GIS-Based Approach to Evaluate the Photovoltaic Potential of a Territory: The Case Study of the Municipality of San Severo in the Apulia Region

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Abstract. This study explores a Geographic Information Systems (GIS)-based approach to assess the photovoltaic (PV) potential of a specific territory, focusing on the municipality of San Severo in the Apulia Region, Italy. The research highlights the growing need for renewable energy sources (RES) in response to climate change and the global energy transition. Using GIS, the study evaluates solar radiation, land use, and technical constraints to identify suitable locations for PV installations, including agrivoltaic systems that integrate agriculture and solar energy production. The methodology combines spatial analysis and environmental data to optimize energy planning while considering landscape and policy constraints. The results demonstrate the effectiveness of GIS tools in supporting sustainable energy development and local decision-making processes. This case study provides a replicable model for assessing solar energy potential in other regions with similar climatic and geographical characteristics.

Keywords: Renewable Energy Sources (RES) · GIS · photovoltaic systems · agrivoltaics · climate change · energy transition

1 Introduction

Critical long-term phenomena, such as climate change, have a direct impact on the cities, their pollution and rainfall levels, the aging of buildings and the relative energy consumption [1–3]. In the light of this, the ongoing climate emergency requires an integrated approach that must encompass the energy transition towards renewable sources [4, 5], in order to speed up the decarbonization process.

Renewable Energy Sources (RES) have the potential to produce clean and low-cost energy, being a driver for the enhancement and development of the territory by

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sharing locally generated energy through models called Renewable Energy Communities (RECs) [6, 7]. In this scenario, photovoltaic (PV) technology plays a leading role for the achievement of the 2050 decarbonization targets, provided by European Union (EU) [8, 9], and national legislation through the Integrated National Energy and Climate Plan (Piano Nazionale Integrato per l'Energia il Clima – PNIEC) [10, 11]. Since ground-based PV farms compete with food production for land allocation, solutions as agrivoltaic systems (APV), namely the shared use of land for food and energy production, allow to implement PV minimizing the related land use [12, 13]. As European, national and regional policies related to RES, in particular the above-mentioned models of energy production and consumption with low environmental impact, require to consider the impact on the agricultural sector, the location of electricity production plants in areas classified as agricultural must take into account this indication, with particular reference to the enhancement of local agri-food traditions, the protection of biodiversity, as well as the cultural heritage and the rural landscape. RECs and agri/photovoltaic systems can help to achieve the objectives within the framework of energy and climate policies at EU and national level and are also a promising solution to grow clean energy in an integrated way with the territory, in a systemic vision that holds together ecology, energy, landscape, with a view to the multifunctionality to which the agricultural systems should tend.

To this end, this research work wants to explore in a GIS environment, built through the Quantum GIS (QGIS) open suite [14], the energy potential, connected with the extensive use of photovoltaic systems installed on existing buildings and agricultural areas, of the Municipality of San Severo belonging to the Apulia Region and located in the southern of Italy, where, as the average irradiation values are among the highest in the Italian peninsula, these plants are generally characterized by high performances [15]. GIS tools have been extensively used to evaluate the economics of utility-scale photovoltaic system [16], to identify the optimal sites for PV power plants [17–19] and assess the photovoltaic potential of particular areas [20, 21]. The specialization of a part of rural areas towards this this form of energy production could represent an effective response to climate change and a reduction in dependence on fossil fuels to mitigate related economic and environmental impacts [22].

2 The Study Area

San Severo is an Italian municipality of about 50000 inhabitants located in the northern part of the Apulian territory close to the borders with Molise region. The economy of this area, based on mercantile and agricultural traditions, it is essentially focused on the tertiary sector. The municipality, positioned at the center of a road network in the northern part of the Tavoliere delle Puglie, which is the second largest plain in the peninsular Italy after the Po Valley, extends between the Dauni Mountains to the west, the Gargano promontory and the Adriatic Sea to the east, the Fortore river to the north and the Ofanto river to the south (Fig. 1).

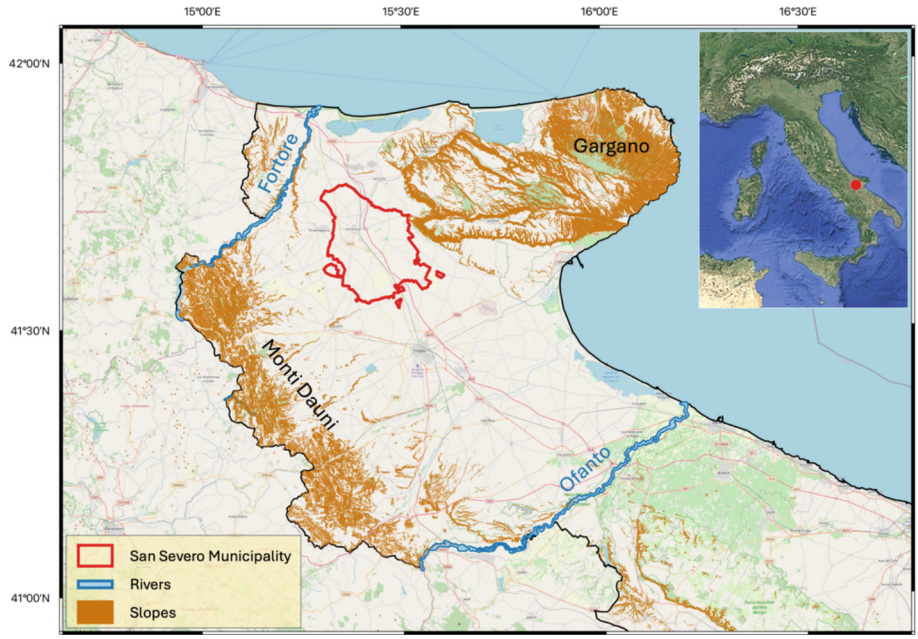

Fig. 1. The municipality of San Severo (highlighted in red), located in the Tavoliere delle Puglie plain (base layer: OpenStreetMap).

3 Methodology of Investigation

The proposed methodological approach aims to create a prototype for a dynamic database easily accessible through a GIS environment and useful for territorial planning purposes, from which retrieving the diffusion of the RES already present in urban and rural areas, as well as the determination of the areas suitable for the installation of plants and the related potential to cover the energy needs of the local community, obtainable from a photovoltaic source.

The investigation has been based on the following steps:

1. the definition of the GIS model, entailing the delimitation of the boundaries and the size of the study area, the choice of the datum and the basic information layers;
2. the acquisition of a vector cartography at an adequate scale (i.e. 1:5000) so as to be able to build a digital model capable of representing the elements of interest (buildings, sites, existing plants, etc.), the complex morphology of the built urban space and the rural one. Specifically, the technical and thematic maps made available through the Sistema Informativo Territoriale (S.I.T.) - Puglia portal [23] (namely digital orthophoto and Regional Technical Map (CTR) were used as base informative layer). The cadastral database has been also added into the system to retrieve information on the surfaces available for hosting photovoltaic modules;
3. the computation of the energy demand at municipal level retrieved by analyzing public databases;

4. the area potentially available for agrivoltaics plants, according to the legislative requirements;
5. the set-up of a quantitative indicator useful to evidence the solar energetic potential at urban and rural scale, to quantify the efficiency of a possible massive use of RES on the study area;
6. as conclusive step, the analysis of locally available energy resources by deriving the potential annual total amount of energy production from RES, in GWh.

Since energy planning cannot disregard the available resources of the territory, the possible location of new production plants has been optimized according to the criteria established for the identification of surfaces and areas suitable (or not suitable) for the installation of renewable energy plants. In this phase of the work, the guidelines and regulatory instruments on renewable energy sources specified in the following sections were taken into consideration. On this basis, the photovoltaic potential of plants located in rural areas and on buildings have been derived following the provisions dictated by technical standards and legislative instruments.

4 Energy Balance at Municipal Level

4.1 Quantitative Analysis of Current Energy Consumption

To properly plan the actions to be taken for sustainable development with a view to energy transition, it is essential to consider the data relating to the energy demand for electricity. To this end, publicly accessible databases have been analyzed, and specifically:

1. as regards the demographic development, the National Statistical Institute (ISTAT) database containing the number of families, inhabitants and production activities;
2. for electricity consumption, the information provided by Terna S.p.A, manager of the national electrical distribution network, albeit as aggregate values at a provincial level.

Starting from the energy consumption at provincial level, the electricity consumed by the municipality of San Severo has been estimated based on the value per inhabitant available for the province of Foggia, as well as the distribution of local consumption in the sectors of agriculture, domestic industry and services, obtaining a total amount of 152.70 GWh for the year 2022. Table 1and Fig. 2 show the energy requirements for the reference year in the study area, with a focus on the domestic and agricultural consumption.

The domestic consumption amounts to 29%, while the agricultural sector covers 7% of the total electricity demand. The share of energy consumption of the agricultural and domestic sectors, as equivalent CO_2 emissions, according to the respective emission factor for national gross thermal production, with an estimated average value of 415.5 g CO_2/kWh, results into 227153.9 tons of CO_2 equivalent of greenhouse gas emissions in one year (Tables 2 and 3).

Table 1. Average electric consumption, municipality of San Severo (FG).

PROVINCE OF FOGGIA					
ELECTRICITY CONSUMPTION (GWh per Year) – source Terna S.p.A. 2022					
YEAR	AGRICULTURE	HOUSEHOLD	INDUSTRY	SERVICES	TOT.
2022	118.46	545.31	537.05	649.77	1848.59
MUNICIPALITY OF SAN SEVERO					
ELECTRICITY CONSUMPTION (GWh per Year)					
YEAR	AGRICULTURE	HOUSEHOLD	INDUSTRY	SERVICES	TOT.
2022	9.79	44.88	44.36	53.67	152.70

DEMOGRAPHIC DATA (Istat 2022)		
	Population	N. of families
Prov. of Foggia	599028.00	
Mun. of San Severo	49481.00	20446.00

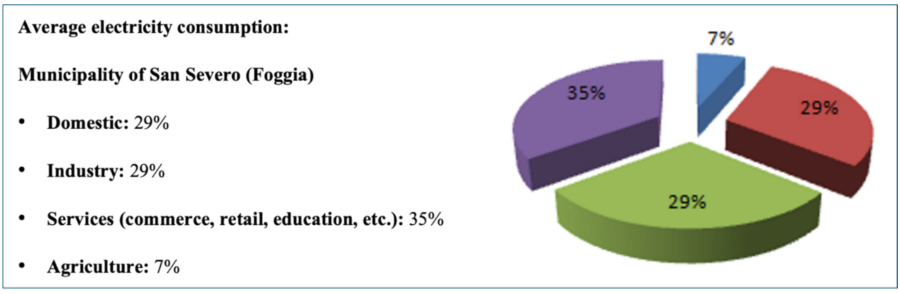

Fig. 2. Average electric consumption of each category, municipality of San Severo (FG).

Table 2. CO_2 emissions by the agricultural and domestic sectors.

CO_2 EMISSIONS (tons)			
Year	AGRICULTURE	DOMESTIC	TOT.
2022	40677.50	186476.40	227153.90

4.2 Energy Plants in the Study Area and Annual Energy Needs

The renewable energies plants, whether from photovoltaics or wind, are by their nature scattered throughout the territory. It is then fundamental to evaluate the impact of already existing plants on the decision-making process. In the following table, the energetic balance of the municipality is analyzed, with a focus on the electricity consumption in the above-mentioned sectors, and the corresponding RES production. A geographic database, containing the main information on renewable energy production plants, has been built starting from the information made available by the Italian Energy Services Manager (Gestore Servizi Energetici – GSE) through the Atlaimpianti Webgis [24], and integrated with the CTR and the cadastral map (Fig. 3).

Table 3. RES energy balance at municipal level.

Energy balance – Municipality of San Severo (GWh/year)					
Sector	AGRICULTURE	DOMESTIC	INDUSTRY	SERVICES	TOT.
Total demand	9.79	44.88	44.36	53.67	152.70
Total production	4.75	1.63	0.08	0.23	6.69
Deficit	**-5.04**	**-43.25**	**-44.28**	**-53.44**	**-146.01**

5 Assessment of the Agrivoltaic Potential

The potential of agrivoltaic of the San Severo territory has been then explored, by identifying the areas with compatibility and sustainability characteristics according to the legislative requirements. Aside of the inevitable land consumption, these infrastructures impact on the surrounding environment also in terms of landscape. Therefore, the relation between areas suitable and not suitable to host these plants has been explored in the GIS environment, to quickly deduce the presence and territorial diffusion of photovoltaic technologies in urban areas and agrivoltaics technologies in rural areas, with the aim of supporting future planning operations.

5.1 Relationship with Energy Planning Tools

The identification of areas suitable for the installation of renewable energy plants, functional to the achievement of the objectives set by the PNIEC, followed the indications in the Legislative Decree no. 199/2021 (par.8) and the Ministerial Decree of 21 June 2024, "Regulations for the identification of surfaces and areas suitable for the installation of renewable infantry plants", according to the context of the Municipality of San Severo (Table 4). The identified areas are shown in Fig. 4.

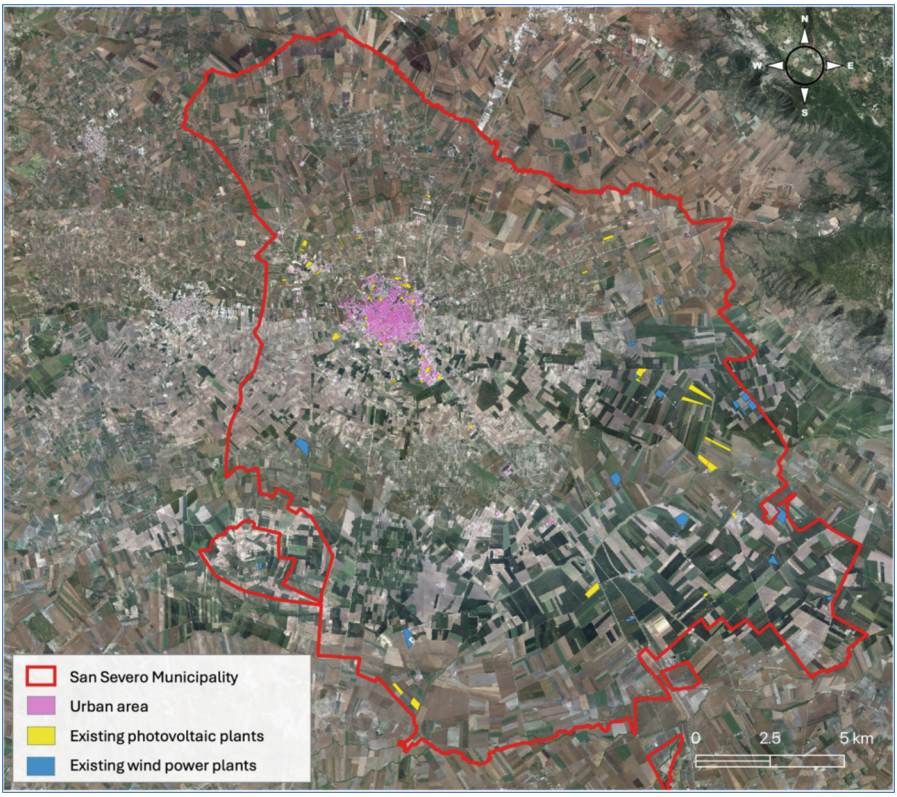

Fig. 3. Existing power plants using renewable resources (base layer:Ortophoto 2019).

5.2 Relationship with the Objectives of Protection

Environmental and landscape requirements have been considered according to the provisions of the current national legislation regarding unsuitable areas and the related planning tools at regional and local level, as follow:

- Ministerial Decree 10–09-2010 National Guidelines for the procedure referred to in Article 12 of Legislative Decree no. 387 of 29 December 2003 for the authorization of the construction and operation of plants for the production of electricity from renewable sources;
- Legislative Decree no. 42 of 22 January 2004, Code of Cultural Heritage and Landscape, pursuant to Article 10 of Law no. 137 of 6 July 2002;
- Puglia Region, R.R. 24/2010, "Guidelines for the authorization of plants powered by renewable sources";
- Regional Territorial Landscape Plan (P.P.T.R.) of Puglia;
- P.U.G. of the Municipality of San Severo;
- Hydrogeological Asset Plan (P.A.I.).

The corresponding areas and their extension are shown in Table 5 and Fig. 5.

Table 4. Area suitable for agrivoltaic system according to the Italian regulatory framework.

	Suitable areas, *ex lege*	**Area (m^2)**
	Existing plants where modification interventions, are carried out for refurbishment, enhancement or complete reconstruction, and do not involve a change in the occupied area of more than 20% (rural areas)	1047888.00
	Areas subject to remediation identified pursuant to Title V, Part IV, of Legislative Decree No. 152 of 3 April 2006 (Environmental Code)	65860.00
	Sites and facilities available to Italian State Railways group and railway infrastructure managers as well as motorway concessionaires	114890.00
	Agricultural areas enclosed in a perimeter within 500 meters from areas for industrial/artisanal/commercial use, including sites of national interest, quarries and mines	116218051.00
	Areas inside industrial plants and plants, the latter as defined by Article 268, paragraph 1, letter h) of Legislative Decree no. 152 of 3 April 2006	2929174.00
	Areas adjacent to the motorway network within 300 metres	12698667.00

5.3 Net Area Usable for Agrivoltaic Plants

The net available area has been first computed in the GIS environment by corelating the planning tools and the regulatory prescription (Fig. 6 and Table 6).

6 Potential of Solar Energy

As part of the methods of using RES for production purposes, photovoltaics, unlike other renewable sources, can be integrated into existing building structures, with an improvement in the energy performance of buildings both in terms of reducing consumption and increasing the use of renewable sources.

Thanks to the favorable location, the municipality of San Severo has an annual global radiation of 1894.00 kWh/m^2, with an annual production of energy from PV of 1462.00 kWh for 1 kWp of photovoltaic installed.

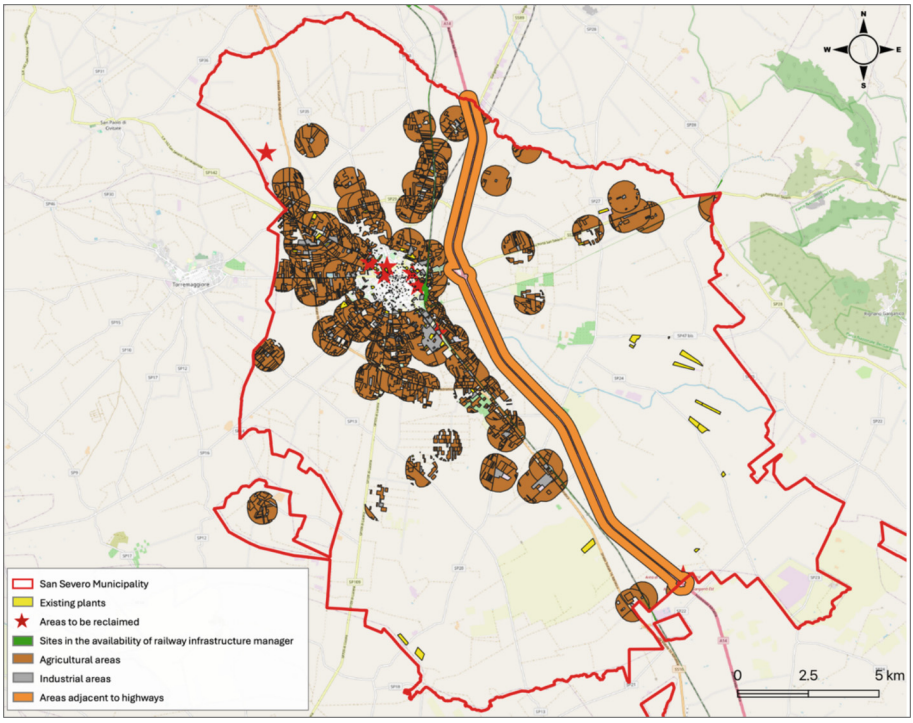

Fig. 4. Area suitable for agrivoltaic system in the municipality of San Severo (base layer:OpenStreetMap).

With the aim of quantifying the efficiency of a possible massive use of RES on the study area, quantitative indicators have been set up to analyze the energetic potential at urban and rural scale.

6.1 Photovoltaic Potential Indicator – Agrivoltaics Plants

To infer an indicator of the producibility of an agrivoltaic plant, reference was made to national and European technical and legislative regulations, summarized by the following indications:

- Minimum area to be dedicated to cultivation (agricultural area - Aa) $\geq$ 0,7 of the total available area (Taa), to consider the need of preserving areas dedicated exclusively to the cultivation, in compliance with Good Agricultural Practices (Buone Pratiche Agricole – BPA) [25];
- Level of shading generated by the plant on the ground, expressed as the maximum acceptable percentage of total area covered by modules (LAOR- Land Area Occupation Ratio), computed as the ratio between the total overall area of the agrivoltaic system (Toa) and the total available area (Taa), and set on 40%;

To estimate the production potential of the plant, the use of a standard monocrystalline photovoltaic module, with half-cut technology cells and integrated power optimizer,

Table 5. Area unsuitable for agrivoltaic system.

	AGRIVOLTAIC SYSTEMS – Unsuitable areas		
	Protection bond	**PPTR/PUG**	**Area (m^2)**
	Areas located near **archaeological parks** and in **areas bordering emergencies of particular cultural, historical and/or religious interest**	*Area of respect for cultural and settlement components (100m-30m). (sheep track network)*	24327312.00
		Area of respect for cultural and settlement components (100m-30m). (historical and cultural sites)	
		Area of respect for cultural and settlement components (100m-30m) (areas of archaeological interest)	
	Wetlands of international importance designated under the Ramsar Convention	*Wetlands*	6200.00
	Areas characterized by **situations of hydrogeological instability and/or risk** delimited in the **Hydrogeological Asset Plans (P.A.I.)** adopted by the competent Basin Authorities pursuant to Legislative Decree 180/98 and subsequent amendments.	*Hydrographic network connecting the Regional Ecological Network. (100m)*	28290742.00
		Rivers, streams, watercourses registered in the lists of public waters (150m).	11317914.00
		Areas subject to hydrogeological constraints	31777152.00
	Areas identified pursuant to Article 142 of Legislative Decree 42 of 2004 by assessing the existence of characteristics incompatible with the construction of the plants.	*Consolidated city*	2492415.00
		Woods	17175.00

sizing 1.80x1.15, and characterized by 360W (0.36 kW) of power and 23.5% of efficiency (European average value of plant productivity) has been assumed.

The PV annual production has been calculated using the Photovoltaic Geographical Information System (PVGIS) [26], a free web application developed by the Energy Efficiency and Renewables Unit of the European Commission's Joint Research Centre, that allows the user to get data on solar radiation and PV system energy production, at any place in most parts of the world [27]. The photovoltaic potential of an agrivoltaic plant (PVAGRI), located in the Municipality of San Severo, resulted in 0.236 GWh/ha/year (Table 7).

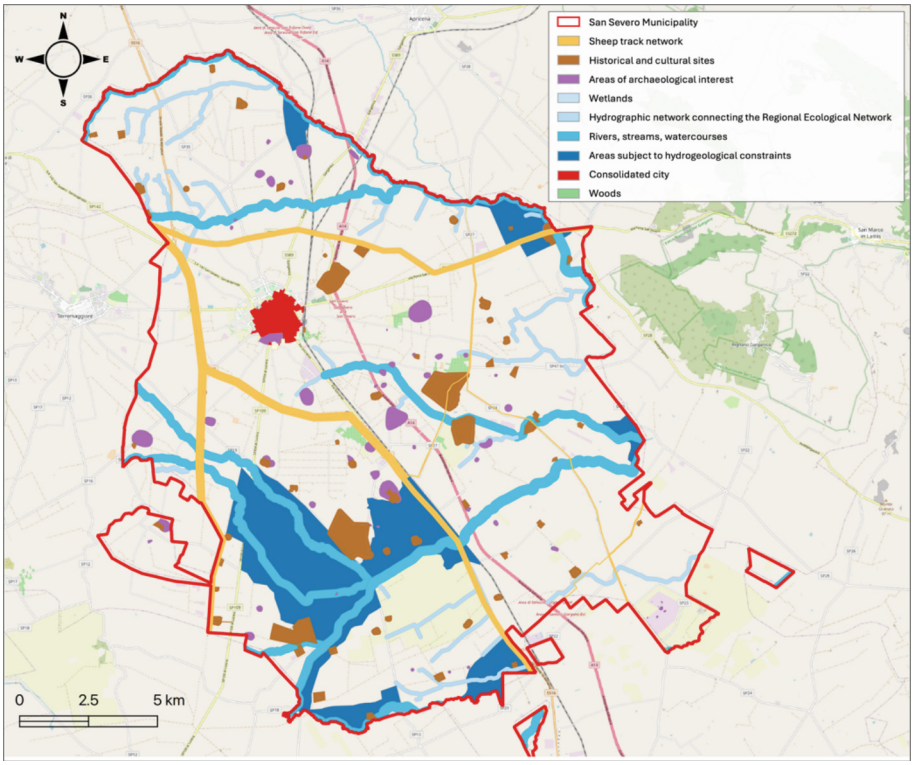

Fig. 5. Unsuitable areas for agrivoltaic system in the municipality of San Severo.

Table 6. Area usable for agrivoltaics plants.

Usable area (m^2)	Usable area (Ha)
12698668.00	1269.87

6.2 Photovoltaic Potential Indicator – Plants on Buildings

The estimation of the production potential of building roofs has been carried out assuming the use of the same standard type of monocrystalline photovoltaic module, while two classes of building roofing have been identified. In order to assess the space required for the installation of the photovoltaic generator with a reference power of 1 kWp, according to the provisions of the Italian Electrotechnical Committee (CEI) 82-25 standard [28], two fundamental cases were distinguished: (a) photovoltaic generator placed on a suitably inclined surface (e.g. pitched roof); – and on a horizontal surface (flat roof, terrace, etc.). The coverage ratio, computed using the mean latitude of the municipality of San Severo (41°41′23′), and following the CEI 82-25 (3.22, 4.3.1 a/b) standards, is equal to 51,42%. For both types of roofing, through PVGIS, the net production of electricity referred to the installation of a photovoltaic system with a power of 1 kWp was

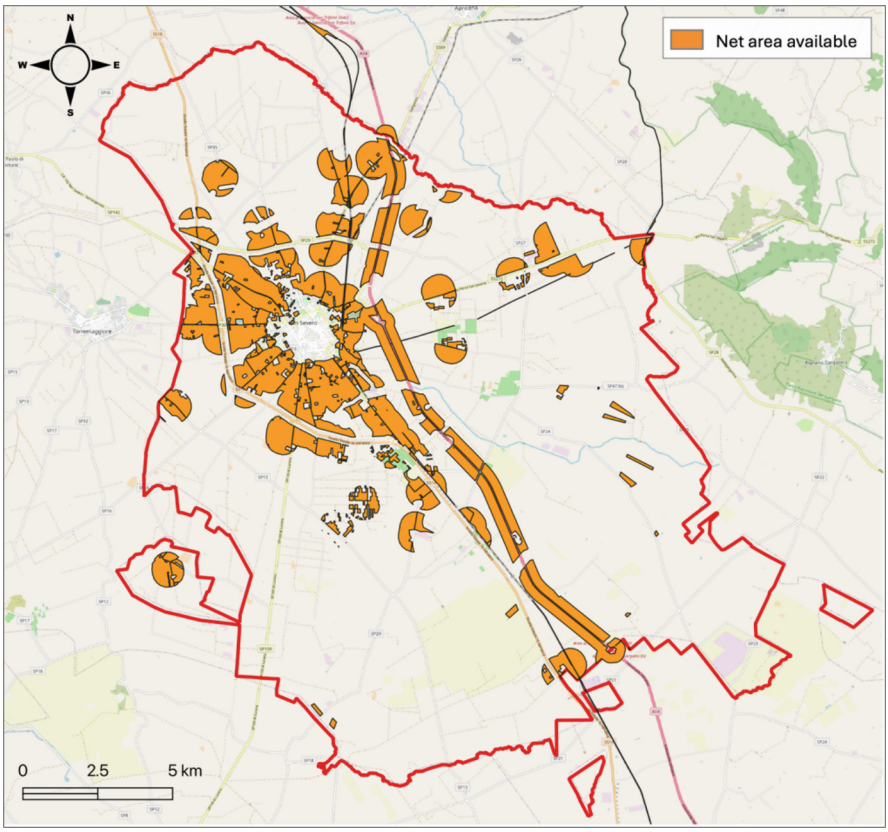

Fig. 6. Net area available for agrivoltaic plants (base layer: OpenStreetMap).

calculated and related to the net coverage available for the installation in the two cases (Tables 8, 9 and 10).

7 Analysis of Locally Available Energy Resources

Following the estimate of the surface area potentially available for the installation of photovoltaic systems and related assumptions on the photovoltaic power potentially installable, and using the indicator derived in the previous section, the potential annual total amount of energy production from RES, in GWh, has been computed. Several factors can affect the surface available for new PV systems, such as chimneys, air conditioning systems, shading from construction elements or nearby buildings.

JRC estimates that the percentage of roofs suitable for hosting plants can vary, at urban level, between 49 and 64%. A further 60% reduction is due to the distance between the panels to allow maintenance [29] (Table 11).

Additional power coming from agrivoltaics that could be installed in rural areas, without increasing land consumption, and would lead to an electricity production of about 46.00 GW (Table 12).

Table 7. PV potential of an agrivoltaic plant in the municipality of San Seevro

		Ha	m²
Total available area	*Taa*	1	10000.00
Minimum area for agricultural activity	*Aa ≥ 0,7 Taa*		7000.00
Total overall area of the agrivoltaic system	*Toa*		3000.00
Max. acceptable percentage of area covered by modules	*LAOR = 40 %*		1200.00
Area covered by modules (%)	*LAOR (≤40 %)*		30%
Single monocrystalline photovoltaic module size			2.07

Number of implantable modules	435	
Total peak power x hectare (kWp)	**156.600**	
PV annual production	302563.51	Derived through PVGIS
Total loss (%) -22.15	67017.82	
Net annual production (kWh)	**235545.69**	
PV Net annual production (GWh/ha/year)	**0.24**	**Agrivoltaic potential indicator**

Table 8. Energy supplied into the grid based on the PVGIS output.

Peak Power 1 kWp	**Energy produced, according to PVGIS**	**Power losses (incidence angle, spectral effects, low temperature/radiation)**	**Net Energy Produced**	**Net Energy Produced (GWh)**
Tot.kWh	1456.21	-307.55	1148.66	0.00115

Table 9. Photovoltaic system placed on an inclined surface.

Standard CEI 82-25 (4.3.1.a)		**Photovoltaic potential indicator (kWh/m²)**
(Kw/module efficiency=23,5%)		
Minimum usable surface area for 1kWp generator installation (**m²**)	Number of panels	
4.26	**2**	**269.93**

Thus, the potential annual total amount (urban PV and agrivoltaic) of energy production from RES, equal to **365.49 GWh**, would be sufficient to entirely cover the needs municipality of San Severo, while generating a surplus of energy.

Table 10. Photovoltaic system placed on a horizontal surface.

Standard CEI 82-25 (4.3.1.b)		**Photovoltaic potential indicator (kWh/m²)**
Coverage ratio=51,42%.		
Minimum usable surface area for 1kWp generator installation (**m²**)	Number of panels	
4.26*1.51=6.44	3	**178.27**

Table 11. Urban area: surface potentially available for the installation of PV on roofs and associate annual production.

Existing plants				
Urban built area	**Total area (m²)**	**Nominal power installed (kWp)**	**Annual production (GWh)**	
	438375.00	2306.84	1.94	
Potentially available areas				
Roofs	**Surface (m²)**	**Suitable roofs (64%)**	**Reduction rate for maintenance (60%)**	**Net surface (m²)**
	1439668.00	21388.00	-552832.00	**368555.00**
Photovoltaic potential indicator (kWh/m²)				**178.27**
			kWh	**65702301.28**
		Annual production (GWh)		**65.70**

Table 12. Rural area: surface potentially available for the installation of agrivoltaic plants and associate production.

	Usable area (**m²**)	Usable area (Ha)
Agrivoltaics	12698668.00	1269.87
Agrivoltaic potential indicator (GWh/Ha)		**0.24**
Annual production (GWh)		**299.69**

8 Discussion and Final Remarks

The presented work was aimed at investigating the potential photovoltaic production capacity of the municipality of San Severo, located in the south of Italy, by corelating different spatial data in a GIS environment. To this purpose, digital cartography, cadastral

data, geo-located information about the existing plants built from the database provided by the Italian Energy Services Manager and models assessing the annual production of photovoltaic plants installed on edifices and agricultural areas have been jointly analyzed. This allowed the production of reasoned maps and quantitative results describing the examined area, useful to highlight its energy potential and the issues related to the correct location of photovoltaic technologies as well as their compatibility with the urban and rural space. The outcomes show how, in principle, the municipality of San Severo could entirely satisfy its energy needs using only renewable energy and generate an energetic surplus.

As highlighted in [30], this methodology evidence some critical aspects, as the identification of the input parameters derived from low-precision databases, or the general lack in the evaluation of the panel degradation throughout its life cycle. Also, the daily variable productivity is often not considered, and geomatics data availability/resolution represents a discriminating factor. Therefore, the building typology analyzed has been standardized to simplify the study.

Nevertheless, even simplified, this study evidences once again the importance of a GIS-based approach in the evaluation and management of energy systems and as a support territorial planning, as it allows to quantify in advance the photovoltaic potential in territorial contexts, however, heterogeneous and complex. The advantage of this methodology is also linked to its high flexibility and scalability, which allows the automatic extension of the assessment of production potential from the single site of specific interest to an entire municipal area, since the workflow analyzed in this study could be easily replied. This certainly can support the planning activities required by the municipalities within the objectives set at national and European level in the energetic field, playing a key role in the growing shift towards renewable energy sources.

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