Mapping the Photovoltaic Landscape of Puglia Using Open Energy Data

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Abstract. The urgent need to address climate change, reduce the environmental impact of oil extraction, and respond to rising energy costs is accelerating the transition toward sustainable energy systems. Italy, like many other European countries, offers favorable conditions for the development of renewable energy, and photovoltaic infrastructure is being increasingly promoted in response to these challenges. In this context, the growing installation of solar power plants plays a central role in the transition to sustainable energy systems. However, comprehensive planning strategies specifically aimed at defining optimal locations for photovoltaic installations and monitoring the sustainability of their spatial distribution are still limited. This study integrates solar power plant datasets provided by the Gestore Servizi Energetici and World Resources Institute with geographical information system tools to evaluate the spatial distribution and characteristics of solar power plants in the Puglia region (Southern Italy). Thus, after creating a dedicated geographical database in the QGIS environment, spatial data analyses were performed to assess the distribution of solar power plants at both provincial and regional levels. The analysis provides insights into the concentration of solar infrastructure and identifies areas with higher renewable energy development. The results reveal a high spatial variability in the distribution of photovoltaic installations in Puglia, reflecting differences in land availability, solar energy potential, and infrastructure availability. There are in total more than 110,307 solar power plants installed, with an overall mean value of 32.88 kW and 12 kW for low-tension and 850 kW for medium-high tension levels, with more than 98% of power plants being small-scale installations (<200 kW).

1 Introduction

The growing demand for sustainable energy sources has accelerated the global transition to renewable energy systems [1]. Among them, solar photovoltaic technology has now become one of the most widely used renewable energy solutions due to its ability to generate electricity without producing greenhouse gases and its adaptability to a wide range of spatial scales, from small rooftops to large-scale solar power plants [2–4]. Thus, their geographical distribution has expanded significantly over the past two decades, as governments around the world promote this kind of renewable energy to mitigate climate change and reduce dependence on fossil fuels [5, 6].

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At the same time, this expansion is not without consequences. Large-scale photovoltaic installations often require substantial land areas, potentially altering existing land use and land cover (LULC) patterns [7]. In many cases, agricultural land or natural ecosystems are converted to energy production sites, raising important questions about sustainability and spatial planning [8]. Renewable energy infrastructure is therefore considered a key element in monitoring land conversion processes. Therefore, mapping and analyzing the spatial distribution of solar power plants can provide valuable information on LULC changes and their impact on the environment [9].

Recent developments in geospatial technologies have significantly improved the ability to monitor LULC at regional and global scales. Remote sensing techniques, including Geographic Information Systems (GIS), can help researchers and policymakers respond to LULC changes with greater precision in landscape models [10, 11]. Satellite missions such as Landsat and Sentinel provide continuous observations to support large-scale environmental monitoring and spatial planning [12, 13]. At the same time, the availability of geospatial energy datasets has improved considerably, allowing researchers and policymakers to better understand the distribution and capacity of renewable energy infrastructure [14, 15].

The Puglia region in southern Italy is a particular case study. Because of the high solar radiation and favorable climate, the region has experienced a massive expansion of photovoltaic installations on both domestic and commercial scales [16]. However, integrating renewable energy data from different sources remains challenging due to differences in structure, completeness, and accuracy [17, 18].

To address these issues, this study integrates and analyzes datasets on photovoltaic energy production using World Resources Institute (WRI) and Gestore Servizi Energetici (GSE) geospatial datasets. WRI is a massive geodatabase portal with both spatial and structured datasets containing information on all types of energy resources, including Wind, Biomass, Thermoelectric, and a few others. The method combines spatial processing and logical validation procedures to improve the accuracy and structural consistency of renewable energy datasets from two different sources. The main objectives of this study were: (i) creation and harmonization of a dataset for optical installations in the Puglia region; (ii) integration of external data on solar energy production from the national energy database; (iii) identify and correct inconsistencies in geographic information and features; (iv) develop an iterative approach based on GIS to maintain reliable spatial information databases for renewable energy sources.

The main contribution of the study is the creation of a harmonized, multi-source geographic database of photovoltaic installations in the Puglia region, which would be the most comprehensive open, database-based geographic database of photovoltaic infrastructure at the regional level in southern Italy. Unlike existing national registries that treat low-voltage or large-scale power plants separately, the proposed system systematically integrates both GSE table records and WRI geographic data at all capacity levels. The resulting geographic database, together with a GIS-based analytical workflow, provides a reproducible method for spatial monitoring of renewable energy, which can be extended to other regions and energy sources.

2 Datasets and Methodology

The overall workflow adopted in this study, reported in Fig. 1, was structured as a sequence of interconnected steps aimed at ensuring both data consistency and spatial reliability. The process began with the collection of photovoltaic datasets from GSE and WRI, which were first examined independently to identify differences in structure, level of detail, and completeness. This preliminary phase was essential to highlight inconsistencies that could affect subsequent analyses. Following data acquisition, a harmonization step was carried out. Attribute fields were standardized, units of measurement were aligned, and naming conventions were made consistent across the datasets. Particular attention was given to removing duplicate entries and resolving conflicting records, which are common when integrating data from heterogeneous sources.

The next stage involved spatial processing within the QGIS environment. All datasets were projected into a common coordinate reference system (EPSG:32633) to ensure geometric consistency. Spatial validation procedures were then applied, including the verification of plant locations against administrative boundaries and the correction of evident positional errors. Once the database was cleaned and aligned, the datasets were merged into a single geospatial framework. This unified database allowed for both descriptive and spatial analyses, including the classification of installations by capacity and the evaluation of their distribution at provincial and regional scales.

Finally, the workflow included a validation and quality control phase. Logical checks were performed to ensure coherence between attributes (e.g., capacity values and plant classification), while spatial consistency was re-evaluated to confirm the reliability of the final dataset. This iterative approach made it possible to refine the database progressively, improving its suitability for further analysis and interpretation.

Integrating this database with solar radiation models and grid infrastructure data will optimize future decisions on the deployment of photovoltaic plants. Ultimately, this approach will accelerate the regional energy transition in a spatially sustainable manner.

2.1 Study Area

This study was conducted in the Puglia region (Fig. 2), located in southern Italy, on the Adriatic and Ionian coasts. Covering an area of approximately 19,500 km^2, the region boasts a Mediterranean climate and abundant sunshine, making it one of the most suitable regions for the development of solar energy in Europe. The Puglia region has seen a rapid expansion of renewable energy infrastructure, especially solar power plants, in the last decade. This rapid development has led to new types of LULC, such as the conversion of agricultural land to solar power plants or the installation of rooftop solar systems in urban areas on a domestic and commercial scale. Since solar power plants are not evenly distributed across municipalities and regions, an integrated spatial framework is needed to process large-scale datasets and provide a consistent spatial view across administrative areas.

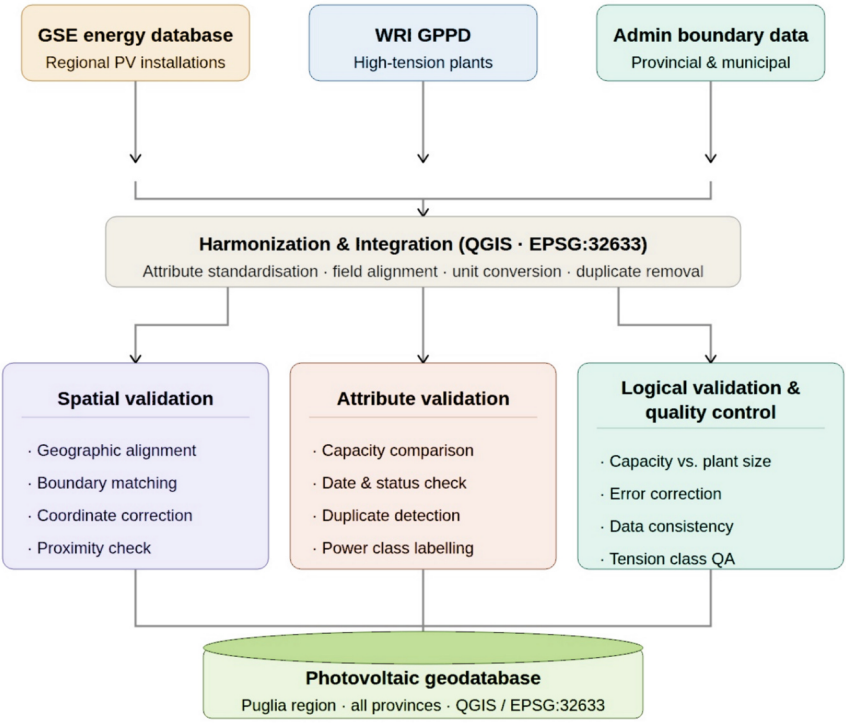

Fig. 1. Workflow of the study

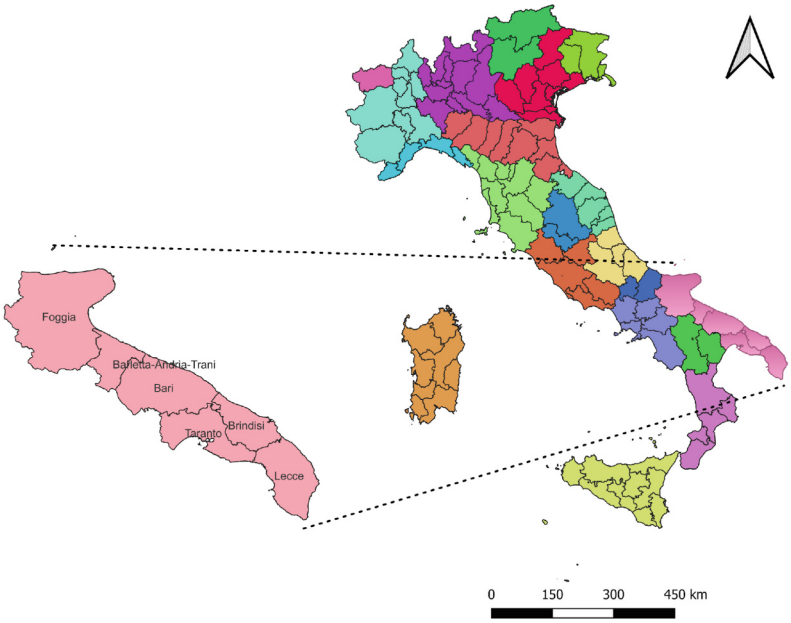

Fig. 2. Study area of the Puglia region, Italy

2.2 Data Sources

Three data sources are used for this study to integrate and harmonize the required data, which is a necessary step to perform spatial, logical, and attribute validation and quality assurance to create a photovoltaic geodatabase: i) GSE; ii) WRI; and iv) administrative boundary layer. They are described in the subsequent paragraphs.

2.2.1 GSE Energy Database

The main dataset used in this study includes tabular and structured data on solar power plants located in the administrative region of Puglia. This dataset contains spatial and descriptive information on solar power plants in the region. The website provides easy access to a GIS web database called Atlaimpianti, which is a key resource for implementing renewable energy projects in Italy. The consultation documents show renewable energy projects, from solar to wind and biomass. The platform provides analysts with tools to categorize real estate needs based on geographic boundaries (region, state, or city), energy sources, and business financing options. In addition to providing metrics such as workload and status of power plants through an interactive map, the portal facilitates the export of large amounts of data, allowing users to extract structured and raw data into spreadsheets for easier integration into analysis.

2.2.2 WRI Infrastructure Dataset

More information on solar power plants can be found on the WRI infrastructure portal (Fig. 3).

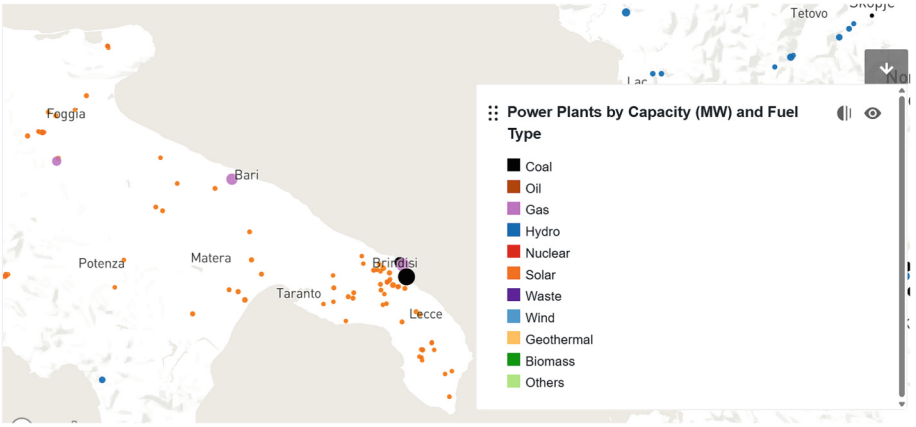

Fig. 3. WRI Global Power Plant database (GPPD) portal showing large-scale photovoltaic installations in the Puglia Region

WRI offers country-level datasets on power plants and transmission infrastructure. However, its coverage of photovoltaic systems is limited, as it mainly includes high-tension installations, while low- and medium-tension systems are not represented. Coordinates for these facilities can be retrieved through the WRI Global Power Plant Database (GPPD) portal, where geographic information is accessible via interactive visualization.

The WRI database includes several related attributes per plant, including installation capacity in megawatts, power plant type, commissioning year, and operating company. Although this makes it a valuable resource for analyzing large-scale energy infrastructure, some limitations need to be considered. In particular, while the integration of the WRI GPPD helps compensate for missing coordinate information in national datasets, it introduces constraints for detailed spatial analysis. The database represents installations as point geometries rather than spatial polygons, which limits the accurate assessment of LULC impacts.

In practice, in the Italian context, this database only includes utility-scale installations, effectively excluding micro and small decentralized plants below approximately 1 MW, which constitute approximately 90% of the physical infrastructure in the region. Therefore, local WRI data should be accurately linked to aggregated national data (e.g., GSE) to avoid overall underestimation of infrastructure.

2.2.3 Administrative Boundary Data

Administrative boundary data at both municipal and provincial levels were used to support the spatial validation of photovoltaic installations. These layers made it possible to verify the positional accuracy of power plant locations and to correctly assign each installation to its corresponding administrative unit. In addition, boundary data were used to identify and correct potential mismatches between recorded coordinates and actual territorial divisions. This step was particularly relevant for high-capacity installations derived from the Terna dataset, where occasional spatial inaccuracies have been

observed. By cross-checking plant locations against administrative boundaries, it was possible to improve the overall reliability of the geospatial dataset.

2.3 GIS Environment and Data Processing

All spatial processing and database management tasks are performed using the open-source software QGIS. The overall GIS workflow consists of a series of sequential steps, each designed to improve the consistency and reliability of the integrated dataset. The process began with preliminary data collection and initial processing, followed by database alignment and reconstruction through the integration of GSE and WRI datasets. Since the WRI database does not include micro-scale installations, particular attention was given to ensuring that smaller systems from national sources were properly incorporated. Subsequent steps focused on spatial validation and coordinate correction. These procedures were necessary to address positional inaccuracies and to ensure that all installations were correctly located within the study area. Finally, logical validation and quality control checks were applied to verify the consistency between spatial features and their associated attributes. All datasets were projected into the EPSG:32633 coordinate reference system (UTM Zone 33N) in order to maintain a consistent spatial framework across the entire analysis.

2.4 Database Alignment and Attribute Standardization

Datasets derived from different sources often present structure variations, naming conventions, and data formats. To address these issues, a series of attribute standardization procedures was implemented to harmonize the integrated database. This process included the alignment of field names across attribute tables, the normalization of text fields to avoid inconsistencies related to case sensitivity or formatting, and the conversion of numerical values, particularly installation capacity, into consistent units. In addition, duplicate and redundant records were identified and removed.

Once standardized, the dataset was further refined through spatial and logical verification. This included cross-checking the relationship between installation capacity and site characteristics, as well as identifying missing or inconsistent entries.

These steps resulted in a coherent and structured geodatabase, suitable for spatial analysis and visualization (Fig. 4). Overall, the applied procedures significantly improved data reliability and ensured that the photovoltaic system was represented as accurately as possible.

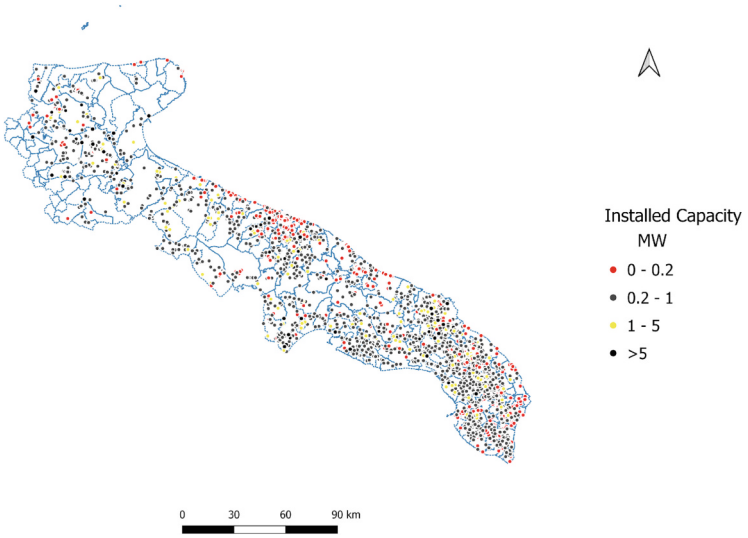

Fig. 4. Spatial Map with PV installation in the Puglia Region

3 Results and Discussion

3.1 Summary of Photovoltaic Infrastructure Data

The integrated geospatial database includes a total of 110,307 photovoltaic installations across the Puglia region, obtained through the combined use of GSE and WRI datasets. After processing and validation within the QGIS environment, the dataset provides a detailed picture of the regional photovoltaic landscape, highlighting its rapid and widespread expansion. The total installed capacity reaches approximately 3,626.96 MW, confirming the central role of solar energy in the regional energy system. On average, individual installations have a capacity of about 0.032 MW (32.8 kW), although this value masks a high degree of variability.

Indeed, installation sizes range from very small systems, close to zero capacity, to large-scale plants exceeding 42.7 MW. High-tension (AAT-AT) systems show an average capacity of around 10.75 MW, further emphasizing the coexistence of very different scales of production (Table 1 and Table 2). Taken together, these figures suggest a clearly heterogeneous structure. The photovoltaic system in Puglia does not rely on a single model but rather on a combination of decentralized rooftop installations and larger, centralized solar plants (Tables 1 and 2). This "hybrid configuration" represents a defining characteristic of the regional energy system.

Table 1. Low and Medium Tension PV Statistics

Metric	Value
Total Number of Installations	110,307

(*continued*)

Table 1. (*continued*)

Metric	Value
Total Installed Capacity	3,207.7 MW
Overall Mean Capacity	0.029 MW
Mean Capacity (Low Tension < 0.2 MW)	~0.012 MW
Mean Capacity (Medium Tension 0.2–5 MW)	~0.850 MW
Minimum Capacity	0.001 MW (1 kW)

Table 2. High Tension (AAT-AT) PV Statistics

Metric	Value
Number of Plants	46
Total Capacity	515.2 MW
Average Capacity	11.20 MW
Median Capacity	8 MW
Minimum Capacity	5.0 MW
Maximum Capacity	42.7 MW

3.2 Distribution of Photovoltaic and Electrical Installations

To better understand the nature of photovoltaic development, the installations have been divided into four power categories based on installed capacity. According to the dataset provided by GSE, small systems (less than 0.2 MW) are the most numerous. The distribution of installations across different power capacities is given in Table 3.

Table 3. Classification of PV sizes in the Puglia Region based on GSE Power Classes (Source: GSE Open Data, 2024).

Classification Size	Power Threshold	GSE Power Classes	n° Plants	Percentage of Total (%)
Micro (Low Tension)	<0.2 MW	Classes A to I	108,100	98.0%
Small (Medium Tension)	0.2 MW–1.0 MW	Classes L to M	1,655	1.5%
Medium (Medium Tension)	1.0 MW–5.0 MW	Class N	442	0.4%
Large (High Tension)	> 5.0 MW	Class O	110	0.1%
Total			110,307	100%

Micro-scale systems (<0.2 MW) overwhelmingly dominate in terms of number, accounting for approximately 108,100 installations, or 98% of the total. These systems are typically associated with rooftop installations in residential and small commercial settings. Despite their large number, their contribution to total installed capacity remains

relatively limited. The intermediate categories, small (0.2–1 MW) and medium (1–5 MW) installations, together represent only about 2% of all systems. However, their role in energy production is much more significant. With a combined capacity exceeding 1,900 MW, these installations account for more than half of the total regional output. Their average size, around 0.85 MW, reflects their importance as a backbone of the regional electricity system. Large-scale plants (>5 MW) are comparatively rare, with only around 110 installations recorded (0.1% of the total). Even so, their contribution is far from negligible. These facilities provide more than 11% of the total installed capacity, with some individual plants reaching up to 42.7 MW, such as the facility located in Cellino San Marco (Brindisi province). These larger systems are generally ground-mounted and tend to be located in agricultural or peri-urban areas, where land availability and infrastructure conditions are more favorable.

Overall, this distribution shows a clear trend, with a large number of small and medium-sized systems and few large-scale solar power plants constituting the renewable energy landscape in the region. This hybrid architecture, combining distributed rooftop generation with centralized solar stations, is a defining structural characteristic of the Puglia PV landscape and has important implications for grid management, land-use planning, and future capacity expansion strategies.

3.3 Spatial Distribution of Photovoltaic Power

The spatial analysis of photovoltaic power plants shows a varied distribution of solar power installations in the Puglia region. It reveals that all six provinces have substantial heterogeneity in both the number of installations and installed capacity, reflecting the combined influence of solar irradiance, available land, population density, and local policy implementation. The provincial distribution of solar energy is given in Table 4, with full statistics confirmed against GSE data.

The province of Lecce is the most powerful, with 33436 solar power systems and a total installed capacity of 883 MW, representing 24.3% of regional installations. This dominance is due to the favorable climate, abundant solar radiation, and the availability of land suitable for the development of the Salento peninsula, as well as a historically supportive environment for the deployment of distributed renewable energy systems. The province of Bari, with over 34868 systems and a total installed capacity of 752.5 MW, indicates a large number of distributed and large-scale solar power systems, with 20.7% of the total. Despite having the largest amount of solar systems, it reflects the province's dense urban and peri-urban fabric and widespread adoption of small rooftop systems; its per-unit average capacity is comparatively lower, indicative of a predominantly micro-scale deployment pattern.

At the same time, Foggia contributed 737 MW, indicating a moderate but strong development of solar energy, with 20.3% of the regional total having 10495 installations. Despite having fewer installations than Lecce or Bari, Foggia's high average plant size reflects a concentration of large-scale utility systems in the Capitanata plain, where land availability and grid connectivity favor utility-scale development. When high-tension (AT/AAT) installations from the WRI dataset are incorporated, Foggia contributes 98.3 MW from six utility-scale plants alone, including the 40.0 MW Vega Apulia facility. The province of Brindisi comes next with the production of 562.7 MW of

solar energy, contributing 15.5% of the regional total with 11153 solar installations. This reflects the concentration of large commercial and utility-scale plants in this province. In terms of high-tension infrastructure specifically, Brindisi is the regional leader with 19 AT/AAT plants, aggregating 192.9 MW, including the region's largest installation, which is the Cellino San Marco facility producing 42.7 MW of energy.

Next is the Province of Taranto, which constitutes 14,563 installations with 473.8 MW of solar production capacity (13.1% of the regional total) and seven utility-scale solar plants contributing 91.4 MW at the AT/AAT level. The last in terms of solar energy production is the Province of Barletta-Andria-Trani (BAT), which, as the most recently established provincial authority, it has the smallest PV footprint with 5,792 installations and 217.9 MW, accounting for 6.0% of regional capacity.

Regarding high-tension (AT/AAT level) infrastructure specifically, the WRI dataset identifies 46 utility-scale installations ($\geq$ 5 MW) in the Puglia region with a combined installed capacity of 515.2 MW, a mean of 11.20 MW per plant, and a median of 8.0 MW. These plants are consistent with the GSE-derived HT category total of 419.2 MW, with the difference attributable to boundary classification and dataset vintage. Despite representing only 0.04% of the total site count, high-tension installations contribute approximately 11.6–14.2% of the total regional installed capacity, underscoring their strategic importance in the regional energy mix. The provincial distribution of these high-tension facilities is presented in Tables 5 and 6.

Table 4. Distribution of Solar PV installations and related energy production capacity per province in the Puglia Region (Source: GSE Open Data, 2024).

Province	Total n° of Plants	Total Capacity (MW)
Bari	34,868	752.5
Lecce	33,436	883.0
Taranto	14,563	473.8
Brindisi	11,153	562.7
Foggia	10,495	737.0
Barletta-Andria-Trani	5,792	217.9
Total Puglia Region	110,307	3,626.9

In summary, the province of Lecce remains the region with the highest number of installations and total installed capacity, reflecting the dominance of distributed PV systems. However, in terms of high-transmission power, the provinces of Brindisi and Foggia emerge as the leading energy hubs, contributing mostly from AAT-AT level installations alone. Bari presents the largest raw installation count driven by distributed micro-scale systems, whereas BAT and Taranto occupy intermediate positions. This spatial differentiation between provinces reflects a fundamental duality in the regional PV landscape: a distributed model of small-scale adoption in densely populated coastal and suburban areas, contrasted with a centralized model in the more sparsely populated agricultural interior.

Table 5. Descriptive statistics of high-tension (AT/AAT) PV installations in Puglia (Source: WRI Global Power Plant Database).

Metric	Value
Number of Plants	46
Total Installed Capacity	515.2 MW
Mean Capacity	11.20 MW
Median Capacity	8.0 MW
Minimum Capacity	5.0 MW
Maximum Capacity	42.7 MW (Cellino San Marco, Brindisi)

Table 6. Provincial distribution of high-tension (AT/AAT) PV installations in Puglia (Source: WRI Global Power Plant Database).

Province	No. of Plants	Total Capacity (MW)	Grid Connection	Largest Plant (MW)
Brindisi	19	192.9	AT/AAT	42.7 (Cellino San Marco)
Bari	11	105.0	AT/AAT	24.0 (Monte di Eboli)
Taranto	7	91.4	AT/AAT	29.3 (Giga)
Foggia	6	98.3	AT/AAT	40.0 (Vega Apulia)
Lecce	3	27.6	AT/AAT	11.0 (Lecce A)
BAT	0	0.0	—	—
Total	46	515.2		

Land use patterns show that the development of solar energy is strongly influenced by land availability, infrastructure availability, and regional energy regulations. The largest solar power installations are located in agricultural and rural areas, where there is sufficient land to support this development. It is acknowledged that this study does not include an independent validation step based on fieldwork or external reference imagery. The internal consistency checks used, including cross-validation between GSE tabular data and WRI spatial records, logical attribute verification, and administrative boundary refinement, serve as a form of indirect validation but cannot fully replace external reference data. This limitation is inherent to the nature of the open datasets used and is highlighted as a direction for future work. Future studies should include high-resolution satellite imagery (e.g., Sentinel-2 or VHR data) to verify feature locations and assess the physical footprint of recorded features, especially for large features, where spatial accuracy is important for assessing land-use impacts.

4 Conclusion

The Puglia region has a highly advanced photovoltaic system, with 110307 installations and an installed capacity of over 3626 MW. This confirms its leading position in solar energy production in Italy. Its distribution varies; Lecce and Bari have the highest concentration and capacity, while areas like Foggia and Brindisi have a much lower distribution but produce a significant amount because of their high-tension, large-scale plants. This reflects regional differences in infrastructure development with variability in each province. The high concentration of small installations, combined with a low number of highly efficient solar power plants, reflects a hybrid energy model that combines decentralized and centralized production. However, the increasing presence of large photovoltaic plants in agricultural areas raises new conflicts regarding land use and the need for sustainable solar power planning. Overall, the development of photovoltaics in Puglia is an essential driver of the regional energy transition and a key factor influencing land use dynamics. Future strategies should help integrate sustainable solar energy systems into the built environment, minimizing the use of fertile land and ensuring a balance between the development of renewable energy sources and the protection of natural resources.

The GIS-based methodology applied in this study by integrating spatial validation, attribute standardization, coordinate correction, and logical quality control, proved effective in resolving the inconsistencies inherent in merging national administrative data (GSE) with a global infrastructure dataset (WRI). The resulting geodatabase provides a reliable and analytically tractable representation of the regional PV landscape. The increasing penetration of utility-scale solar plants into agricultural and perirural areas raises important challenges regarding land-use competition, soil sealing, and coexistence with agrivoltaics. Future research should extend this framework to integrate temporal monitoring of land-cover change using remote sensing data (e.g., Sentinel-2), enabling quantitative assessment of the landscape transformation associated with PV expansion. The integration of this database with solar radiance models and data on grid infrastructure could further help optimize future decisions on the deployment of photovoltaic plants and accelerate the regional energy transition in a spatially sustainable manner.

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