A GeoSpatial Information System for Photovoltaic Plants Development and Monitoring

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Abstract

Photovoltaic (PV) energy production is supposed to hugely increase during current and next decades. PV plants of any extension, technology and power are supposed to be developed and monitored, with the awareness that monitoring phase lasts around 25 years. One of the major challenges of PV plant industry is to choose suitable sites for plant installation and optimal configuration to maximize energy production. In fact, not all places are suitable for solar energy generation, due to several factors, like environmental factors (e.g., solar radiation, wind, shading), technical factors (e.g., distance from the distribution line), economic factors (e.g., development of local economies), and social/political factors (e.g., public acceptance, protected areas). We propose to address the problem of solar PV site selection using a multi-criteria decision-making (MCDM) approach together with geographic information system (GIS) software to determine the most suitable area or alternative, both in case of rural environments and smart city installations. The resulting framework, highly-integrated with several EU sources and initiatives, can be used for crucial steps in PV plants lifecycle, from initial design to monitoring and maintenance.

1. Introduction

Photovoltaic (PV) energy production plays a crucial role in sustainable energy transition policies. PV installations are in fact supposed to hugely increase during current and next decades. All these PV plants may differ widely both in terms of sizes (from individual users, passing through big buildings and plants installations, to huge-size utility-scale applications) and technological choices (single or bifacial panels, potentially equipped with 1 or 2 degrees of freedom sun solar trackers).

The choice of the technology to be installed, in fact, may strongly depend on intrinsic site characteristics defining the intensity and frequency of the energy source (e.g., site Direct Normal Irradiance (DNI) and Diffused Horizontal Irradiance, (DHI)), as well as on the control and maintenance abilities of the plant owner (which may span from a single common citizen to a multinational energy player).

The European Green Deal is a package of policies and initiatives presented by the EU in 2019 as a central part of the EU strategy to implement the United Nation's 2030 Agenda and its sustainable development goals. It aims to build a new and green economic model which will transform Europe in the first climate-neutral continent by 2050, by switching energy, industry, and transport to clean tech. This ambitious road map towards a climate-resilient society comes in an age when some European economies are still heavily reliant on coal and thus the package is considered one of the most consequential legislative efforts in the history of the European Union, comprehensive of every aspect of society and the economy and across all policy areas. The best-known objective of the European Green Deal consists of cutting carbon dioxide net emissions to zero by 2050, and already by 55% by 2030 (compared to 1990 levels).

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According to TERNA, in 2022 Italy needed 316.8 TWh of electrical power. Renewable energy installed was in total in 2022 just 63.6 GW, of which 25.05 GW solar energy. In order to reach the 2030 emission cut goal, TERNA foresees Italy should have to gain the goal to 75 GW installed of photovoltaic, mining +200% in just 8 years (from 2022). Therefore, each component of our society (government, utilities, manufactures, research and so on) will be involved in reaching so challenging goals.

Recently, the EU Commission launched a new strategic initiative: Copernicus Thematic Hubs, focused on specific thematic areas and regions, namely, for the first four, energy, health, coastal zones and Arctic regions (https://www.copernicus.eu/en/news/news/observer-depth-look-copernicus-energy-thematic-hub). The Copernicus Energy Hub comes at a critical time for the energy-related policies of the EU, in particular, the European Green Deal (read ahead in this document). The path to energy independence and climate neutrality requires us to significantly expand our renewable energy infrastructure. A crucial initial step includes the decision on where to build new renewable power plants. This is a challenge in itself: the effectiveness of renewable energy sources is closely linked to benefitting from the right conditions, so it's important to use climate variables and data to predict and plan the location of sites. This is where the Copernicus Energy Hub comes in.

In this paper, we move toward a new project aiming to develop methodologies and enhanced prototypes in order to provide energy industry with advanced tools, making players able to gain production efficiency and cost reduction, in PV plants' designing, building and monitoring.

The rest of the paper is structured as follows: in Section 2, we briefly revise the state of the art. In Section 3, we describe the general methodology of the proposed geospatial system, with

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particular attention to the analysis of multispectral satellite images discussed in Section 4. In Section 5 we describe three use cases dealing with the situation of selecting and managing a PV site in different contexts. Section 6 concludes the paper discussing further work.

2. State of the art

In recent years, a large amount of work has been carried out to try to review and categorize the countless techniques and issues about the selection of installation sites. The focus spreads from analytical hierarchy process extension (Al Garni and Awasthi, 2018) to systematic review of the literature itself, providing a direct analysis and assessment, and addressing gaps in knowledge in the solar energy research (Spyridonidou and Vagiona, 2023).

Different kinds of PV plants have some specific features, that require different approaches and tools for plants development and monitoring. So far one of the most adopted technology for plants' monitoring is by UAV (Unmanned Aerial Vehicle) especially by drones. UAV technology presents several inconveniences, especially in terms of costs and frequency of run. A more promising approach adopts Satellite Remote Sensing (SRS) imagery, as suggested by the EUSPA EO and GNSS Market Report (EUSPA, 2022). However, even if SRS data is becoming over and over a commodity, there are several difficulties in their utilization. Many scientific contributions have been proposed, such as in (Bartkowiak et al., 2019, Buster et al., 2021, Li et al., 2017).

SRS technology is increasingly and quickly improving. So far, the use of satellite data for addressing very small objects on Earth surface, has been not always simple because of the low frequency or low spatial resolution of satellite coverage over regions of interest. Even when moderate-resolution satellite imagery is available multiple times per day, the spatial resolution of these data is too coarse to enable most applications.

So far, SRS is not fully applied for supporting major activities needed from PV plants, especially for monitoring activities. This limitation is actually due to the low spatial resolution of thermal sensed data. Whereas spatial resolution of sensed data in the visible spectrum has significantly increased over last years, reaching 30 cm, data sensed in the infrared spectrum are still around tens of meters.

Nowadays many scientific works, aiming to fill the current gap from SRS data and applications' requirements, are available (Alhammad et al., 2022, Jörges et al., 2023). Furthermore, satellite technology is improving at a very quick pace, making possible to get high-spatial resolution data at affordable prices.

Among the literature we have analysed, we have selected (Cui et al., 2023), (Nakata and Ogata, 2023) and (Baghani, 2023) contributions as candidate works to compare with. In detail, (Cui et al., 2023) develops a deep learning based method for estimating power generation by rooftop PV plants installed in urban areas, that is one of our use cases. (Baghani, 2023) provides an efficient method to estimate the solar energy production potential from the rooftops. However, it uses UAV photogrammetry. Finally, the work of (Nakata and Ogata, 2023) provides a model for estimating low-risk agrivoltaics plants installation, that is also included in our use cases.

The results of our survey definitely confirmed the importance of LST downscaling (Pu and Bonafoni, 2023) in order to define effective methods for rooftop PV plant installation and monitoring in rural areas.

3. Methodology

The PV plant industry faces numerous challenges due to several factors that impair the development of renewable energy systems. Sites' selection is the critical initial step that influences all the PV plant life-cycle together with the plant' optimal configuration in order to maximize energy production and to facilitate the plant's monitoring. The factors that influence the plant site selection can be categorized in (1) environmental, 2) technical, (3) economic, and (4) social/political (Deveci et al., 2021):

1. Environmental factors include uneven solar radiation, temperature, dust allocation, soiling, wind, shading, humidity, and so on.
2. Among technical factors, the distance of the PV plant to network connection is critical, since the amount of power system loss is proportional to the length and type of the transmission or distribution line, affecting the economic investment as well.
3. Regarding economic factors, there are several issues to be considered ranging from the impact on the surrounding environments (potential damage to the ecological system) to the impact on regional development and local economies, to the presence of government subsidies to promote renewable energy resources.
4. Social/political factors for PV plants installation include public acceptance and policy support, besides all regulatory and legislative issues related to land use, protection areas, engineering construction permits, and the like.

To link all these factors, a multi-criteria decision-making (MCDM) approach is here proposed making use of satellite data gathered in a geographic information system (GIS) software with other geo-referenced data sources (Greene et al., 2011). The architecture of the DSS needs to be integrated with several existing and on-going EU sources and initiatives in this domain.

Heterogeneity and multiplicity of factors that are involved in the problem domain suggest a decomposition in subsystems, each with its own models, which are changeable and updatable, allowing the parallelization of interventions and contributions by the research community, the generalization of some aspects and, at the same time, the specialization for particular subdomain aspects. Each subsystem is fed by its own data sources, is made up of a set of models (recallable from a database) in relation to each other, and provides intermediate data as output, which passes to the final Decision Support System (DSS); a simplified overview is shown in Figure 1.

The overall architecture can be mostly based on open source technologies and off.the.shelf hardware (see Figure 2), giving the opportunity to scientific and industrial communities to build from the bottom geographical data layers for a complete and comprehensible picture of cost and benefits for each candidate installation site.

As depicted in Figure 1, a decoupling of three main domains is applied, managing them in subsystems: Environment Subsystem, Socio-political Subsystem, Economic Subsystem. For each subsystem (hereafter SubS), three main interfaces are suggested to be used:

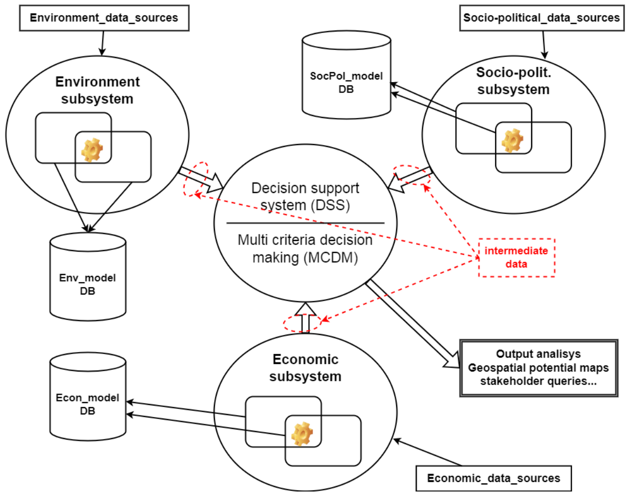

Figure 1. System overview.

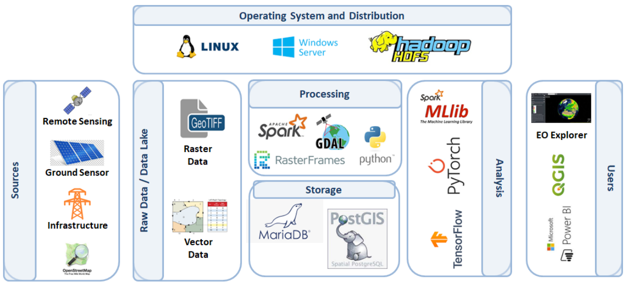

Figure 2. Technologies and tools.

1. **Datasource interface**, required by the SubS, that is used to get data for all the variables involved in the SubS. It is worth noting that each variable is intrinsically georeferenced, or can be georeferenced in an aggregate manner, and carries with it not one, but two values that are of interest: costs and benefits. A crucial point is that the final balance is not simply the difference of the two values, as this can vary in combination with other variables. Here comes the first application of cost/benefit models available in the second interface.
2. **Model interface**, required by the SubS, that is used to load (and store) different models of computation for the intrinsic variables. Here specific weights, or combinations of them can be applied for single or multiple variables. The advantage of such an approach is that different models can be combined or quickly replaced for a first comparison and for subsequent iterative refinements. Domain experts find an application point for their specific knowledge here and can provide a booster to the overall system.
3. **DSS interface**, provided by the SubS, is the one that finally produces a set of intermediate, aggregate and georeferenced data that are representative of the SubS, also providing the possibility of exporting the SubS variables in separate flows, for their possible subsequent use in the DSS/MCDM.

With such a decomposition and structure it is possible to address a complex problem of heterogeneity of the factors involved in decision making and build a good and scalable architecture, e.g., for energy-domain software systems (Figure 3).

Putting focus on the Environment SubS, a crucial aspect and

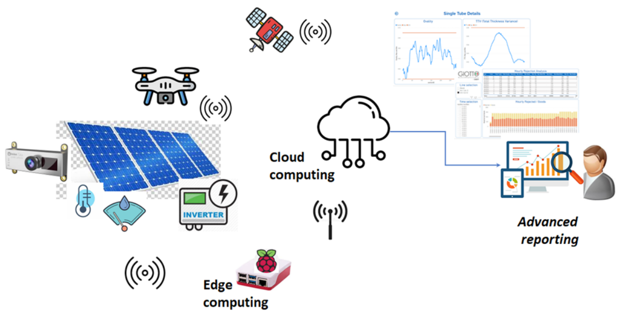

Figure 3. Architecture.

a powerful datasource is satellite imagery. An innovative approach in this paper is about the use of data gained by high resolution periodic satellite observations, both in the visible and in the infrared (IR) spectrum, to be used both in the PV design phase (e.g. in the choice of the optimal installation site) and in plant control, monitoring and maintenance. For this reason we face a separate discussion in next section.

4. LTS Downscaling

The employment of satellite imagery and GIS to assess renewable energy resources at different locations can inform the optimal placement of new PV plants. The resulting geospatial information system will be able to integrate data coming from different sources:

- Earth observation data: Earth Observation (EO) is rapidly changing, as a result of exponential advances in sensor and digital technologies. The speed of change has no historical precedent. Recent decades have witnessed extraordinary developments in ICT, including the Internet, cloud computing and storage, which have all led to radically new ways to collect, distribute and analyse data about our planet. This digital revolution is also accompanied by a sensing revolution that provides an unprecedented amount of data on the state of our planet and its changes.
- Geometric data: in this category, we include vector data describing the PV plant scenarios, such as geometric configurations, cadastral data, land use data, electric power lines networks.
- Ground monitoring coming from sensor networks or UAVs.
- Other territorial data coming from social and economic indexes.

Regarding the use of SRS data in Environments SubS, the key factor is to design the effective methodology and develop the consequent software, able to obtain high-resolution data in the Thermal InfraRed (TIR) spectrum. In fact, one the most crucial measure for many cross-domain applications is the Land Surface Temperature (LST). This work aims to give, as an intermediate result, a unifying method for downscaling LST, at least in landscapes useful for PV plants installation.

Remote sensing technologies can be used for monitoring and maintenance of PV plants, to identify potential issues, assess the condition of equipment, and improve the overall system reliability. Over the last four decades, most advanced remote sensing sensors/systems can acquire TIR data at a low spatial resolution but high temporal resolution. However, for different application purposes, both high spatial and temporal resolution TIR data are needed. Therefore, the turning key factor is the ability to obtain high-resolution TIR data, from low and medium resolution TIR imagery.

We aim to define a methodology quite general that can be applied in several domains, but developing its software version tailored for solar energy and PV plants. This though challenge will be afforded by integrating several different approaches. Each methodology pairs its own sources of data with coarse TIR data. Basically, the sources of data proposed for the down-scaling process are: physical measurements coming from ground positioned sensors; visible RGB high-spatial resolution data.

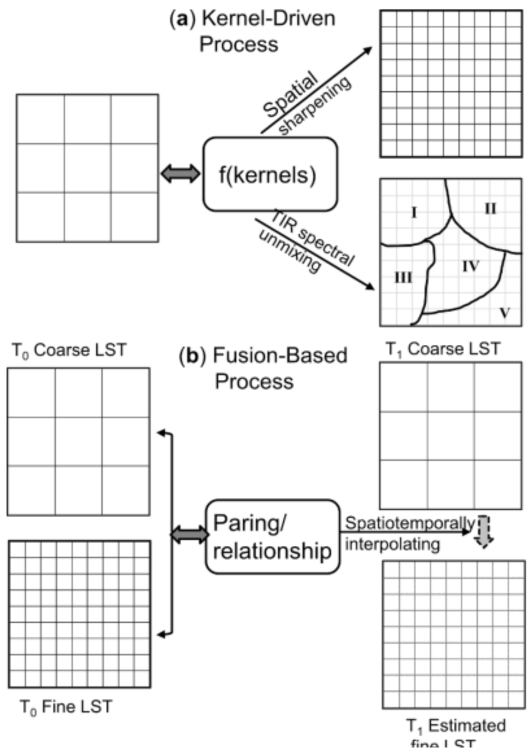

Figure 4. Down-scaling methodologies.

Starting from recent scientific results, such as in (Pu and Bonafoni, 2023), this work aims to give, as a preliminary goal, an enhanced overview of various polar orbits and geostationary orbits' satellite TIR sensors/systems and of scaling factors' determination and selection techniques/ methods suitable for LST down-scaling processes, that will be presented and assessed. Furthermore, limitations and future research directions will be identified and recommended.

As the result of this activity, the main techniques of LST downscaling will be investigated and illustrated, including (1) coarse spatial resolution but high temporal resolution MODIS TIR data; (2) kernel-driven processes; (3) machine-learning methods; (4) compared to fusion-based method; (5) combination of a kernel-driven process with a fusion-based process method. Once achieved the TIR data down-scaling, it could be possible to reach the final goal as well, by integrating geospatial technologies with energy management, making energy players able to make data-driven decisions, optimize resource allocation, and enhance the overall efficiency and sustainability of their energy systems. Figure 4 (from (Pu and Bonafoni, 2023)) shows the flow diagram of two basic categories of down-scaling LST methods: (a) the kernel-driven process methods and (b) the fusion based process methods.

5. Case Studies

The proposed methodology is intended to be applied and evaluated firstly in a set of selected different scenarios, that cover most of the domain heterogeneity.

5.1 PV plants over city buildings

Rooftop PV plants installation over city buildings is difficult, but it becomes very challenging if the installation is supposed to be done over buildings of ancient and often high-density neighborhoods, located in historical centers (Figure 5). In order to install PV plants over ancient buildings, besides complex geometrical shapes, shading effects and rooftop availability, most often, other criteria are binding, such as safety and architectonic rules and policies applied by local governments. Nonetheless, rooftop PV plants represent a great opportunity for smart energy systems, not only to increase green energy production, but also for reducing urban greenhouse gas (GHG) emissions and the overload of electrical distribution networks.

Figure 5. A building in Rome's historical center.

Some of the architectonic constraints can be met by technological solutions, such as by the adoption of bifacial, transparent and flexible PV modules and the use of vertical arrays instead of classical horizontal ones. Other constraints can be met by GIS solutions, such as suggested in (Jiang et al., 2022), to split up each rooftop into grid cells, with a granularity (size of each cell) equal to the size of a single PV module. This technique is perfectly suitable with respect to spatial resolution of RGB satellite data. In the monitoring phase, to make buildings efficient and reduce their GHG emissions, an approach would be to continuously check their activity by TIR images.

5.2 Rooftop Agrivoltaic Systems

Building rooftops are the most suitable places for installing PV panels, in urban and rural areas as well. PV power generation is booming in rural areas, not only to meet the energy needs of local farmers, but also to provide additional power to urban areas. Furthermore, it has created competition in land use between the need for electricity and food. Rooftop PV plants can help solve this problem by increasing land use efficiency through the co-production of electricity and food and, better yet, they have also entered local industrial clusters and stimulated the local economy, at least by reducing the power costs. Conversely, PV plants installed in rural areas have often a lack of safety, due to the tough environmental conditions (wind, humidity, cold, warm) usually affecting those areas. Therefore, effective methods for predicting power generations are crucial. Many existing methods for estimating the spatial distribution of PV power generation potential either have low accuracy and rely on manual experience or are too costly to be applied in rural areas.

Accurate estimation of radiation received by the rooftops requires the existence of detailed 3D information about them, because the received radiation values is mainly caused by the area of each roof and its slope and azimuth. The following Figure 6 from (Baghani, 2023) shows the results of estimating the amount of annual radiation received for some rooftops.

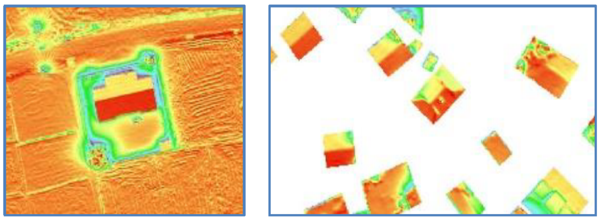

Figure 6. Effect of azimuth, slope, and area on rooftop radiation.

In order to define effective methods for power generation by PV rooftop plants in rural areas, it is then required to model the economics of these areas, especially the amount of proximity consumption by local farms, because it can well predict the local economy boosting.

Most scientific efforts have been directed toward the study of rooftop PV plants in urban areas. Therefore, the proposition of an overall method for estimating localization and power generation of PV rooftop plants in rural areas must be built by integrating more different methods.

5.3 GIS-assisted PV monitoring

Once the PV plants are designed and installed, due to high cost constraints (which are required to foster PV energy production penetration), the monitoring level of operating conditions is normally not very high. Only the most advanced PV installations are monitored on a single PV panel basis (through a detailed info about its open and closed circuit voltage, current and possibly about panel temperature in one "representative" point), while most of them are, instead, only monitored through the diagnostic capabilities of the controlling inverter (acting on a number of single serialized and/or paralleled panels). Full and correct control, optimization and diagnosis of the plant could instead only be possible having very detailed info about voltage, current, and temperature over time of the single PV cells. These informations would make it easy to evaluate whether or not those are optimally behaving and making it possible to foresee and define very fast and focused maintenance actions (e.g., single cells substitutions, panel reorientation and/or cleaning, aimed cooling actions and so on), which could substantially increase plant energy yield.

To verify whether or not the proposed approach is feasible and promising, different types of existing PV plants, varying both in size and characteristics (private/industrial, fixed/orientable, crystalline/amorphous, single/double faced) will be chosen. The performances of the newly-designed DSS, oriented to plants monitoring and maintenance, basing on data gained by high resolution periodic satellite observations both in the visible and in the infrared (IR) spectrum, will so be analytically evaluated.

Both stand-alone and plant-integrated approaches will be analysed. In this latter option, GIS data will be integrated with those coming from simple monitoring data coming from the plant itself: this approach will be more applicable in case of industrial PV plants, while the stand-alone approach is more likely to produces mobile PV plant monitoring Apps to be used on a much wider single private user scale.

Some expected outcomes of this monitoring applications could be the following:

1. Satellite observations may detect and highlight specific thermal gradients in the panels, identifying the zones where those are more frequent during panel exercise.
2. Specific monitoring algorithms may then try to identify the specific causes leading to those observed thermal gradients (e.g. panel shading; surface dirtiness; possible electric malfunctioning or partial/total disconnections; snow/ice coverage) and suggest correspondent maintenance actions.
3. Data coming from satellite images analyses will also integrated with local GIS data coming from meteo-stations (using info about icing possibility; rain presence, wind speed, air humidity), bettering the diagnoses about the plant state of health.
4. As underlined, a much deeper plant analysis will be performed in those test cases where all these GIS data will be integrated with data coming from the PV plant and describing its operative performances. Expectations are high, in this case, that GIS integrated monitoring algorithms could also lead to a substantial increase in plant energetic performances on a yearly base.

6. Conclusions

In this paper, we introduced a methodology for PV plants site selection and monitoring in the context of smart energy management. A geospatial information system should be able to collect data from various sources, such as satellite imagery, weather data, land use data, and power line network and supervise the MCDM approach to define parameters for site selection and monitoring. A first phase of data collection and integration from existing plants could be used as ground truth for new sites selection. The methodological approach, then, will be based on a scalable geospatial architecture with a user interface for both decision makers and administrators. The DSS needs algorithms for site suitability analysis based on environmental, technical, and other factors, needs to implement scenario analysis for PV plant placement, and needs to integrate risk assessment tools for potential changes of external conditions. In the monitoring phase, once the PV plant has been deployed, the geospatial system needs to be able to integrate sensors and IoT devices for data collection. In this analysis we underlined firstly the importance of LTS downscaling as a key-enabler for many activities, exposing three use cases representative of the domain. Next steps in this work will cover the implementation of the specific models for the use cases and the comparison with baselines from literature and from deployed sites' real data.

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