatial Data Infrastructures (SDIs) are web-based GIS tools [27]. SDIs can store different types of geospatial data, which can be visualized and queried [28]. Presents the use of an SDI for an analysis of the solar potential in an urban environment. Most tools require user data input to perform a more complex study.

Rooftop data can be computed with different methods [29]. Presents a methodology for the computing solar energy in a city through artificial intelligence and image segmentation techniques [30]. Proposes the automatic detection of buildings from a photogrammetric digital surface model (DSM) and a digital orthophoto map (DOM) with the help of historical digital line graphic (DLG) data [31]. Presents the detection of residential buildings with a combination of neural networks and LiDAR data.

However, the solar energy computation requires not only the detection of each building but also the computation of geometric parameters: height, orientation, tilt angle and useable area. Since none of the methodologies mentioned for rooftop analysis found in literature include this additional step, the methodology presented in Refs. [14] is applied for the generation of data from rooftops automatically, as it is the only one that provides all the information required for the design of a PV system in rooftops, in an automatic way.

1.2. State of the art in solar radiation mapping and computation tools

Scientific developments in solar radiation mathematical modeling and building rooftop geometric modeling have enabled the development of tools (open access or under license) for user design of solar PV installations. However, the level of automation of the existing tools is generally low; most require manual user input of the rooftop geometric data.

One of the most advanced tools is Google SunRoof [32], which allows the user to search for a building in Google Maps and analyze the rooftop's solar potential. However, the tool is only for existing rooftops, works in 2D with satellite imagery and does not consider the variation in solar radiation with height. In addition, the geometric parameters of the roof must be manually input.

Other tools, such as Solmetric and PVSOL, provide numerical values for solar irradiation, but do not generate a map for its visual interpretation. There is also variability in the frequency in which existing tools compute solar data: although some tools compute solar energy hourly, others provide only monthly data. These last tools are consequently limited to use for PV installation design but cannot be used daily to assess the energy consumption and generation once the PV panels have been installed.

Table 1 presents more information about existing tools, but as a summary, existing tools for the computation of solar radiation have one or more of the following limitations: (i) manual input of rooftop geometry; (ii) the solar radiation is computed numerically, and no visual interpretation is provided; and (iii) the frequency of the datum of solar radiation is not enough for the management of the PV installation. Thus, Ener3DMap-Solar Web is generated with the aim at overcoming all the limitation mentioned.

2. Materials and methods

2.1. Materials

Ener3DMap-SolarWeb hosts all the data required for the rooftop PV potential computation characterized by its different nature and format. Indeed, it combines raster, vector and alphanumeric data with different roles, serving as: base-maps, descriptive information about rooftops and PV systems (geometry parameters, performance), key data for querying

Table 1
Characteristics of existing solar computation tools for comparison with ENER3DMAP-Solar Web Tool.

	LOCATION	SCALE	SOLAR POTENTIAL MAPPING	ROOF DATA PROVIDED	AUTOMATION LEVEL	MANUAL PV CUSTOMIZATION	RESULTS	TEMPORAL RESOLUTION OF SOLAR ENERGY PRODUCTION
ENER3DMAP-SOLAR WEB	Spain	Roof	Yes	Area, tilt, orientation, height	High	Yes	Per roof (built and unbuilt): longitude, latitude, orientation, area, tilt angle, panels, annual, monthly, daily or hourly PV production, equivalent hours of sun, climatic zone, cadastral data	Hour, Day, Month or Year
UVEK-GIS	Switzerland	Roof	Yes	No	High	No	Suitability level (low, medium, high and very high) for the use of solar energy + kWh estimation	Year
MAPDWELL	USA & Chile	Roof	No (installed capacity mapping based on the most favorable roof characteristics)	No	Medium	Yes	No. Of panels, PV installed capacity, investment plan, efficiency, yearly PV production and carbon footprint	Year
NYSOLARMAP	New York	Region	No	No	Medium	No	Information about installed capacity by region, investment plan	No data on PV energy production
SUNROOF	USA	Region	No (installed capacity mapping based on the most favorable roof characteristics)	No	Low	No	Maximum useable sunlight per city and year available for PV panels and general statistics on: number of roofs with higher installable power, roof orientations	Year
SUISSEENERGIE.CH	Switzerland	Generic Roof	No	No	Low	Yes	Annual production kWh, part of own consumption, solar current injected into the grid, installation costs, payback period	Month
PVSOL	International	Generic Roof	No	No	Low	Yes	Longitude, latitude, annual global irradiation, annual consumption estimation, best PV configuration	Year
EASY-PV	International	Generic Roof	No	No	Low	Yes	Number of panels, PV installed capacity, investment plan	No data on PV energy production
LGENERGY	International	Roof	No	No	Low	Yes	Number of panels, PV installed capacity	No data on PV energy production

databases and key data for computing the PV production (mainly location, orientation and tilt angles). There are two levels of layers according to their importance in the process: (i) exclusive base layers for which only one can be visible at a time, and (ii) overlays, or layers placed over the base layers to provide key information about the rooftops.

Base layers are included in the tool in order to facilitate the navigation of the user for the location of the rooftop of interest.

The overlays are two: the rooftop geometry layer, and the layer with cadastral data. The first is the core of the tool, since it includes all the information about the rooftops required for the analysis of the incoming solar radiation (height, orientation, tilt angle and useable area). This layer is generated with the procedure proposed in Ref. [14]. The selection of this procedure is justified by the fact of being the only procedure that provides, automatically, all the information needed for the solar analysis.

The layer with cadastral data, is a complementary layer, is not required for the analysis of the solar radiation received on the rooftop. This layer enables the estimation of the electrical consumption in the building, providing an overview of the benefits of installing PV panels on each rooftop.

2.1.1. *Base layers*

Currently, there are a variety of base maps available that can be used as a cartographic base for web mapping. These are maps from different sources, from national mapping agencies or companies to crowd sourcing initiatives [33,34] that have global or national coverage. Specifically, Ener3DMap-SolarWeb hosts three widely used web map data services:

- OpenStreetMap [35]: This collaborative project allows the visualization, creation and editing of vector maps by any user to create a global map that is as complete and current as possible (Fig. 1a).
- Google Maps [36]: This web-mapping service developed by Google offers a wide variety of cartographic resources, from satellite images and maps to 360° panoramic images. It also presents other interesting features, such as planning a route on foot, by car or public

transportation and real-time traffic conditions. Ener3DMap-SolarWeb uses its orthoimagery service (Fig. 1b).
- Spanish Plan for Aerial Orthophotography (PNOA) [37]: This plan contains the most recent orthophotos of the Spanish territory updated and offered by the Spanish Geographic Institute. Among its wide range of geoinformation, its high-resolution orthoimages are implemented in the web tool (Fig. 1c).

The reason for linking two seemingly equal base-maps (Fig. 1b and c) is because Google Maps offers more updated data than PNOA, while PNOA offers true orthoimages instead of the unrectified aerial images of Google Maps. This means that the PNOA base map can support geometric measurements directly, while Google Maps incorporates camera lens distortion in its images, invalidating the map as a reliable geometric information source [38]. In addition, the possibility of visualizing a map (Fig. 1a) or a photorealistic view (Fig. 1b or 1c) is included in order to adapt the tool to the preferences of the users, who can choose each visualization mode to facilitate their orientation in the study area.

2.1.2. Rooftop geometry layer

Rooftop geometry plays a key role in the SolarWeb platform, since it is the basis for computing the solar potential. Rooftop geometry is defined by several parameters that were previously obtained by the methodology presented in Ref. [14], which combines aerial images with LiDAR data and automatically obtains the orientation, tilt angle, height and dimensions of the rooftops. The advantages of using these two data sources together are reported in Ref. [14] and mainly result in increased precision. The output of this methodology is a vector layer (the rooftop geometry layer) with the parameters of orientation, tilt angle, height and useable surface associated to each roof. The vector layer is incorporated into the web tool as an overlay layer in GeoJSON format (Fig. 2a). This format is widely used in web mapping, due to its simplicity, computational lightness, quick visualization and easy data exchange.

2.1.3. Cadastral data

The cartographic database with associated building alphanumeric information which is linked to the web tool belongs to the Spanish Ministry of Finance. Among the building information provided is location, identification code, building use or destination (residential, commercial, etc.), built area, year and quality of the construction, common elements, and a graphic representation of the building (Fig. 2b). This layer is included because it is the only free dataset that provides information about the use of the building. In contrast with the base layers (raster layers), and the rooftop geometry (vector layer), cadastral data is included through a WMS connection. This type of inclusion is selected for two main reasons: (i) space optimization, and (ii) continuous updating of cadastral data in Ener3DMap Solar Web.

From all this information, Ener3DMap-SolarWeb only requires the built area and the use of the building to estimate the electrical consumption of the house or building under study. With this information, the web tool calculates the energy balance of the dwelling and the potential percentage of self-consumed electricity. This information is extracted after a proper query to the administrative database with the building location coordinates.

2.1.4. Solar radiation data

Solar radiation data is not included as a layer in the tool. In this case, due to the proven good performance of the PhotoVoltaic Geographic Information System (PVGIS) database [39], a connection is created between the SolarWeb platform and PVGIS. Specifically, a request is performed in PVGIS from the SolarWeb platform, and the results of the request are visualized in the SolarWeb platform.

PVGIS from the European Commission is a tool of the Energy Efficiency and Renewable Energy Unit of the Joint Research Center that provides solar radiation information. Ener3DMap-SolarWeb uses the PVGIS web service [40] to compute the amount of energy that can be obtained from different types of PV systems. The PVGIS solar radiation model computes the sun's irradiance by integrating the direct and diffuse radiation based on [41]. The direct radiation is modeled per hour as a function of the solar position relative to the position of interest for the computation (that is, the roof position), with computational inputs of extraterrestrial solar radiation, the distance between the Sun and the Earth, and the solar angle [42]. With this input data, the absorption of radiation from the atmosphere is included in the model. For the inclusion of the Sun position in the model, the hourly variation is considered using the position at the middle of each hour (Sun position at 10:30 for the hour between 10 and 11) [43]. The diffuse radiation is modeled based on the scattering caused by clouds as a fraction of the contribution of scattering to the direct radiation.

The radiation at each rooftop location is obtained in PVGIS after an inner query to meteorological data (solar irradiance and weather patterns) from the last 30 years, in such way that all the latest meteorological behavior variability is considered. The most important value in this case is the sky cloudiness, which determines the ratio between direct and diffuse radiation. In addition, the historical data computation allows setting different working ranges, to estimate variations in the real production of the installation in future years.

2.2. Methodology

Ener3DMap-SolarWeb Roofs is a SDI that correctly manages all the data and queries to the databases required to compute rooftop PV energy production, facilitating its use by both expert and novice users. For this reason, the tool development requires two main steps: (i) identification of the rooftop geometry and generation of the rooftop geometry layer; (ii) generation of the SDI, including its interface, the integration of all the data and the development of its functionalities (mainly the rooftop

Fig. 1. Set of base-maps offered by Ener3DMap-SolarWeb Roofs: (a) OpenStreetMap, (b) Google Maps, and (c) PNOA orthophotos.

Fig. 2. (a) Layer with geometric information of existing roofs superimposed on the orthoimage from Google Maps and (b) graphic viewer of the cadastral cartographic database linked to Ener3DMap-SolarWeb Roofs.

selection and the connection with PVGIS).

2.2.1. *Generation of the rooftop geometry layer from LiDAR and imagery data*

The rooftop geometry (orientation, tilt angle and area) is automatically computed by using the processing methodology presented in Ref. [14]. In this methodology, detailed in Fig. 3, LiDAR data and aerial orthophotographies are combined to compute all the parameters required: LiDAR data provides orientation and tilt angle information, while the orthophotographies stand the computation of precise information about the rooftop area.

2.2.2. *Generation of Ener3DMap-SolarWeb roofs SDI*

Ener3DMap-SolarWeb Roofs is based on Leaflet, an Open Source JavaScript library launched in 2011. This library allows working with georeferenced data, similar to other libraries such as OpenLayers and Google Maps API. However, Leaflet is chosen because it is the only one that is open-access and lightweight, that has a fluid performance on mobile devices. In addition, Leaflet library is the most complete in terms of plugins available to extend its capabilities and functions. It supports several geographic data formats, such as WMS, GeoJSON, GeoCSV and KML, among others.

The main interface of the web tool is divided into two main parts: (a) a multilayer web viewer on the left side and (b) a complete form with all the parameters required to query the different databases on the right side (Fig. 4). In turn, the parametric part of the solar-web is subdivided into four sections: (i) a noneditable form with information regarding the location and geometry of the selected rooftop, (ii) an editable form with all the parameters required for the PV system design, (iii) a section to

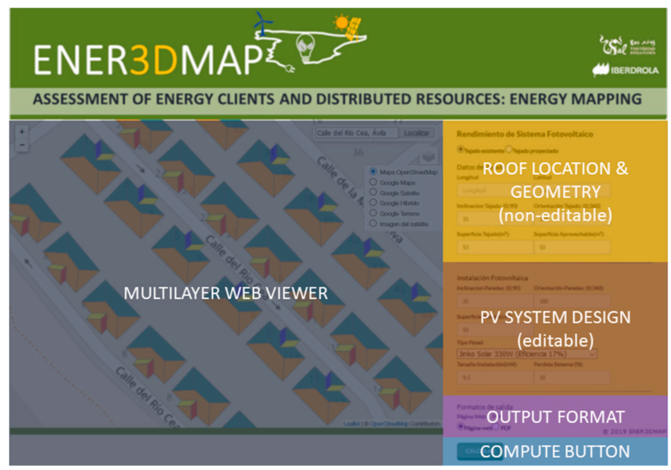


Fig. 4. The Ener3DMap-SolarWeb main interface, with its different sections.

choose the output report format and (iv) a button that activates the query to the database for the PV energy production computation.

The queries are made to the PVGIS application through its API. The call includes the location, the available area for solar panel installation, the orientation, the slope and, if desired, the climate data of the rooftop of interest. The web-based tool outputs the photovoltaic energy production of the area under study by applying the solar model behind PVGIS. The results, in JSON format, are collected from a PHP page to be

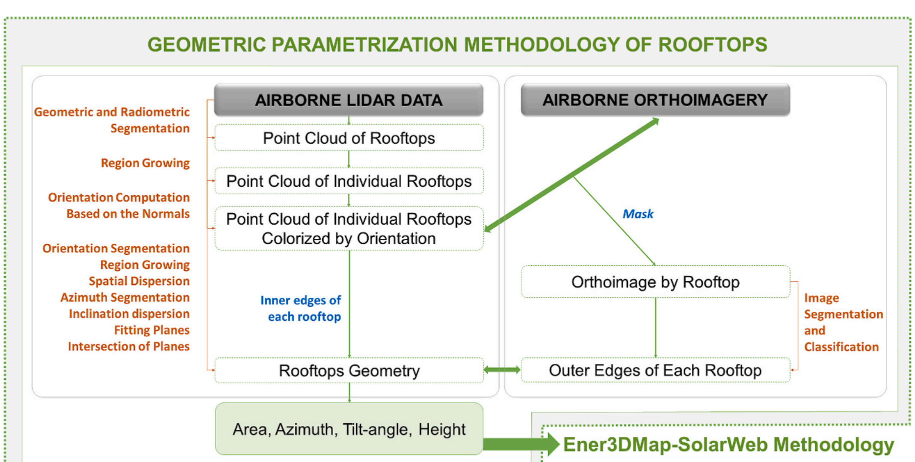


Fig. 3. Detailed workflow of the methodology for generating the Rooftop Geometry Layer from geospatial data.

displayed through the web or exported in PDF format. For the latter, the free FPDF class, written in PHP, is required.

The web-based tool is installed on a web server, using host memory; the user only needs an internet connection to access the data and results. This type of tool extends the usability of the tool to every user, without requiring a previous installation and optimizing the memory resources of the used device. The base layers and coding of the geo-database occupy 5.57 MB on the server, while the rooftop geometry layer size depends on the number of rooftops and their geometries. In particular, the memory size depends on the number of rooftop vertices; rectangular rooftops occupy more memory than triangular rooftops. In addition, data from a 1000 m^2 plot occupies the same memory as a 10 m^2 plot, provided the rooftop shape is the same. For example, the mean memory occupation is 5 KB per 1000 m^2 for the most typical rooftop shapes (hip roofs and M-shaped roofs in industry).

The integration of all the data layers and the connections to the Cadastral data and PVGIS APIs yields the following outputs:

- Production of the system under study per month (numerically and graphically)
- Mean solar radiation (in kWh per m^2 and day)
- Plane of Array, or total incident radiation on the panel, adding direct solar rays, diffuse irradiance and irradiation reflected by the ground onto the panel
- Estimated energy balance, which provides a guide for the energy savings produced by the installation

The energy balance consists of estimating the energy consumption based on the extension and use of the building, and computing the energy generated by the PV installation. The building extension and use information is extracted from the cadastral data integrated in the geo-database (Section 2.1.3). In this sense, ENER3DMAP-SolarWeb approximates the energy consumption as other solar tools provide (PVSOL), based on the building area. The approximation is based on a top-down approach [44] using consumer profiles from the Spanish Electricity Network. This approach is selected to avoid requesting more data from the user, since an accurate energy consumption estimation requires actual consumption data, or data about the time of active occupancy, the number of occupants [45] and the energy use [46]. In addition, accurately estimating the energy consumption is beyond the current scope and objective of the proposed tool, the focus and potential of which are in calculating the photovoltaic solar potential of built and unbuilt roofs.

3. Operation of the Ener3DMap SolarWeb-Roofs SDI

The main body of the SDI corresponds to the area which allows the visualization of the different layers integrated into the web tool: the base layers (Section 2.1.1) and the vector layer with the roof geometric information (Section 2.1.2). The latter represents the geometry of the existing rooftops in plan view with a color assigned to each slope according to its orientation: blue for North, turquoise for Northwest and Northeast, yellow for West and East, orange for Southwest and Southeast, and red for South. The user can easily locate the target rooftop (either existing or under construction) by using the search bar and investigate different possible PV panel configurations in the right side of the web tool.

The procedure for tool use and its inner operation are detailed in the following sections and described in Fig. 5.

There is no mention in the manuscript to the Forecast API included in Fig. 5 because it is a connection analogous to the connection made with PVGIS. The Forecast API has been linked to Ener3DMap SolarWeb-Roofs tool for management purposes once the PV installation is done. Since this part is out of the scope of the study, it has not been described in detail.

3.1. Case study selection

Once the target rooftop, or the desired solar installation position, are selected in the viewer by clicking on the base layer (Section 2.1.1), the query form is automatically populated or left for the user to define, depending on whether the analysis is targeted at pre-existing rooftops. For existing rooftops (Fig. 6a), the latitude, longitude, tilt angle, orientation and useable area of the target rooftop are automatically populated in the form from the Rooftop Geometry Layer. For a solar panel installation position without a building (Fig. 6b), once the area of interest has been selected, the longitude and latitude of the study location is automatically populated into the form.

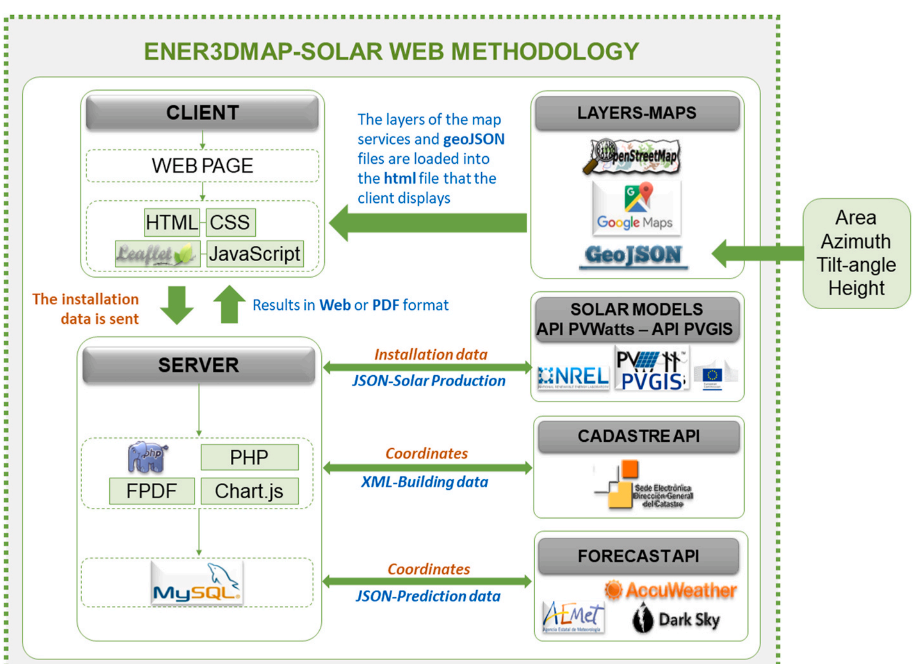


Fig. 5. Operation of the ENER3DMAP SolarWeb-Roofs SDI.

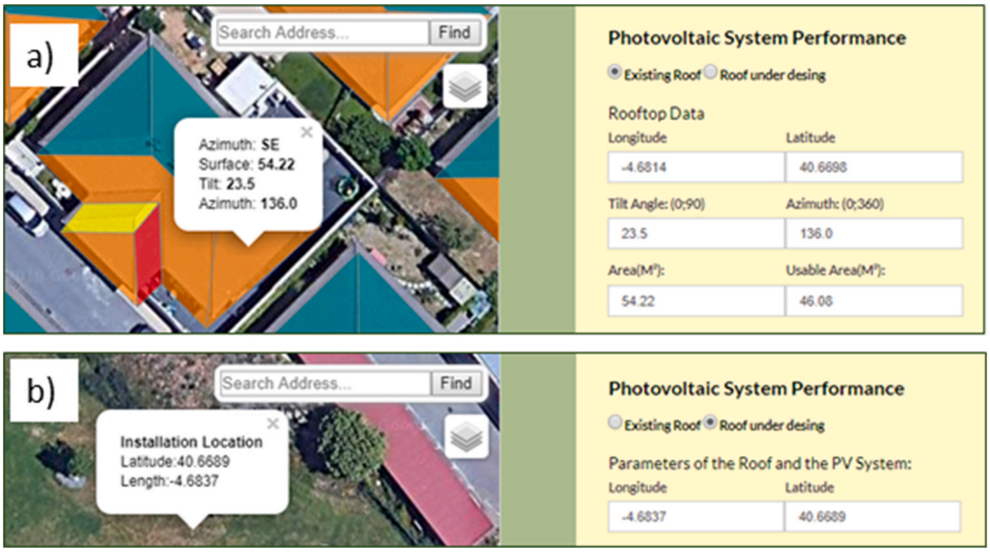


Fig. 6. Roof location parameters automatically populated into the form for a query for (a) an existing rooftop or (b) a parcel without a building.

3.2. PV system design

In addition to the rooftop data form, the interface has a form for PV system design. The contents of this form also depend on whether the target is an existing or projected rooftop. For both cases, the form is editable. For existing rooftops, the PV system design form is automatically populated with default parameters obtained from the rooftop geometry layer, assuming an integrated PV system: the panels follow the same orientation and inclination as the target rooftop (Fig. 7a). However, the form can be edited to set different configurations to check their energy performance. For locations with no building or no roof, there is a blank form with four tabs that must be filled by the user with the preferred design and configuration parameters and two tabs that are automatically populated based on the previous manually entered parameters (Fig. 7b).

In both cases, the three most widely used panel models and configurations are presented as user choices (Fig. 7): (i) Canadian Solar 275 W, (ii) Jinko Solar 330 W and (iii) Canadian Solar 330 W. In addition, for each model and configuration, the solar capacity in kW and the system losses in % are automatically computed.

This data entry form offers different alternatives for computing the PV potential for both existing rooftops and locations without a building.

3.2.1. Photovoltaic solar potential of existing rooftops

The rooftop geometry is important when calculating the PV solar potential of existing rooftops since it affects both the number of solar panels and the way in which the panels receive solar radiation. Due to the great PV technology development, currently there are several photovoltaic glass solutions and types of solar panels that suit any geometry. However, since the objective of this web tool is to offer information about the PV solar potential of rooftops when installing the most common panels in the market, the computation is performed for the panels selected in the tool, with approximately 2 m^2 of surface area.

In addition to rooftop geometry, the way in which the panels are installed is another factor that determines both the installation cost and the final energy production. PV panels can be (i) integrated on the rooftop or (ii) fixed on structural supports that modify their tilt angle and orientation. For both cases, the web tool performs the calculation based on the rooftop geometry, the site location, and the solar radiation model (Sections 2.1.2 and 2.1.4).

3.2.1.1. PV panels integrated on the rooftop. This is the most commonly

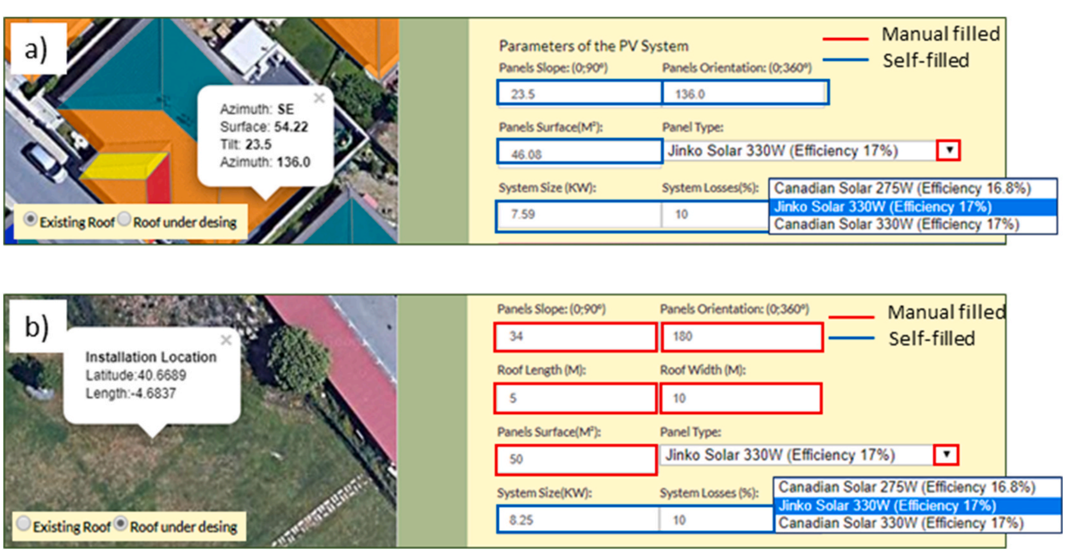


Fig. 7. Form for the introduction of data for the PV system design, for cases with (a) an existing rooftop or (b) a location without a building.

adopted solution; since the solar panels are completely aligned with the rooftop, no visual integration problems occur. It is necessary to ensure that the rooftop geometry layer is activated to show a layer in which the rooftop slopes are in color (blue, turquoise, orange, yellow or red, depending on the orientation).

The rooftop of interest must be located through the search bar or with the mouse controls and selected. The desired panel type among the three offered must be selected. The remaining rooftop parameters and those of the PV system are automatically populated.

By clicking on the compute button, the query to the solar radiation database is launched and after few seconds the solar potential of the chosen roof slope is shown in the user-selected output format. To obtain the total rooftop solar radiation, a query must be made for each roof slope [14].

3.2.1.2. PV panels on support structures modifying the rooftop geometry. This solution optimizes the production by modifying the inclination and orientation of the PV panels with respect to the rooftop. Fewer panels fit on the roof, since gaps between consecutive panel rows must be established to ensure that no shadows are projected among the panels. To compute the reduction of useable area for the panels, the date for which the largest shadow is projected must be considered, which corresponds to the winter solstice. On this date, a panel's shadow is approximately the same size as the panel, such that, for example, for 330 W panels, which are approximately 1.95 m^2, the spacing between consecutive panel rows must be approximately 2 m, reducing the rooftop's useable area by one-half.

For this reason, a percentage reduction is applied by default to compute the useable rooftop area. This percentage is computed as a function of the tilt angle selected for the solar PV installation.

3.2.2. Photovoltaic solar potential for locations without a building

When planning a PV solar installation during a building's design or construction phase, it is possible not only to determine the optimal rooftop orientation/tilt angle to maximize the production of the PV installation but also to optimize the rooftop geometry to maximize the useable area for the placement of solar panels, to choose the best roof material option to facilitate the installation of the panels and to consider PV installation loads together with wind loads on the rooftop to ensure the structure's stability.

In addition, the possibility of introducing the solar installation parameters manually allows the use of the web tool to design PV solar

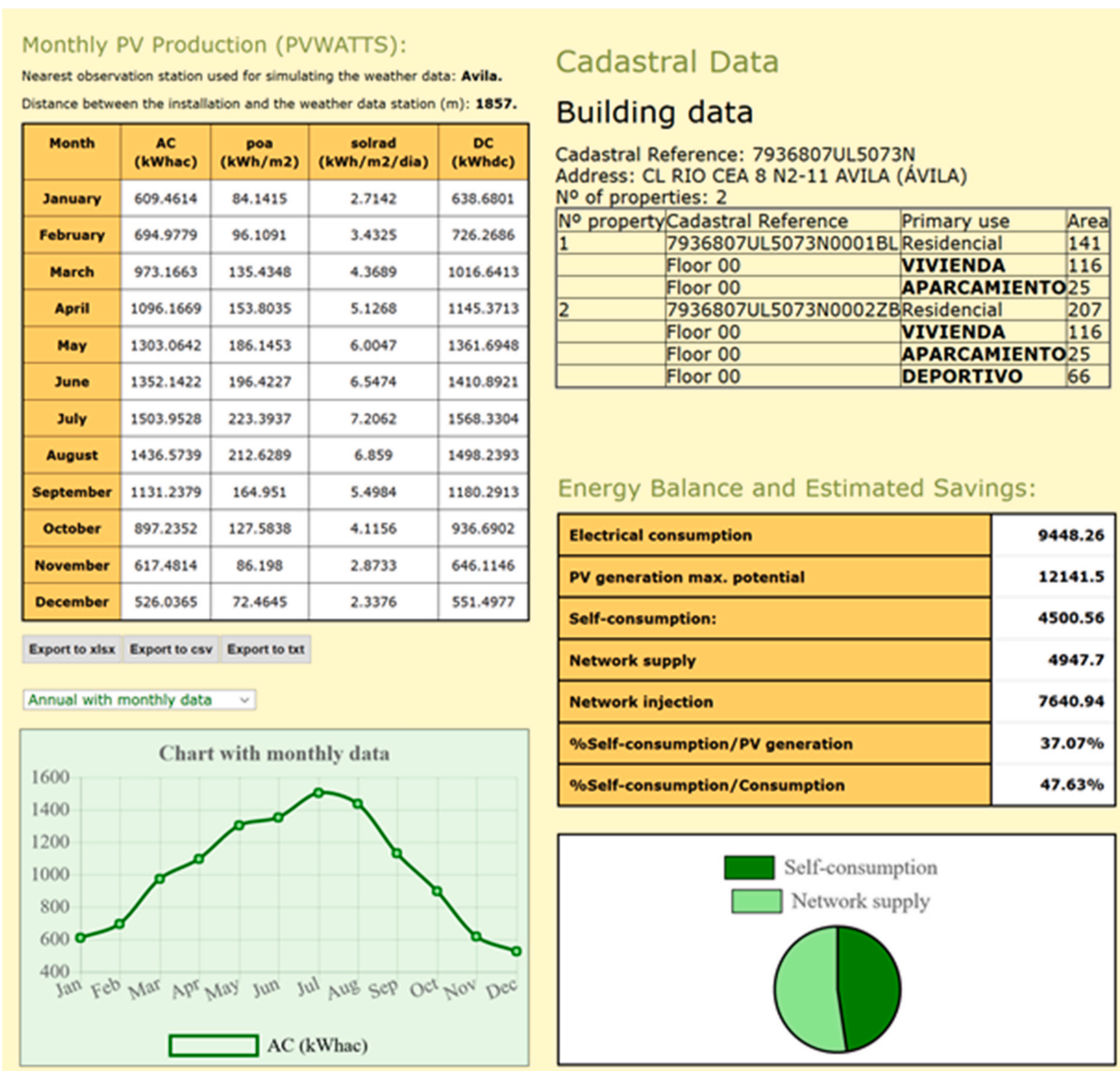


Fig. 8. Output of the web tool in web format: results of PV energy production and approximate energy balance of the case study.

farms directly on the ground, with no roof required.

3.3. Computation of solar energy parameters

Once the rooftop geometry parameters and the PV system configuration have been established, the result of solar production is obtained after establishing the output format, either via the web or through a pdf file (Figs. 8 and 9), and after pressing the execution button (Fig. 4). Output generation implies a query has been sent to the cadastral and the solar radiation (PVGIS) layers, which requires 4–5 s. However, the computation time depends on the user's web connection speed.

4. Evaluation of the Ener3DMap Solar-Web Roofs Tool

This section aims to show the versatility and robustness of the Solar-Web Roofs geospatial tool not only in terms of effective multisource data management but in terms of automation and query efficiency. Due to the data forms in the web tool, it is possible to make consecutive queries to find the optimal PV solution based on the end user's economic and/or energy priorities. Thus, this tool helps find ad hoc solutions-based not only on the 3D geometric characteristics of the rooftop under study and its PV solar potential but also considering different panel configurations to maximize energy production, minimize the number of PV panels or find intermediate solutions.

4.1. Experimental validation

To show these prospects, several studies have been performed to compute the energy production of adopting different rooftop and solar panel configurations. Specifically, three different-use buildings in the city of Avila were selected: a single-family residential building with a 7-slope hip-valley roof (Figs. 10–1a), a multifamily building with 8 residential units and a 4-slope hip roof (Figs. 10–2a), and an industrial building with a 4-slope M-shaped roof (Figs. 10–3a). For each building, three simulations with the following configurations were carried out:

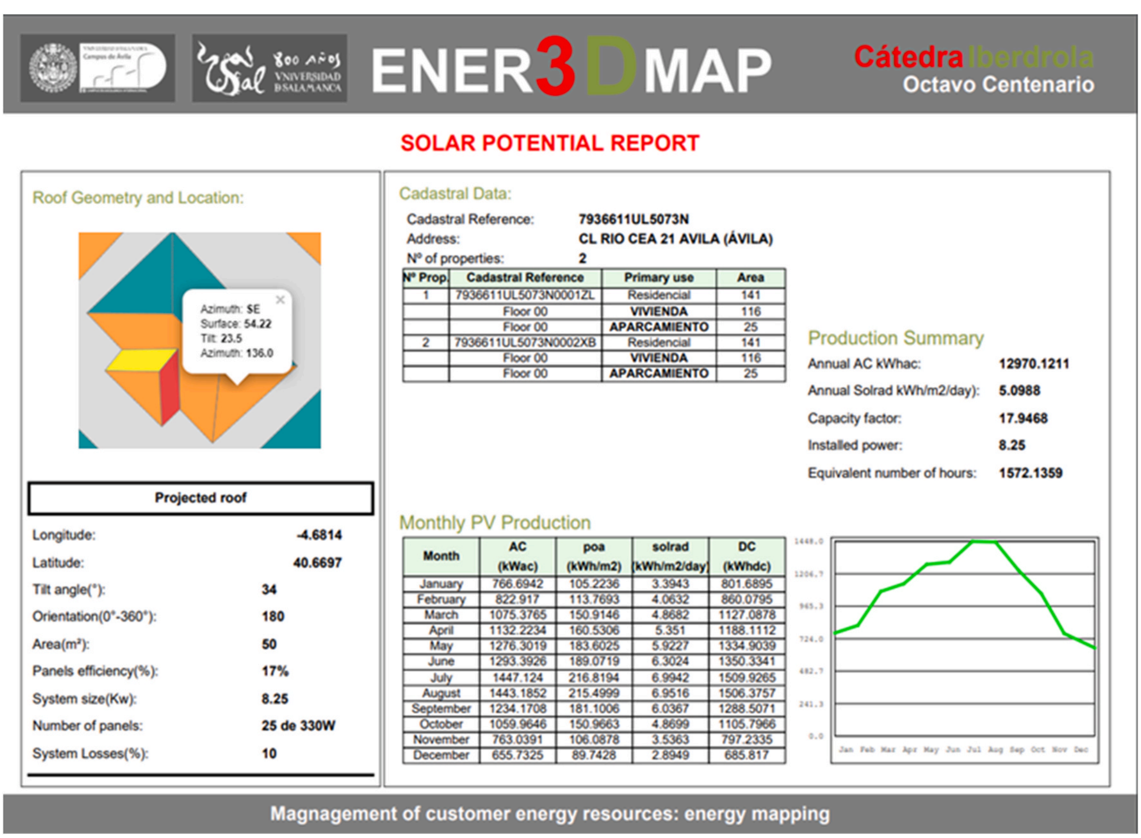
- Fig. 10c: maximum number of PV panels integrated on the rooftop considering all roof slopes.
- Fig. 10d: maximum number of PV panels integrated on the rooftop considering only slopes facing West, Southwest, South, Southeast and East (W, SW, S, SE, E).
- Fig. 10e: maximum number of PV panels with the optimal tilt angle and orientation.

For the latter (Fig. 10e), the following assumptions were considered:

- Since the case studies were in the northern hemisphere, the simulation was established with the panels facing to the South (180° azimuth) and with the tilt angle that maximizes the annual energy production (tilt angle of 37° - 39°). For the case studies shown, located in the city of Ávila (at a 40.67° North latitude), a panel inclination of 34° guarantees the maximum annual energy production [47].
- Since slanted panels cast a shadow, enough space must be provided between consecutive rows of panels to ensure they are not shaded. To size the installation, the date of the winter solstice is considered, which corresponds to December 21st in the northern hemisphere and 13:12 p.m. local time for Ávila, when the sun reaches an inclination of 25°. On this date, the spacing between consecutive rows of panels of 330 W must be approximately 2 m, which reduces the rooftop useable area by one-half.

The main spatial and geometric characteristics of the studied rooftops as well as the PV system configuration for each case are listed in Table 2.

Table 3 shows the annual energy production simulation result with


ENER3DMAP
Cátedra Iberdrola Octavo Centenario

SOLAR POTENTIAL REPORT

Roof Geometry and Location:

Projected roof

Longitude:	-4.6814
Latitude:	40.6697
Tilt angle(°):	34
Orientation(0°-360°):	180
Area(m²):	50
Panels efficiency(%):	17%
System size(Kw):	8.25
Number of panels:	25 de 330W
System Losses(%):	10

Cadastral Data:

Cadastral Reference: 7936611UL5073N
Address: CL RIO CEA 21 AVILA (ÁVILA)
Nº of properties: 2

Nº Prop.	Cadastral Reference	Primary use	Area
1	7936611UL5073N0001ZL	Residencial	141
	Floor 00	VIVIENDA	116
	Floor 00	APARCAMIENTO	25
2	7936611UL5073N0002XB	Residencial	141
	Floor 00	VIVIENDA	116
	Floor 00	APARCAMIENTO	25

Production Summary

Annual AC kWhac:	12970.1211
Annual Solrad kWh/m2/day):	5.0988
Capacity factor:	17.9468
Installed power:	8.25
Equivalent number of hours:	1572.1359

Monthly PV Production

Month	AC (kWac)	poa (kWh/m2)	solrad (kWh/m2/day)	DC (kWhdc)
January	766.6942	105.2236	3.3943	801.6895
February	822.917	113.7693	4.0632	860.0795
March	1075.3765	150.9146	4.8682	1127.0878
April	1132.2234	160.5306	5.351	1188.1112
May	1276.3019	183.6025	5.9227	1334.9039
June	1293.3926	189.0719	6.3024	1350.3341
July	1447.124	216.8194	6.9942	1509.9265
August	1443.1852	215.4999	6.9516	1506.3757
September	1234.1708	181.1006	6.0367	1288.5071
October	1059.9646	150.9663	4.8699	1105.7966
November	763.0391	106.0878	3.5363	797.2335
December	655.7325	89.7428	2.8949	685.817

Magnagement of customer energy resources: energy mapping

Fig. 9. Output of the web tool in pdf format: results of PV energy production and approximate energy balance of the case study.

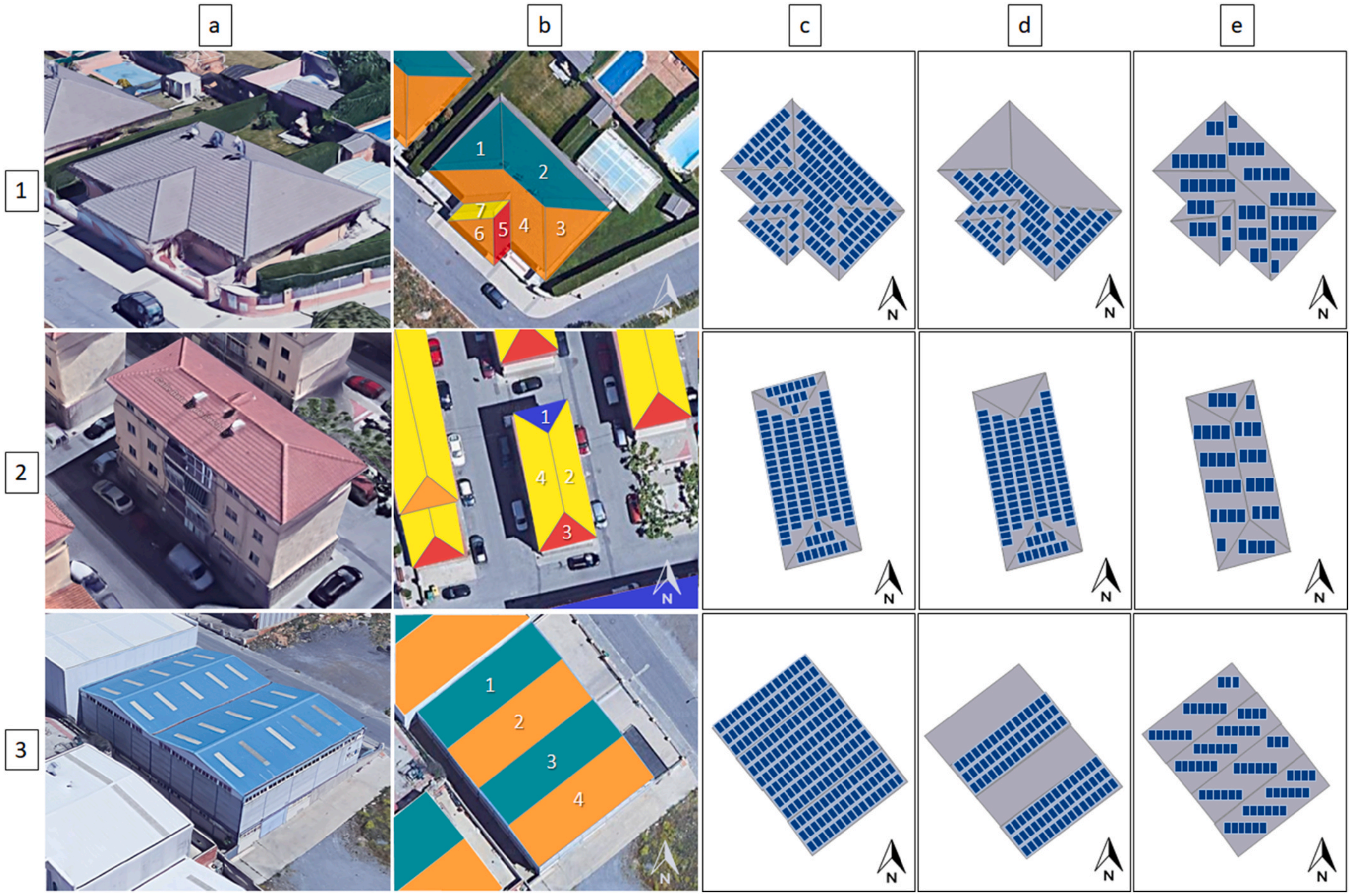


Fig. 10. Validation tests performed for the Ener3DMap-SolarWeb tool: 1, 2 and 3 are the different studied cases. Columns: (a) actual roofs; (b) rooftops automatically identified by the tool; (c) integration of the panels using all the useable area; (d) integration of the panels using only slopes facing West, Southwest, South, Southeast and East, considered optimal for the reception of solar radiation; (e) panel installation with optimal orientation and tilt-angle (nonintegrated panels).

Ener3DMap-SolarWeb Roofs and the three different PV panel installation configurations (c, d and e). To draw conclusions about the production-cost ratio of each PV configuration, in addition to the data offered by the web tool (total energy production per year and per month), the energy production per panel and per unit of rooftop surface was calculated (Table 2).

For all cases studied:

- The highest energy production per year is obtained with configuration (c), that is, covering the rooftop completely with PV panels integrated at the orientation and tilt angle of the rooftop (Fig. 9).
- The highest annual energy production per unit of rooftop surface (highest roof productivity) is obtained with configuration (d), that is, the installation of the maximum number of PV panels integrated on the rooftop considering only slopes facing W, SW, S, SE, and E.
- The highest annual energy production per panel (best panel performance) is obtained with configuration (e), that is, the installation of the maximum number of photovoltaic panels in their optimal inclination and orientation.

Fig. 11 shows the annual evolution of the energy production for each studied case and panel configuration. The small difference in production between configurations (c) and (d) in case study 2 is because only one roof slope presents a nonoptimal orientation and thus the reduction in panel area from one configuration to the other is minimal.

Table 4 compares the time required to perform each of the previous studies. The time required to analyze configurations c and d with Ener3DMap SolarWeb-Roofs tool is 40% less than that required with PVGIS. The reduction is due to proposed tool's automatic introduction of rooftop data. For the study of configuration e, PVGIS has similar computation times as Ener3DMap, because PVGIS includes an automatic introduction of parameters to "optimize tilt angle and orientation". As a complementary contribution, Ener3DMap SolarWeb-Roofs computes the number of panels for each configuration, in addition to the solar radiation per unit area, while PVGIS only computes the solar radiation per unit area.

The aim of these simulations is not to draw a generic conclusion about the ideal PV configuration since many configuration possibilities were not considered, and because the ideal configuration also depends on factors such as users' energy needs, their economic resources and the building use (main or secondary use, for example). The purpose of these simulations is to validate the usefulness of the different data types included in the tool, and the versatility and support offered by the web tool developed to calculate PV solutions. In addition, the tool does not perform a structural study of the roof including the PV panels, such that the preferred installation viability study is incomplete in this sense. In fact, Ener3DMap-SolarWeb Roofs gives a warning in this regard.

4.2. *Theoretical validation*

The precision and accuracy of the results obtained by the Ener3DMap Solar-Web Roofs tool involve a combination of the precision and accuracy of its two components: the accuracy of the geometry determination with the algorithms developed and presented in Refs. [14], and the model's precision in computing the solar energy production in PVGIS.

For the rooftop geometry [14], determines that the methodology

Table 2
Spatial and geometric characteristics of the analyzed rooftops and their PV panel configurations.

Case Study		Roof Location		Rooftop 3D Geometry				PV System			
Roof/config.	Roof slope	Lat.[a]	Long.[b]	Az.[c]	Or.[d]	Tilt[e]	A.[f]	Az.[c]	Or.[d]	Tilt[e]	A.[f]
1c	1	−4,68	40,67	318	NW	23,50	60,30	318	NW	23,50	51,26
	2			45	NE	24,00	112,21	45	NE	24,00	95,38
	3			136	SE	23,50	57,95	136	SE	23,50	49,25
	4			223	SW	21,00	107,49	223	SE	21,00	91,37
	5			182	S	16,00	18,51	182	S	16,00	15,73
	6			224	SW	19,00	25,47	224	SW	19,00	21,65
	7			275	W	17,00	16,54	275	W	17,00	14,06
1d	3	−4,68	40,67	136	SE	23,50	57,95	136	SE	23,50	49,25
	4			223	SW	21,00	107,49	223	SE	21,00	91,37
	5			182	S	16,00	18,51	182	S	16,00	15,73
	6			224	SW	19,00	25,47	224	SW	19,00	21,65
	7			275	W	17,00	16,54	275	W	17,00	14,06
1e	1	−4,68	40,67	318	NW	23,50	60,30	180	S	34,00	25,63
	2			45	NE	24,00	112,21	180	S	34,00	47,69
	3			136	SE	23,50	57,95	180	S	34,00	24,63
	4			223	SW	21,00	107,49	180	S	34,00	45,69
	5			182	S	16,00	18,51	180	S	34,00	7,87
	6			224	SW	19,00	25,47	180	S	34,00	10,83
	7			275	W	17,00	16,54	180	S	34,00	7,03
2c	1	−4,69	40,66	350	N	14,00	16,56	350	N	14,00	14,08
	2			82	E	16,00	61,85	82	E	16,00	52,57
	3			170	S	14,50	20,67	170	S	14,50	17,57
	4			260	W	17,00	73,55	260	W	17,00	62,52
2d	2	−4,69	40,66	82	E	16,00	61,85	82	E	16,00	52,57
	3			170	S	14,50	20,67	170	S	14,50	17,57
	4			260	W	17,00	73,55	260	W	17,00	62,52
2e	1	−4,69	40,66	350	N	14,00	16,56	180	S	34,00	7,04
	2			82	E	16,00	61,85	180	S	34,00	26,29
	3			170	S	14,50	20,67	180	S	34,00	8,79
	4			260	W	17,00	73,55	180	S	34,00	31,26
3c	1	−4,67	40,66	321	NW	10,50	285,18	321	NW	10,50	242,40
	2			143	SE	10,80	300,47	143	SE	10,80	255,40
	3			321	NW	10,50	289,55	321	NW	10,50	246,12
	4			143	SE	10,50	293,64	143	SE	10,50	249,59
3d	2	−4,67	40,66	143	SE	10,80	300,47	143	SE	10,80	255,40
	4			143	SE	10,50	293,64	143	SE	10,50	249,59
3e	1	−4,67	40,66	321	NW	10,50	285,18	180	S	34,00	121,20
	2			143	SE	10,80	300,47	180	S	34,00	127,70
	3			321	NW	10,50	289,55	180	S	34,00	123,06
	4			143	SE	10,50	293,64	180	S	34,00	124,79

[a] Latitude (°).
[b] Longitude (°).
[c] Azimuth (0°–360°).
[d] Orientation.
[e] Tilt Angle (°).
[f] Area (m^2).

Table 3
Energy production for the cases studied.

Case	Num. Panels	Production[a]	Production/Panel[a]	Production/m^2 rooftop[a]	Installed Power	Equivalent hours PS[b]
1c	173	73,666	425,81	184,87	57,09	9346,60
1d	98	47,346	483,12	209,53	32,34	7217,58
1e	84	43,579	518,81	109,37	27,72	11,004,95
2c	75	32,731	436,41	189,60	24,75	5257,80
2d	68	30,103	442,70	192,88	22,44	4120,33
2e	36	18,677	518,81	108,19	11,88	6288,54
3c	509	223,100	438,31	190,87	167,97	5305,49
3d	259	122,219	471,90	205,72	85,47	2859,92
3e	254	131,776	518,81	112,74	83,82	6288,54

[a] kWh/year.
[b] Peak Sun.

error is 0.19% and 0.45% for the computation of the orientation and the tilt-angle of the roof, respectively, and 4.6% for the determination of the useable area. As stated in Ref. [14], this error can be considered negligible, as it implies the underestimation or overestimation of one or zero panels.

With respect to the PVGIS results, a thorough evaluation of the software used to compute the solar energy production is presented in Refs. [39]. The analysis shows that PVGIS is the most accurate free software package for estimating annual solar energy, with a mean deviation of 2.5%, compared to 8.8% and 8.1% for PVWatts and RETScreen, respectively. For all cases, the winter energy production has a higher deviation due to the complexity in predicting the weather for

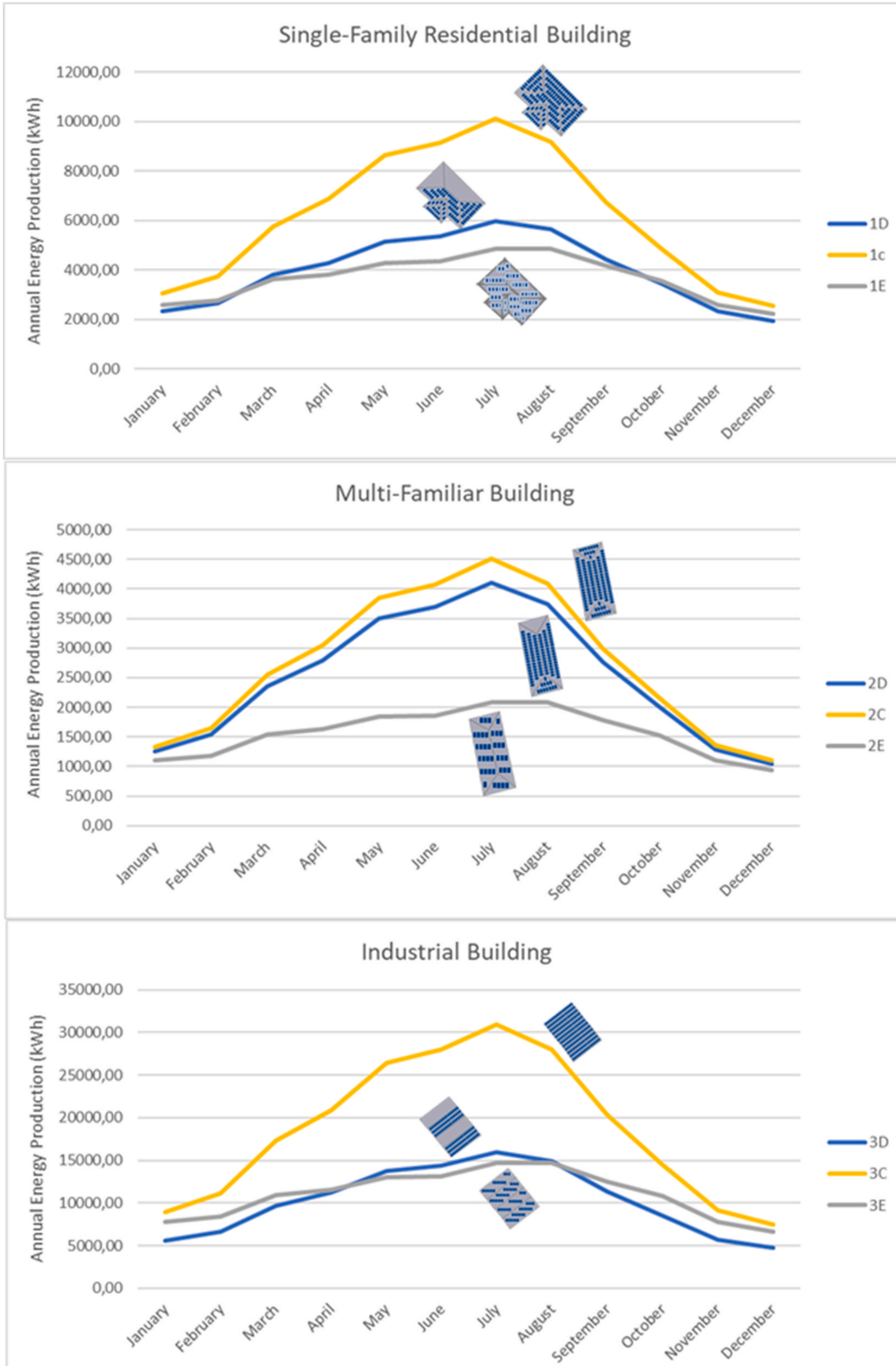


Fig. 11. Evolution of the annual energy production for different building uses as a function of the different solar panel installation configurations.

this season, despite that all approaches use historic weather data.

To assess the performance of PVGIS compared with commercial software [48], PVGIS and TRNSYS, Archelios, Polysun, PVSyst and PVSOL were analyzed with real data from a PV installation, all using weather data measured at the installation position, except for PVGIS. According to this study, the estimation accuracy of PVGIS is in the same range as the commercial software that perform PV planning and analysis, such as PVSyst and PVSOL, with similar RMSE, MAD and MAPE values (root mean square error, mean absolute deviation, mean absolute percentage error) of 244.88; 21.42 and 9.24%, respectively [49]. Also

Table 4
Processing time for the different case of studies and configurations: Ener3DMap vs. PVGIS.

	Case 1			Case 2			Case 3		
	Conf.c	Conf.d	Conf.e	Conf.c	Conf.d	Conf.e	Conf.c	Conf.d	Conf.e
Ener3DMap-SolarWeb	42 s.	24 s.	38 s.	21 s.	15 s.	20 s.	25 s.	11 s.	24 s.
PVGIS	76 s.	55 s.	45 s.	43 s.	30 s.	25 s.	46 s.	25 s.	32 s.

determines the error of PVGIS for the simulation of the global irradiance with respect to the ground measurements, with an R^2 between 0.82 and 0.92. Thus, PVGIS can be considered an accurate alternative for estimating solar PV potential, and the error regarding this issue in the Ener3DMap SolarWeb tool is considered acceptable, since the tool is based on PVGIS.

5. Conclusions

This paper presents the development of a web-based tool called Ener3dmap Solar-Web Roofs. The tool is based on Leaflet and supports the main formats for geospatial data: WMS, GeoJSON, GeoCSV and KML.

The tool integrates 3D rooftop geometry data with a widely validated solar radiation model, PVGIS, with a high level of automation. The level of automation is accomplished with algorithms that compute rooftop geometric parameters from LiDAR data and aerial orthophotography. The availability and format of these datasets is standardized in European countries under the INSPIRE Directive. With the use of these data, the replicability of the tool in other European countries is ensured.

In addition to automatic data entry, the tool provides user editing capability, both for the solar PV installation design and for the introduction of data for parcels without buildings. The developed tool matches the capability of existing tools, of allowing the introduction of data by the user.

Last, the integration of a validated solar radiation model such as PVGIS presents an advance over existing tools in the frequency with which the solar radiation results can be computed: hourly, monthly and annually. Most other tools only provide annual solar radiation data.

The tool presented in this work provides an accuracy below 0.50% for computing the rooftop angular parameters (orientation and tilt-angle), and below 5% for the determination of the useable area. The error in computing the solar energy production is 2.5%. With these values, the contribution of the tool is two-fold:

1 With respect to roof modeling tools, Ener3DMap SolarWeb Roofs provides the solar energy production per hour, month and year.
2 With respect to existing solar planning tools, Ener3DMap SolarWeb Roofs provides the rooftop geometric parameters automatically from geomatic data.

An example of the proposed tool's versatility is that it enables the study of different solar panel configurations with agility (with a mean computation time reduction of 40% with respect to the solar energy computation of PVGIS alone). In this way, for example, it was possible to determine that, for a certain rooftop, the highest energy production per year is obtained when the rooftop is completely covered with PV panels that are integrated with the rooftop's orientation and tilt angle.

Taking these facts into account, the main contribution of the study to society is the availability of a tool for the accurate but easy computation of solar PV installations, facilitating the incorporation of this renewable and clean energy to the electricity network and increasing the accessibility to solar energy for all types of users (residential, industrial), promoting self-consumption and reducing energy poverty.

Future studies will address the further improvement of the integrated solar radiation model, to reduce the 2.5% deviation of PVGIS, either by integrating additional historic weather data, or by incorporating satellite measurements (land surface temperature, albedo, solar radiation on the atmosphere) into the mathematical model.

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CRediT authorship contribution statement

M. Sánchez-Aparicio: Validation, Writing - original draft. **J. Martín-Jiménez:** Software, Visualization. **S. Del Pozo:** Methodology, Writing - original draft. **E. González-González:** Resources. **S. Lagüela:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] European Commission (EC). Europe 2020: a strategy for smart, sustainable and inclusive growth. Working paper {COM (2010) 2020}. 2010.
[2] Mohajeri N, Perera ATD, Coccolo S, Mosca L, Le Guen M, Scartezzini JL. Integrating urban form and distributed energy systems: assessment of sustainable development scenarios for a Swiss village to 2050. Renew Energy 2019;143:810–26.
[3] Zhao Z, Zhang S, Hubbard B, Yao X. The emergence of the solar photovoltaic power industry in China. Renew Sustain Energy Rev 2013;21:229–36.
[4] Gautam B, Li F, Ru G. Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal. Energy Build 2015;86:735–44.
[5] Hartner M, Ortner A, Hiesl A, Haas R. East to west – the optimal tilt angle and orientation of photovoltaic panels from an electricity system perspective. Appl Energy 2015;160:94–107.
[6] Luthander R, Widén J, Nilsson D, Palm J. Photovoltaic self-consumption in buildings: a review. Appl Energy 2015;142:80–94.
[7] Kabir E, Kumar P, Kumar S, Adelodun AA, Kim KH. Solar energy: potential and future prospects. Renew Sustain Energy Rev 2018;82:894–900.
[8] Zhang Y, Ren J, Pu Y, Wang P. Solar energy potential assessment: a framework to integrate geographic, technological, and economic indices for a potential analysis. Renew Energy 2020;149:577–86.
[9] Petrichenko K, Ürge-Vorsatz D, Cabeza LF. Modeling global and regional potentials for building-integrated solar energy generation. Energy Build 2019;198:329–39.
[10] Phap VM, Huong NTT, Hanh PT, Van Duy P, Van Binh D. Assessment of rooftop solar power technical potential in Hanoi city. Vietnam. J Building Eng 2020:101528.
[11] Zurqani HA, Post CJ, Mikhailova EA, Schlautman MA, Sharp JL. Geospatial analysis of land use change in the Savannah River basin using Google Earth Engine. Int J Appl Earth Obs Geoinf 2018;69:175–85.
[12] Eskandari S, Chuvieco E. Fire danger assessment in Iran based on geospatial information. Int J Appl Earth Obs Geoinf 2015;42:57–64.
[13] Choi Y, Suh J, Kim SM. GIS-based solar radiation mapping, site evaluation, and potential assessment: a review. Appl Sci 2019;9(9):1960.
[14] Martín-Jiménez J, Del Pozo S, Sánchez-Aparicio M, Lagüela S. Multi-scale roof characterization from lidar data and aerial orthoimagery: automatic computation of building photovoltaic capacity. Autom ConStruct 2020;109:102965.

[15] Directive, I. N. S. P. I. R. E.. Directive 2007/2/EC of the European parliament and of the council of 14 march 2007 establishing an infrastructure for spatial information in the European community (INSPIRE). Published in the official journal on the 25th april. 2007.
[16] Mahdy M, Bahaj AS. Multi criteria decision analysis for offshore wind energy potential in Egypt. Renew Energy 2018;118:278–89.
[17] Gigovic L, Pamucar D, Bozanic D, Ljubojevic S. Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: a case study of Vojvodina, Serbia. Renew Energy 2017;103:501–21.
[18] Santilano A, Donato A, Galgaro A, Montanari D, Menghini A, Viezzoli A, et al. An integrated 3D approach to assess the geothermal heat-exchange potential: the case study of western Sicily (southern Italy). Renew Energy 2016;97:611–24.
[19] Choudhury S, Parida A, Pant RM, Chatterjee S. GIS augmented computational intelligence technique for rural cluster electrification through prioritized site selection of micro-hydro power generation system. Renew Energy 2019;142: 487–96.
[20] Castro-Santos L, García GP, Simóes T, Estanqueiro A. Planning of the installation of offshore renewable energies: a GIS approach of the Portuguese roadmap. Renew Energy 2019;132:1251–62.
[21] Chukwuma EC. Facility location allocation modelling for bio-energy system in Anambra State of Nigeria: integration of GIS and location model. Renew Energy 2019;141:460–7.
[22] Omitaoumu OA, Blevins BR, Jochem WC, Mays GT, Belles R, Hadley SW, et al. Adapting a GIS-based multicriteria decision analysis approach for evaluating new power generating sites. Appl Energy 2012;96:292–301.
[23] Firozjaei MK, Nematollahi O, Mijani N, Shorabeh SN, Firozjaei HK, Toomanian A. An integrated GIS-based Ordered Weighted Averaging analysis for solar energy evaluation in Iran: current conditions and future planning. Renew Energy 2019; 136:1130–46.
[24] Hong T, Koo C, Park J, Park HD. A GIS-based optimization model for estimating the electricity generation of the rooftop PV (photovoltaic) system. Energy 2014;65: 190–9.
[25] Wong MS, Zhu R, Liu Z, Lu L, Peng J, Tang Z, et al. Estimation of Hong Kong's solar energy potential using GIS and remote sensing technologies. Renew Energy 2016; 99:325–35.
[26] Dehwah AHA, Asif M. Assessment of net energy contribution to buildings by rooftop photovoltaic systems in hot-humid climates. Renew Energy 2019;131: 1288–99.
[27] Budhathoki NR, Nedovic-Budic Z. Reconceptualizing the role of the user of spatial data infrastructure. Géo 2008;72(3–4):149–60.
[28] Freitas S, Catita C, Redweik P, Brito MC. Modelling solar potential in the urban environment: state-of-the-art review. Renew Sustain Energy Rev 2015;41:915–31.
[29] Huang Z, Mendis T, Xu S. Urban solar utilization potential mapping via deep learning technology: a case study of Wuhan, China. Appl Energy 2019;250:283–91.
[30] Chen S, Zhang Y, Nie K, Li X, Wang W. Extracting building areas from photogrammetric DSM and DOM by automatically selecting training samples from historical DLG data. ISPRS Int J Geo-Inf 2020;9(1):18.
[31] Zhou Z, Gong J. Automated residential building detection from airborne LiDAR data with deep neural networks. Adv Eng Inf 2018;36:229–41.
[32] https://www.google.com/get/sunroof. [Accessed 11 June 2019].
[33] Skopeliti A, Stamou L. Online map services: contemporary cartography or a new cartographic culture? ISPRS Int J Geo-Inf 2019;8(5):215.
[34] Wang Cong. Usability evaluation of public web mapping sites. ISPRS Ann Photog Rem Sens Spat Inform Sci 2014;2:4.
[35] https://www.openstreetmap.org/#map=6/40.007/-2.488. [Accessed 11 October 2019].
[36] https://www.google.com/maps. [Accessed 11 October 2019].
[37] https://pnoa.ign.es/. [Accessed 11 October 2019].
[38] Dall JA. Perfect base for a GIS: digital orthophoto, second national specialty conference on civil engineering applications of remote sensing and geographic information systems. 1991. Washington, USA.
[39] Psomopoulos CS, Ioannidis GC, Kaminaris SD, Mardikis KD, Katsikas NG. A comparative evaluation of photovoltaic electricity production assessment software (PVGIS, PVWatts and RETScreen). Environ Proc 2015;2:S175–89.
[40] PVGIS web service. https://re.jrc.ec.europa.eu/pvg_static/web_service.html. [Accessed 11 June 2019].
[41] Pérez R, Ineichen P, Seals R, Michalsky J, Stewart R. Modeling daylight availability and irradiance components from direct and global irradiance. Sol Energy 1990;44 (5):271–89.
[42] Ideriah FJK. A model for calculating direct and diffuse solar radiation. Sol Energy 1981;26:447–52.
[43] Dobos AP. PVWatts version 5 manual. NREL Publications; 2014. NREL/TP-6A20-62641.
[44] Swan LG, Ugursal VI. Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. Renew Sustain Energy Rev 2009;13(8): 1819–35.
[45] López-Rodríguez MA, Santiago I, Trillo-Montero D, Torriti J, Moreno-Muñoz A. Analysis and modeling of active occupancy of the residential sector in Spain: an indicator of residential electricity consumption. Energy Pol;62:742-751.
[46] McKerracher C, Torriti J. Energy consumption feedback in perspective: integrating Australian data to meta-analyses on in home displays. Energy Effi 2013;6(2): 387–405.
[47] Jain D, Lalwani M. A review on optimal inclination angles for solar arrays. Int J Renew Energy Resour 2017;7(3):1053–61.
[48] Axaopoulos PJ, Fylladitakis ED, Gkarakis K. Accuracy analysis of software for the estimation and planning of photovoltaic installations. Int J Energy Environ Eng 2014;5:1.
[49] Psiloglou BE, Kambezidis HD, Kaskaoutis DG, Karagiannis D, Polo JM. Comparison between MRM simulations, CAMS and PVGIS databases with measured solar radiation components at the Methoni station, Greece. Renew Energy 2020;146: 1372–91.