From Open Land to Built Surfaces: Spatial Analysis and Remote Sensing for Photovoltaic Energy Computing

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Abstract. This work comes from a simple but urgent question: how can we produce clean energy without consuming our most precious resources, namely soil, landscapes and the memory of places?

Photovoltaics is one of the great hopes of the energy transition. But when it is installed on the ground, transforming countryside, hills and natural areas into fields of panels, we risk replacing one problem with another. The landscape changes, the soil is lost, and local communities perceive it as an imposition rather than a shared transformation.

Our contribution aims to change this point of view: what if all this energy could be generated without consuming new space, but by enhancing what already exists? The roofs of houses, agricultural sheds and industrial buildings can become a new "energy surface", capable of producing without taking away, thus minimizing the impact on the landscape and land consumption.

The research proposes an integrated method of spatial analysis and remote sensing that helps to design scenarios in which the ecological transition respects the meaning of places and does not pit energy against landscape, but allows them to coexist; in fact photovoltaics can only be sustainable if we start from a new perspective, capable of accompanying the use of technology.

Keywords: photovoltaic · landscape · spatial analysis · solar radiation · remote sensing

1 Introduction

The energy transition is a global challenge that is increasingly affecting public policy, with significant effects on territorial, economic and social systems. In Europe, with the "Clean Energy for All Europeans" package, the Commission has been promoting since 2016 an acceleration of the transition to clean energy by 2030, promoting an increase in the share of energy from renewable sources to 42.5% by that date [1]. Subsequently, Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources [2] and the Communication on the European Green Deal and Regulation (EU) 2021/1119 [3], establish the framework for achieving climate neutrality.

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The EU's commitment is therefore focused on reducing emissions and promoting sustainable growth models, which has led, especially in recent years, to a significant increase in the number of renewable energy plants.

However, while the spread of renewable energy sources is an essential step towards low-emission energy systems, the methods used to install the related infrastructure are not always without problems. The installation of large photovoltaic (PV) plants in rural areas or areas of environmental and landscape interest contributes to land consumption, alters the hydrogeological balance of the land and has a negative impact on the quality of the landscape and the protection of natural environments, raising questions about the real sustainability of such choices. The transformation of large rural areas into "photovoltaic fields" is perceived by local communities as an irreversible alteration and aesthetic degradation of the rural landscape, which is often protected for its historical and cultural value [4, 5].

With regard to the aforementioned land consumption, according to the European Green to Grey project (https://greentogrey.eu/), Europe loses approximately 1,500 km^2 of natural and agricultural areas every year. This data shows us how land transformations must be carefully evaluated and planned within the context of territorial and energy policies.

This project therefore aims to identify a methodological approach based on spatial analysis and remote sensing capable of estimating, once a large sample area has been identified, how much energy can be produced by converting the installation of panels on buildings and whether this energy is sufficient to cover the energy needs of the study areas. Consequently, energy modelling and scenario assessments are carried out, allowing energy suitability maps to be set up and the real contribution of PV on buildings to the decarbonisation of the local energy system to be assesses.

The expected results will provide evidence-based recommendations to support policy makers, spatial planners and stakeholders, promoting a more balanced integration of renewable energy, land use planning, agricultural landscape conservation and cultural heritage protection.

2 Study Area

The study area includes the three neighboring municipalities (Fig. 1) of Tito, Sant'Angelo Le Fratte and Satriano di Lucania, located in the Basilicata Region (southern Italy) and treated as a single case study, as they have similar geomorphological, settlement and climatic conditions. In particular, with regard to settlement, all three municipalities have historic centers with a strong landscape identity and the simultaneous presence of an industrial and craft area, which is particularly developed in Tito. In addition, all three municipalities have fairly active agricultural areas.

The sample chosen is representative of many rural areas in inland Italy, meaning that the proposed framework can easily be transferred to other similar contexts.

A preliminary mapping of the PV panels present in the studied area shows the results reported in the Tables 1 and 2 and represented in Figs. 2 and 3: in Tito, PV is distributed in a complex mix, energy-intensive but land-consuming, as a large number of plants are located on industrial land, but also on agricultural land. In Satriano di Lucania, there is

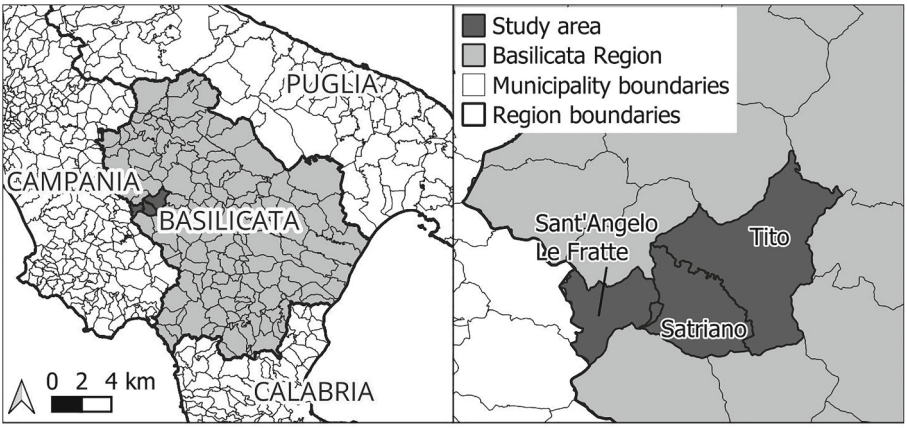

Fig. 1. Territorial overview of the study area.

strong pressure on the land as PV is mainly ground-mounted. In Sant'Angelo Le Fratte, mainly already built-up areas have been exploited, so at present, land consumption by PV plants is practically zero.

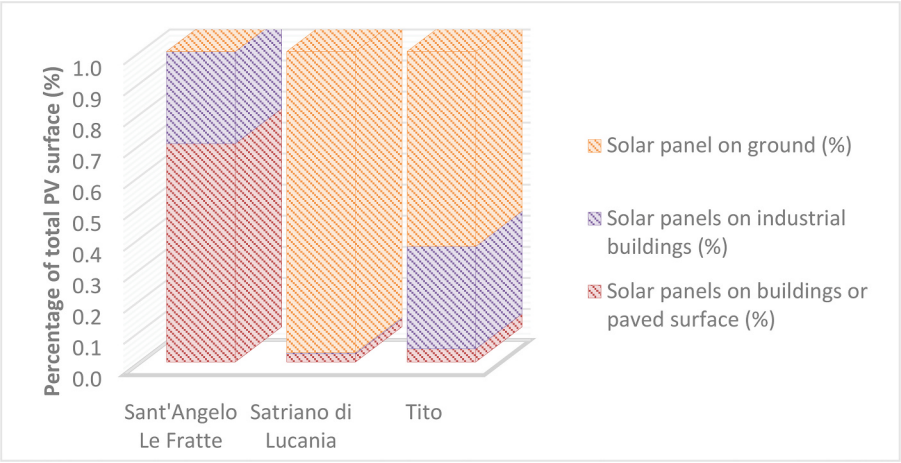

Fig. 2. Distribution (%) of PV installations by support type in the three studied Municipalities.

In addition, a building density was calculated for the study area (Fig. 4). The upper box shows the density taking into account only buildings, while the lower box also includes PV panels located in the area. The areas outlined in black show how the construction of these plants leads to an increase in density and, consequently, to land consumption.

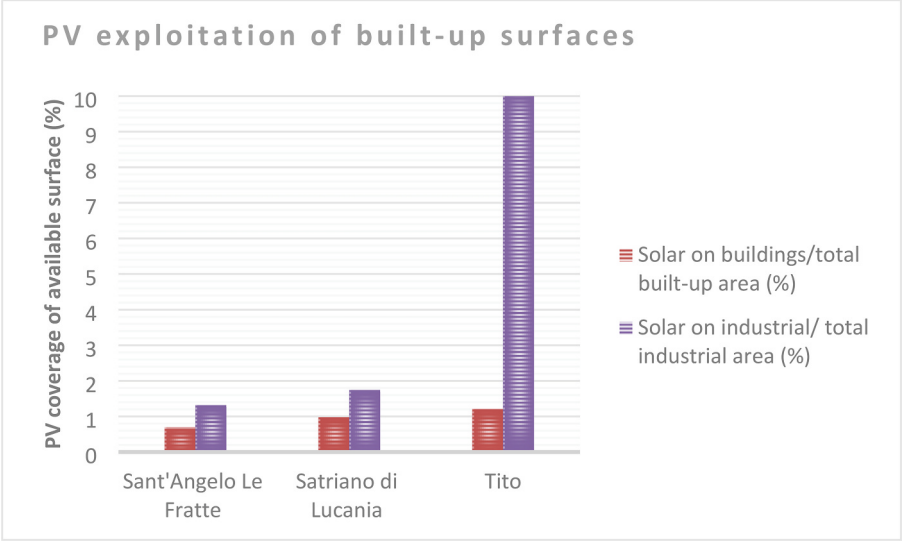

Fig. 3. PV exploitation (%) of built-up surfaces (not-industrial in red vs industrial in violet).

Table 1. PV areas extension (m^2) and percentage on buildings/paved, industrial elements and ground-mounted for the municipalities studied.

Municipality	PV areas on buildings or paved surface (m^2)	PV areas on industrial buildings (m^2)	PV areas on ground (m^2)	Total PV areas (m^2)	% PV on buildings or paved surface (%)	% PV on industrial buildings	% PV on ground
Sant'Angelo Le Fratte	1118	472	0	1591	70.3	29.7	0.0
Satriano di Lucania	2696	433	99359	102488	2.6	0.4	96.9
Tito	7149	55966	106152	169267	4.2	33.1	62.7

3 Materials and Methods

3.1 Datasets Used in This Work

In this paper multi-source spatial datasets were used to spatial assess the comparison between PV suitability on built and agricultural surfaces. More in particular the following resources were used:

Table 2. Data related to PV areas distribution in not-industrial or industrial built-up areas.

Municipality	Built-up areas excluding industrial (m^2)	Industrial areas (m^2)	% PV areas in built-up areas	% PV areas in industrial areas
Sant'Angelo Le Fratte	161931	35436	0.69	1.33
Satriano di Lucania	275038	24861	0.98	1.74
Tito	585005	543865	1.22	10.29

- Digital Surface Models (DSM), provided by Basilicata Region, to consider elevation and including buildings and vegetation. From the DSM slope and aspect were derived, in order to calculate solar radiation in a more realistic way.
- Building footprints, from the Regional Spatial Data Infrastructure (RSDI) of Basilicata, also containing the use information for each polygon.
- Data about the features protected by the Regional Landscape Plan, from the Regional Spatial Data Infrastructure (RSDI) of Basilicata, also containing the needed information for each polygon.
- Cloud cover, provided by Copernicus Sentinel-2 MSI Level-2A Surface Reflectance, accessed via Google Earth Engine (GEE; collection: COPERNICUS/S2_SR). In particular cloud information was derived from the Scene Classification Layer (SCL).
- Population data were obtained from Istituto Nazionale di Statistica (ISTAT).

3.2 Google Earth Engine©

GEE is a free, powerful platform that allows the analysis and monitoring of remote sensing big data at the planetary scale.

The first GEE version went out in 2001, but it was publicly released in 2010. 2001 could be the internal release date of the platform. And today it is still used very much in many application fields [6] in general for the global-scale earth observation data extraction and analysis [7], but more in particular, just to cite some examples, for land use mapping [8] and monitoring and natural risk assessment ([9] and reference therein), for population mapping [10] and climate data analysis [11].

The use of GEE offers many advantages. It gives the possibility to work with large dimension data (satellite data but also vector GIS data), without downloading them on pc, even if the download is possible, also because many of these data are freely available. At the same time, the calculation time is very fast, thanks to the cloud elaboration, more than it would be possible on a personal computer. It also gives the possibility to upload the user's data, if needed. Moreover, the GEE platform has an efficient versioning system and offers a flexible access to its code through APIs. Finally, even if the code developed by the user is online, the ownership remains to its developer, even if it could decide to share it.

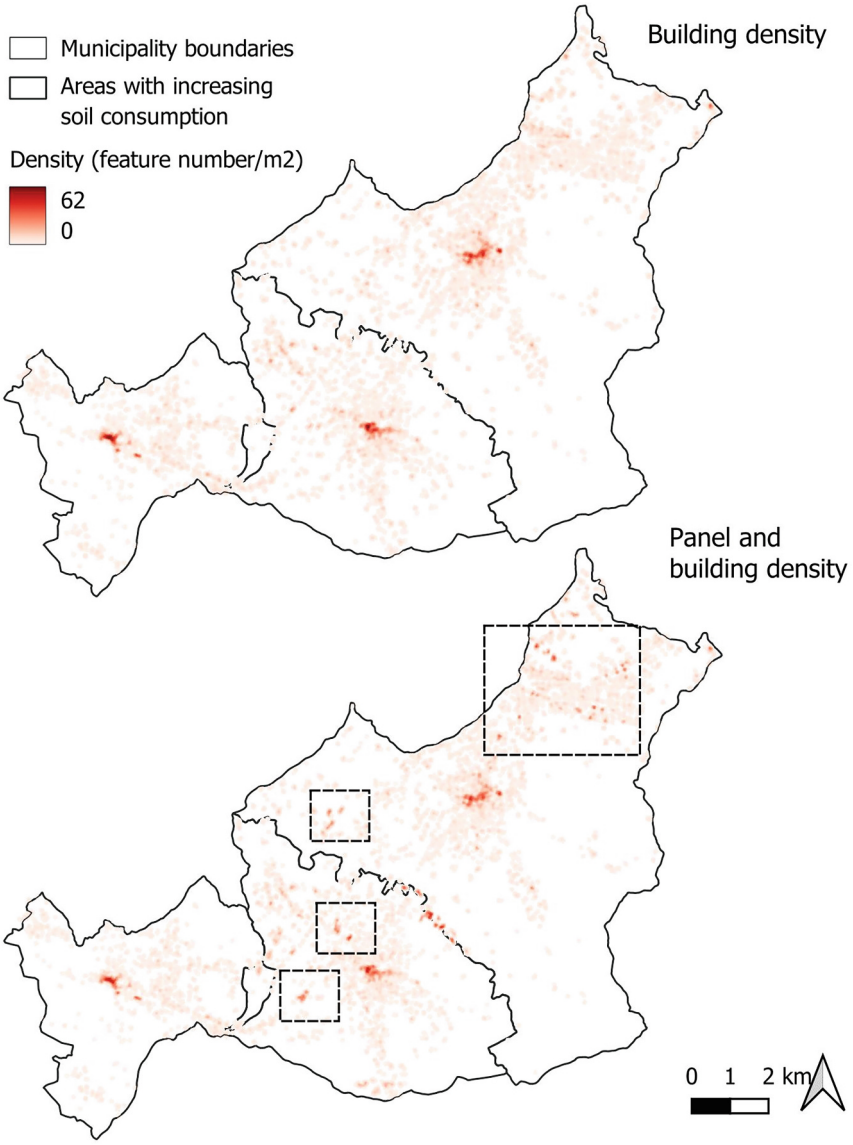

Fig. 4. Building and panel plus building density distribution.

3.3 Solar Radiation

The global solar radiation is the sum of the direct, diffuse and reflected radiation coming from the sun.

In this paper, for the calculation of the solar radiation direct and diffuse components, the Raster Solar Radiation tool [12–14] in ArcGIS Pro (ESRI) was used. It allows to map

the effects of the sun in a chosen period; in particular it allows to compute the incoming solar radiation, also called insolation, in every pixel of a raster surface.

To do this, the tool implements a multistep process:

1. It implements an upward-looking hemispherical viewshed, overlayed with a sky map expressed as azimuth angle useful to see how much of the sky is visible in the chosen time interval, by azimuth direction and for each angle of elevation; in this way a sort of horizon profile is then produced.
2. After this, the Direct Normal Irradiance can be calculated, because for the considered hours, days and latitude, it is possible to understand if from each pixel the sky (and consequently the sun) is visible or covered.
3. Then the Diffuse sky map is calculated. In this case the radiation derives from all the sky vault even if the local horizon is considered.
4. The first three steps are repeated for all the pixels, where the direct and diffuse radiation are summed for all the period considered.

The result is an insolation map expressed in kWh/m^2.

The main parameter that influences this calculation is topography; in fact, the spatial variation of elevation, slope, aspect and hillshade affects the total of insolation registered in each pixel. For this reason it is important to have: (1) high-resolution layers representing topography (2) to use, together with a Digital Elevation Model (DEM) a Digital Surface Model (DSM). This last, in fact, by reporting the presence of object on the terrain surfaces could change dramatically the hillshade distribution during the day and consequently also the cumulated insolation.

It also depends from time of the day (night vs day) and of the year (seasonality) and from the presence of clouds or dust, that scatters it.

4 Results

4.1 First Solar Radiation Calculation

Firstly the solar radiation was calculated for each season (Fig. 5). As expected, the seasonal solar radiation map varies depending on spatial variations in the morphology of the territory, increasing on south-facing slopes and ridge areas and decreasing on north-facing slopes and valley floor areas. The radiation classes represented were adapted to the range of each season, with an increase in cumulative radiation in spring and especially in summer, while it decreases in autumn and especially in winter.

4.2 Cloud Coverage Correction

At this point, in order to make a realistic estimate of the solar energy that can be produced in the study area, cloud cover must also be assessed. In fact, solar radiation is calculated in ArcGIS under unrealistic conditions of constant clear skies. For this purpose, a script has been developed in Google Earth Engine (GEE) that can estimate, with the help of Sentinel-2 Surface Reflectance data, the fraction of cloud cover on a daily basis using the Scene Classification Layer (SCL). This makes it possible to extrapolate, on

a daily basis, the average area fraction of the study area covered by medium and high probability cloud cover and cirrus clouds (8, 9 and 10). Of these bands: (1) 8 is more representative of widespread cloud cover involving moderate attenuation, (2) 9 reports the presence of very opaque clouds and therefore strong attenuation of direct radiation, but underestimates the presence of days with more extensive but less thick cover, 3) 10 takes into account cirrus clouds, which have a variable but generally less intense effect on radiation. Therefore, for prudential purposes and to obtain a summary indicator of cloud cover, the maximum value among the three daily fractions was calculated, thus considering the most penalising conditions.

The cloud cover values were then aggregated into four percentage classes (0–25%, 25–50%, 50–75% and 75–100%) on a seasonal basis for 2025, as shown in Table 3.

In order to calculate a seasonal weighted average based on the frequency of atmospheric conditions in relation to the type of sky, Cloud Reduction Factors (CRF) were introduced (Table 4). These are useful for attenuating solar radiation with clear skies (R_{cs}) and calculating a more realistic radiation value (R_{real}), according to Eq. 1.

$$R_{real} = R_{clear-sky} \cdot F_{season} \tag{1}$$

The correction factor (F_{season}) was calculated by combining the day number (d_i) and the CRF_i with a i cloud coverage percentage according to (Eq. 2):

$$F = \frac{d_{0-25}CRF_{0-25} + d_{25-50}CRF_{25-50} + d_{50-75}CRF_{50-75} + d_{75-100}CRF_{75-100}}{N} \tag{2}$$

where N is the total days of the season.

4.3 PV Surfaces Selection

After calculating solar radiation, buildings suitable for PV installation were selected, on the basis of which solar energy production was subsequently estimated.

The following criteria were used:

1. Buildings not belonging to the cultural heritage, including those located in the historic centers of the three municipalities in question.
2. Buildings with available surfaces of no less than $10m^2$.
3. Buildings with roofs with a slope of no more than 60°. This was calculated by estimating the median slope derived from the DSM.
4. Buildings with an industrial use all have a flat slope, so they were all considered.
5. Buildings with a residential use mainly have roofs with a gable roof. The direction of the ridge line was calculated. If the roof has a north and south orientation the half of the surfaces was considered for PV (only for the part exposed to south). Otherwise, with an east-south orientation the total surface was considered suitable for PV installation.

Furthermore, only free elements on which PVs are not already positioned were considered in the calculation, as already explained in Sect. 2. Totally 1,054,800 m^2 of suitable rooftop surfaces were found.

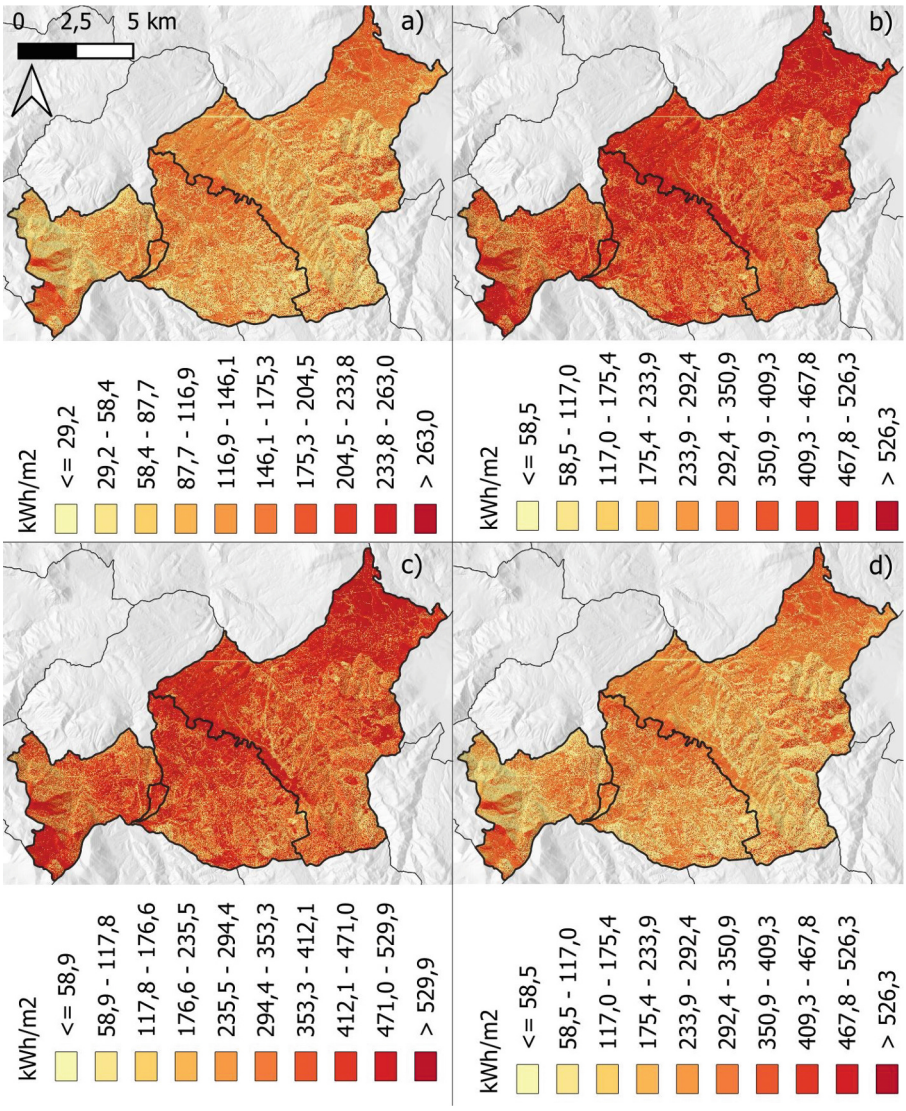

Fig. 5. Solar Radiation in (a) winter, (b) spring, (c) summer, (d) autumn.

4.4 Energy Production

In order to calculate the yield of the panels, at this point, each suitable building was associated with the average seasonal global solar radiation calculated as explained in Sect. 4.2 using zonal statistics. Then the energy producible (E_p) can be calculated as (Eq. 3)

$$E_p = R_{real} \cdot \eta \cdot PR \cdot \mathrm{A} \tag{3}$$

where

Table 3. Number of days with cloud (cirri, high and medium) probability clouds coverage percentage for each season.

Season	Cloud coverage %	Cloudy days	Season	Coverage %	Cloudy days
Winter	0–25%	28	Spring	0–25%	62
	25–50%	11		25–50%	9
	50–75%	24		50–75%	6
	75–100%	28		75–100%	14
Summer	0–25%	81	Autumn	0–25%	64
	25–50%	6		25–50%	8
	50–75%	2		50–75%	7
	75–100%	2		75–100%	12

Table 4. Data related to FV areas distribution in not-industrial or industrial built-up areas.

Coverage percentage	CRF	Meaning
0–25%	0.98	mostly clear skies, slight attenuation
25–50%	0.80	moderate attenuation
50–75%	0.55	heavy cloud cover
75–100%	0.25	very overcast sky

- η is the module efficiency, linked to the technology used in the panels and represents the ratio between the power output and the solar energy converted into electricity under STC conditions (ground irradiance of 1000 W/m^2, temperature of 25 °C and spectral distribution AM = 1.5).
- *PR* is a performance ratio of the panels. It provides information on the quality/yield ratio of the system, and therefore on system losses, such as those resulting from temperature, the inverter, mismatch situations, shading, soiling, etc. (related to system losses).
- *A* is the usable surface area (as described in Sect. 4.3) of suitable buildings (Table 5).

A summary of the technical literature in the field [15–17] shows that the average values of the indices mentioned can be those shown in Table 6. A conservative assumption was made when selecting these values in order to avoid overestimating the energy potential. Consequently, the actual energy production could be higher than the calculated values.

4.5 Energy Consumption

In order to estimate energy consumption, the average annual per capita electricity consumption was considered, equal to 5047kWh [18]. This one refers to total electricity

Table 5. Average η and PR values for Energy production.

Scenario	η	PR	Usage
Conservative	0.20	0.75	Regional studies with high uncertainty regarding shadows, dirt, BOS quality; or when you want to avoid overestimates
Central	0.22	0.80	Default for rooftops in Italy with modern modules and standard systems
Optimistic	0.24	0.85	Best-case scenario with premium modules (>24%) and excellent design/management (PR towards the high end of the modern range)

consumption and has been multiplied by the total number of inhabitants deduced from the ISTAT 2025 population data. The method used was intended as an estimate of electricity demand based on demographic proxies and was necessary due to the lack of disaggregated and updated data available at the sub-municipal level. This is consistent with the approach taken, which does not aim to provide a detailed analysis of sector energy loads but rather to summarise the overall electricity demand in order to compare it with energy production and understand whether the supply of PV, shifted to rooftops, can meet the demand. Table 6 shows the final calculated values, which identify a supply potential in terms of energy produced (E_p) that is significantly higher than the energy consumed (E_c).

Table 6. Conversion of the solar radiation in Energy producted (E_p), seasonally and annually and comparison with annual Energy consumption (E_c).

Season	Solar radiation (kWh/m^2)	E_p (kWh)	Annual E_p (kWh)	Annual E_c (kWh)
winter	874,761	13,768,300	152,794,600	53,361,931
spring	3,601,130	55,391,100		
summer	4,172,990	64,174,000		
autumn	1,237,340	19,461,200		

5 Discussion and Final Conclusion

This study aimed to propose an integrated approach that combines spatial analysis and remote sensing in order to verify if the installation of landscape-aware photovoltaic systems, which can be installed on building roofs, is capable of guaranteeing energy potential comparable to ground-mounted installations, thereby minimizing the consumption of agricultural land and the impact on the landscape. In light of the results obtained, it

can be said that this hypothesis is solidly supported by empirical evidence in the sample area analysed.

The analysis conducted with the aid of geospatial analysis tools (GIS) was based on the integration of seasonal solar radiation modelling, cloud cover correction using Sentinel-2 data processed in Google Earth Engine, and morphological and functional selection of building coverings, which made it possible to construct a realistic and prudent energy scenario. The application of CRFs to radiation in clear sky conditions further improved the reliability of the estimates, surpassing the simplified approach typical of some GIS modelling based on ideal atmospheric conditions.

The total area of suitable roofing identified (1,054,800 m^2), selected by excluding listed buildings belonging to the cultural heritage and located in historic centres, and buildings with morphological and dimensional limitations on roofing, as explained in Sect. 4.3, represents a "latent energy infrastructure" already integrated into the urban and productive fabric. The adoption of conservative parameters for module efficiency (η) and Performance Ratio (PR), consistent with the indications in the literature, has avoided overestimating the producible potential. It follows that the values obtained can be considered a minimum precautionary threshold.

The energy balance carried out by comparing producible energy (E_p) and consumed energy (E_c), this last estimated by using a demographic-proxy based on ISTAT population data for 2025, highlights a potential production that resulted significantly higher than the total electricity demand in the study area.

This result is particularly significant considering the context of European decarbonisation policies, outlined in Directive (EU) 2018/2001 and Regulation (EU) 2021/1119 on climate, which aim to achieve climate neutrality by 2050. In fact, this study shows that the objectives of increasing renewable energy sources can also be pursued through territorial strategies that do not involve further consumption of agricultural land or compromise the rural landscape. This responds to the critical issues frequently associated with large ground-mounted photovoltaic plant.

From a spatial planning perspective, this work aims to emphasise that buildings are no longer merely a passive element of urban metabolism, but are becoming an active support for energy transition. The available surface area of building roofs, when properly mapped and assessed, can form the backbone of local energy communities and distributed generation models, reducing territorial conflicts and promoting the social acceptability of interventions.

The methodology presented in this paper could also have further improvements. For example, there is the need to deepen the analysis by using disaggregated energy data, possibly at the building level. This would make possible to refine electric demand estimates, by also considering and integrating data related to socio-economic and performance variables of buildings and of people who live in them. Furthermore, the integration of photovoltaic production and energy efficiency in the building stock is an essential condition for maximising the environmental and social benefits of the transition.

Looking ahead, extending the analysis to other already impermeable surfaces (car parks, production areas, urban and peri-urban vacant lots) could further strengthen the

capacity to produce energy without taking away agricultural or natural land, consolidating an energy development strategy consistent with landscape protection and the principles of sustainable planning.

In conclusion, the results show that photovoltaic planning supported by GIS and geared towards enhancing existing buildings can offer energy potential comparable to ground-mounted solutions, significantly reducing the impact on the landscape and land consumption. From this perspective, the energy transition is not a process of spatial replacement, but rather an operation of reinterpretation and reactivation of existing territorial heritage, in line with a model of sustainability that integrates energy, landscape and local communities.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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