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Abstract: In order to achieve climate goals and limit the global temperature rise, an increasing share of renewable-energy sources (RESs) is required. However, technologies for the use of RESs need to be integrated into the landscape and ecological heritage to ensure a fully sustainable energy transition. This work aims to develop a scalable technique for integrating the estimation of rooftop PV and wind potential into spatial planning, providing a framework to support decision-makers in developing energy policies. The methodology is applied to the minor Sicilian islands, which are characterised by significant environmental and landscape constraints. The methodology is used to identify the areas eligible for the installation of onshore wind turbines and the usable roof surfaces for the installation of PV systems. It is shown that the available technical potential of rooftop PV installations could ensure a higher production than the actual consumption on 13 of the 14 islands studied. Nevertheless, efforts must be made to improve the legal framework, which currently places major limits on the use of wind energy.

Keywords: GIS; photovoltaic; wind; energy transition; technical potential; renewable-energy sources

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1. Introduction

1.1. Background

The issue of climate change and global warming has come to the fore in recent times. The reason for this is the steep increase of temperatures compared to pre-industrial levels. According to the IPCC report, to curb this process, it is necessary to limit the temperature increase to 1.5 °C by 2050, a target envisaged and set also by the Paris Agreement [1]. However, the energy transition cannot be achieved overnight, as the current economic model is strongly linked to the use of fossil fuels. It is necessary to completely rethink the supply chain of production processes, especially energy, mobility and everyday life in a more general sense. The method adopted with the EU Sustainable Finance Taxonomy (2020) [2], and the Renew Sustainable Finance Strategy (2022) [3] to reform sustainable investments, the real driver of the clean energy transition, is part of this framework. Today, this is especially true: the current geopolitical instabilities have encouraged governments to rapidly look to a future without fossil fuels, strengthening the role of renewable-energy sources (RESs). However, it is worth noting that technologies for RES exploitation have environmental and social impacts which must be carefully evaluated. In this framework, small remote islands—which are often not interconnected with the national power grids—represent a valuable test bed for the achievement of a fully sustainable energy transition, because of their remarkable and scenic heritage, as well as the limited availability of land [4]. Careful spatial constraints analysis and RES assessment are therefore required when planning new RES power plants, especially when it concerns the clean energy transition of small non-interconnected islands.

To achieve sustainable development of an area, it is necessary to understand the specificities of its environment and the availability of RES. The geographic information system (GIS) enables the representation of information about the region under study and collects all the data needed to exploit the RES potential: GIS is a powerful tool that can perform complex spatial queries with georeferenced data, as explained by Wang et al. [5].

Estimating the technical potential of rooftop photovoltaic systems and onshore wind turbines is a common problem in the energy transition roadmap, addressed by many authors from different perspectives. Several researchers addressed the energy and spatial planning problem using GIS-based multicriteria analysis methods [6]. Singh et al. [7], for example, addressed the determination of rooftop photovoltaic potential at the urban scale using GIS-based and analytical methods for solar radiation estimation, starting from meteorological databases (e.g., DHI). In addition, Gomez-Exposito et al. [8] performed a spatial analysis of all Spanish rooftops to evaluate the available area for the installation of PV systems using a GIS tool; instead, the evaluation of the photovoltaic potential of the rooftops follows the methodology presented in [9] based on PVGIS. Determining the technical potential of onshore wind is an additional challenge in decarbonising an island's electricity mix. A methodology based on GIS combined with a careful analysis of the conditions in the Canary Islands is presented by Schallenberg-Rodriguez and Notario-del Pino in [10]. In addition, some authors follow a GIS-based multi-criteria analysis, where both solar and wind potential are investigated. An example of this is the study by Ramachandra et al. [11], which examines the energy mapping of different renewable-energy sources in the state of Karnataka (India) using different criteria (spatial and technical) and looking at different targets (solar, wind, hydropower potential, etc.). Moreover, the MCA issue has been addressed on a large scale by different authors. For instance, Ermolenko et al. [12] provided an analysis of the analytical technical potential in the Russian Federation based on a large-scale grid, about $1^\circ \times 1^\circ$ resolution, both for solar and onshore wind. In contrast, Ghasemi et al. [13] evaluated only the technical ground PV potential in the Iran region providing an exclusion criterion based on the proximity with main infrastructures (i.e., airports, roads, cities) and the slope level of the ground. In addition, Jain et al. [14] dealt with the technical potential of both wind and solar in India on a large scale (i.e., $1^\circ \times 1^\circ$ resolution); the authors provide a hierarchical scale to find suitable areas for RES exploitation, imposing buffer layers that surround UN-protected bodies, water bodies and infrastructure. For instance, the high-resolution MCA (i.e., 1 km^2 of resolution) was issued by Elkadeem et. al. [15]: the authors elaborated an MCA based on sixteen criteria in order to estimate the potential (i.e., geographical, technical and economical) in Egypt using a dense resolution grid, where the resource assessment is based on numerical methods implemented in the Matlab environment. Based on the existing literature, this study aims to present a comprehensive multi-criteria methodology based on GIS for assessing the technical potential of rooftop solar PV and the technical potential of onshore wind on non-interconnected islands, on a very small scale.

1.2. Framework: Clean Energy Transition of Minor Islands

Non-interconnected minor islands have a special status depending on their specific geographical and energy characteristics. Their energy transition pathways are already being developed within the framework established by the European Commission thanks to the actions of the Clean Energy Secretariat for EU islands, which outlines the guidelines through the Clean Energy Transition Agenda (CETA) instrument [16].

The framework covers more than 2.200 inhabited European islands, home to 2% of the European population. Moreover, most of them are not interconnected today and are supplied by medium-sized diesel power plants. As mentioned above, a non-interconnected minor island represents a closed grid where carbon neutrality can only be achieved through careful integration of different renewable-energy sources, taking into account variable renewable-energy sources (VRESs). Despite the wide availability of RESs, especially solar, wind and wave energy, the path towards decarbonisation should take into account the technical potential shown by the identification of suitable areas, respecting local regulations and taking into account the morphological structure and environmental beauty. The research by Prina et al. [17] underlines the above and suggests a careful review of the energy system model applied to a decarbonisation pathway for islands.

However, a successful path to decarbonisation should also be socially acceptable. The study proposed by Kallis et al. [18] provides a review of the extensive literature that contains the key points for a successful strategy for the transition to clean energy. The study highlights that where control over agendas and decisions is outside communities, such as external political and economic interests, tensions are more pronounced: for example, the 'not in my backyard' (NIMBY) phenomenon arises from this lack, as illustrated by the case study analysed by Devine-Wright [19] about the installation of power lines near a town in south-west England. On the other hand, a structured participation strategy can make an energy project worthwhile, as explained in the study by Heaslip and Fahy [20] on the success of using a transdisciplinary approach to involve the local community of the Aran Islands in energy planning.

CETA aims to answer this question by proposing a collaborative process that takes into account the proposals and needs of local citizens.

1.3. Scope and Structure of Work

The paper contribution swivels around the development of a methodology that is able to sustain the policy-making processes in the elaboration of a new decarbonisation strategy for the non-interconnected minor islands. To do so, this paper introduces a comprehensive technique for the evaluation of rooftop PV technical potential and onshore wind technical potential widely based on the GIS approach. Moreover, based on the existing literature, this paper provides a spatial and resource analysis on a small scale (i.e., 2 m^2), referring to exclusion criteria, for the identification of suitable areas, in accordance with the local regulations in force. Estimating the technical potential of renewable-energy sources is indeed an important input for energy system models aimed at planning the energy transition [21].

The aim of this work is to develop a scalable methodology to assess the technical potential of rooftop solar photovoltaic and wind turbines in consideration of local, regional and national constraints. It makes use of a case study of Sicilian islands: Pantelleria, Ustica, Egadi Archipelago, Pelagic Archipelago and the Eolian Archipelago.

The paper starts with an overview of the most common areas of interest for spatial analysis and planning, presented in Section 2 and in particular in Section 2.2. Then the Sections 2.4 and 2.5 provide the methodology for the technical potential of rooftop PV and onshore wind power estimation. Then, there is an overview of the regulations in force on the fourteen Sicilian minor islands presented in Section 3. Section 4 applies the method to calculate the technical potential for each island providing also the RES contribution to the islands' self-sufficiency. The paper concludes in Section 5 with a discussion of the results obtained and their contribution to the energy self-sufficiency of the islands in terms of the technical potential of rooftop PV and wind power.

2. Materials and Methods

This section presents the method developed for the evaluation of the solar rooftop photovoltaic and wind turbines' technical potential.

According to Jäger et al. [22], the renewable energy potential can be divided into five categories. The different types of renewable energy potential are:

- Theoretical Potential: the physically usable amount of energy within a given region and time.

- Geographical potential: the area available for energy production, taking into account constraints such as natural protected areas and other land uses such as urban structures and transport routes.
- Technical Potential: the amount of installable capacity under technical constraints within a given region and time.
- Economic Potential: the technical potential that can be realised economically within a given region and time.
- Feasible Potential: the actual achievable economic potential, also taking into account market, organisational and social barriers, which means that the economic potential is not fully realised in practice.

The management and processing of data for the calculation of the technical potential of RES makes use of a GIS. This paper focuses on the technical potential evaluation only; however, in the following sections, the theoretical and geographical potentials, both wind and solar rooftop will be presented. Section 2.4 provides a general workflow to calculate the theoretical and geographical potential of the whole region under study using the WaSP software. Subsequently, the paper presents the steps needed to identify the suitable areas and the windfarm layout in order to calculate the technical potential. The onshore wind technical potential values will be presented in Section 4 for each island. Regarding the solar rooftops' technical potential, the study followed the same path exposed previously; a theoretical and geographical assessment was applied using a hierarchical flow, discussed later, to screen the eligible areas. After that, the method presented in Section 2.5 was applied to evaluate the technical potential on rooftops. The evaluation of the economic potential and the feasible one is beyond the scope of this study.

2.1. Geographic Information System for Spatial Energy Planning

The GIS is an information system developed to represent and manage different types of data referenced by spatial or geographic coordinates using a projection system [23]. In this work, the QGIS software [24] is used for the management, processing and visualisation of spatial data. GIS can play a key role in spatial energy planning; in fact, the system can combine renewable energy availability with regulatory plans and natural constraint layers, supporting decision-making processes. The use of a GIS system allows the representation and integration of different types of data in a given geographical area, as shown in Figure 1.

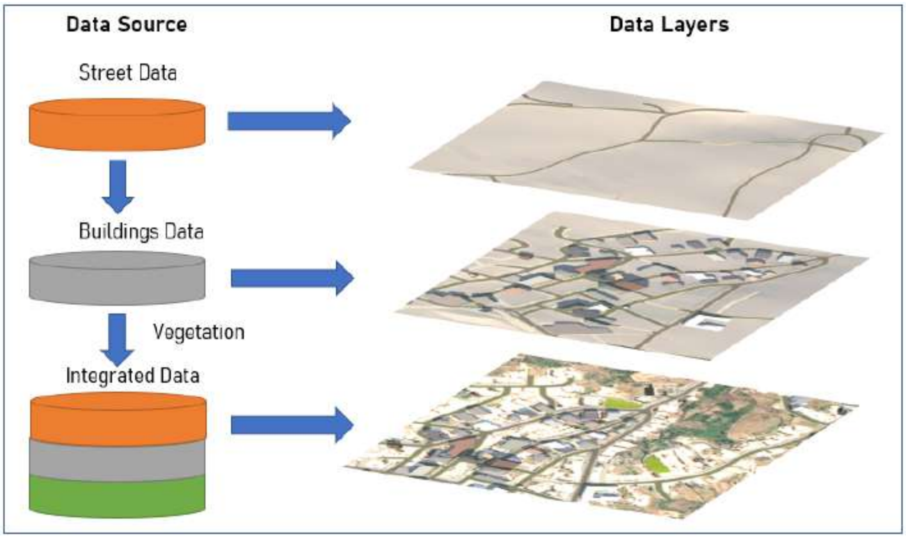

Figure 1. GIS data source and layers.

2.2. Layer of Constraints

The most common protected areas or constraints to be considered in new RES facility installations are available in the institutional regional and national information systems and allow presentation of the environmental constraints affecting the assessed area. This subsection deals with the presentation of the most common environmental and landscape constraints in the Italian regulation that should be considered in new RES facility installations. All the source layers, such as the environmental, landscape and hydrogeological areas, are available in the national and regional geographical information system. Each data layer has been analyzed overlapping it with the ortho-images of the island of Pantelleria, in order to provide a graphical representation of the layouts. Commonly, this information is distributed in *shape file format*, data that can be manipulated easily using Boolean operations. Each data layer could be analyzed individually or superimposed on another one, due to the path decided in the QGIS environment, following the line shown in Figure 1.

2.2.1. Natura 2000 Network

The Natura 2000 Network is an EU instrument for the protection of biodiversity on the territory of the European Community. It is an ecological network composed of the SCI (Sites of Community Importance), introduced by the Habitat Directive 92/43/CEE, and SPA (Special Protected Areas for birds), established by Birds Directive 2009/147/CE. Natura 2000 Network seeks to create a standard of regulation that can link environmental protection areas with traditional human activities. More specifically, SCI and SPA zones do not prohibit new RES plant installations a priori, but they are the reference for the in force national and regional regulations on the RES facility theme. In the example provided for the Pantelleria's SPA and shown in Figure 2, the layer almost covers the whole island, only the three city centres are unconstrained.

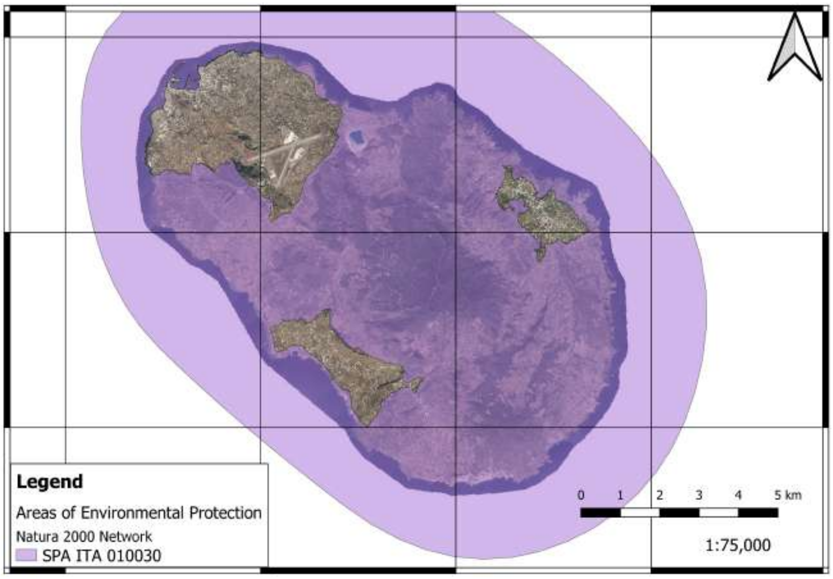

Figure 2. Special protected area.

2.2.2. Important Bird Areas

Important Bird Areas (IBAs) are protected areas based on criteria developed by BirdLife International, a non-governmental organisation [25] dedicated to birdlife. Despite the IBA not having a cogency level, this classification is the reference for the establishment of the SPA and, moreover, is adopted by national and/or regional governments as a reference to identify areas not eligible for RES development. For instance, the IBA area assigned to the island of Pantelleria (code 168 and 168 M), and represented in Figure 3 superimposing the IBA layers onto the ortho-image of the island, covers the whole island territory and a sea buffer of about 2 km. As said above, the IBA layer aims to provide graphical information of the territory sensitivity in terms of birdlife: moreover, the IBA value is not actually related to danger for the birdlife in a general sense, but is applicable only if those protected species are really present in particular sites. Overall, the IBA value materialises itself only after a careful environmental analysis.

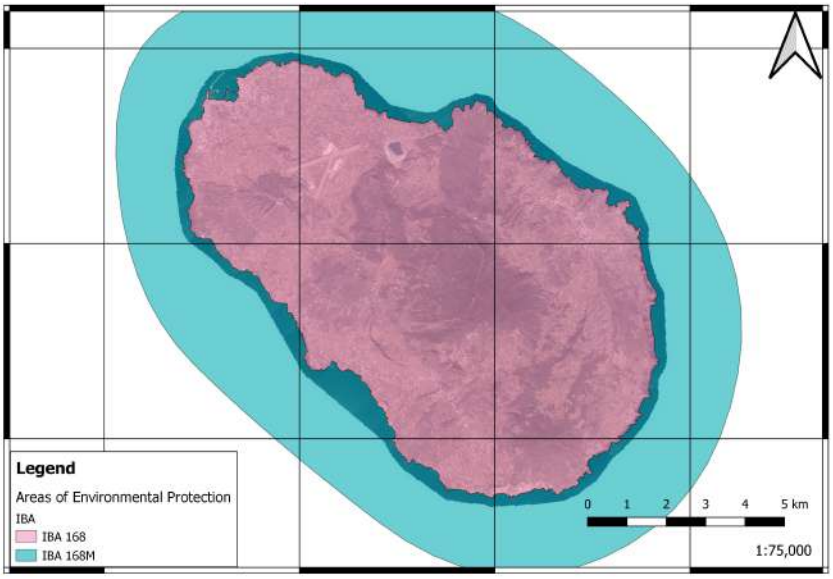

Figure 3. Important Bird Area.

2.2.3. Hydrogeological Risk Area

The hydrogeological condition of the local territory plays an important role in deciding which areas should be considered for new RES facilities, to safeguard both the integrity of the facilities and the stability of the surrounding territory. A spatial planning cycle, in accordance with national regulations, should also take into account the hydrogeological and morphological structure that highlights risk and hazard areas. Hazard is generally defined as the probability that a phenomenon of a certain magnitude will occur in a certain period of time and in a certain place. At the same time, risk results from hazardousness, vulnerability and exposure. Figure 4 shows the hydrogeological and morphological situation on the island of Pantelleria. The layers provided by the regional geographical information system classified the hazaordousness and the risk in four increasing level. Commonly, the fourth level represents the highest risk and hazardouness situation, this is shown in Figure 4; Pantelleria presents spots with the highest value of risk and hazardousness. Moreover, the *hydrogeological constraint area* layer can be represented to complete the framework, giving information about a generic weakness situation concerning a territory. The national and regional regulations for the new RES facilities installations require a careful hydrogeological analysis and forbid any installation in the proximity of areas characterised by a high level of risk and hazardousness.

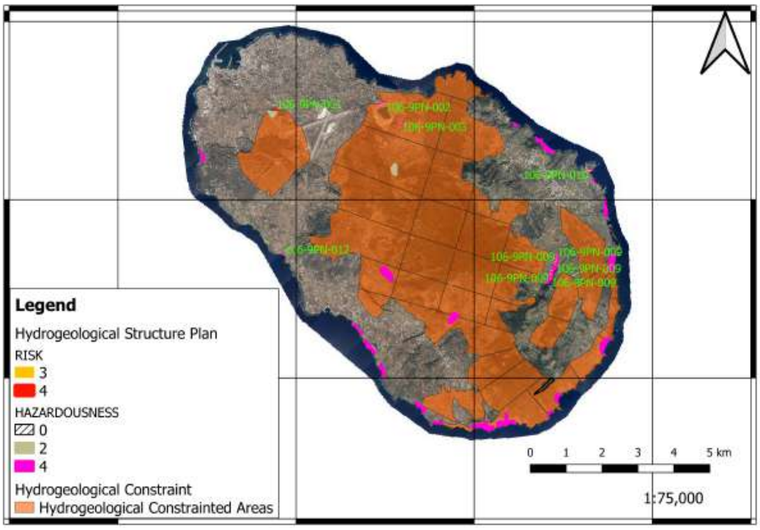

Figure 4. Hydrogeological structure plan and restricted areas.

2.2.4. Cultural Areas of Interest

Spatial energy planning must consider landscape and other cultural constraints in its analyses, such as to limit the impact on the local cultural heritage and, therefore, the social impact. National and local standards provide the method to identify distinct cultural heritage sites, archaeological areas and protected zones that exist on the territory. Figure 5 provides an example of protected areas on the island of Pantelleria, which is almost entirely covered by cultural constraints. However, normally the regulations do not prohibit the use of all RES plants, but provide recommendations and procedures to be followed in order to preserve the cultural landscape.

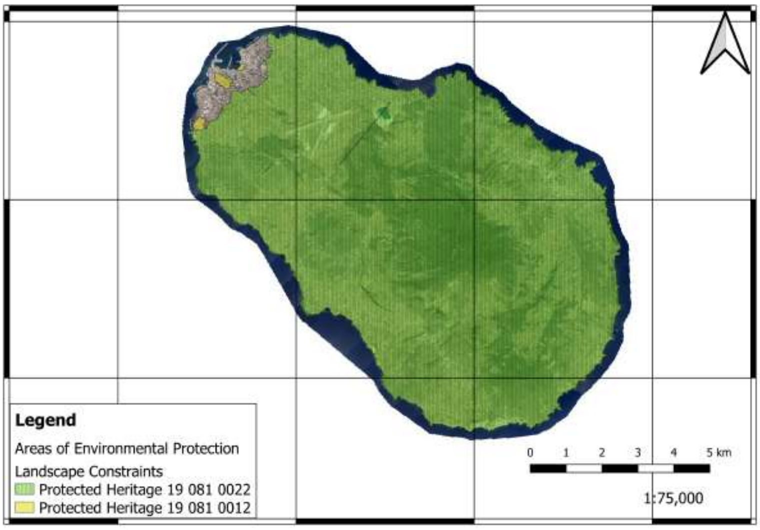

Figure 5. Landscape constraints

2.2.5. Land Cover

Land cover analysis is also often considered in the permitting procedures and should, therefore, be taken into account in a planning phase. Increasing attention is in fact given by legislators to the progressive reduction of cultivated areas, which could put at risk food supplies. In accordance with the European Environment Agency (EEA), and in particular with the data provided for the Italian territory shown in Figure 6, the available agricultural land decreased by about 0.516% in the period 2000–2018. At the same time, forest and semi-natural areas decreased by 0.117%, and artificial land grew by 5.83%.

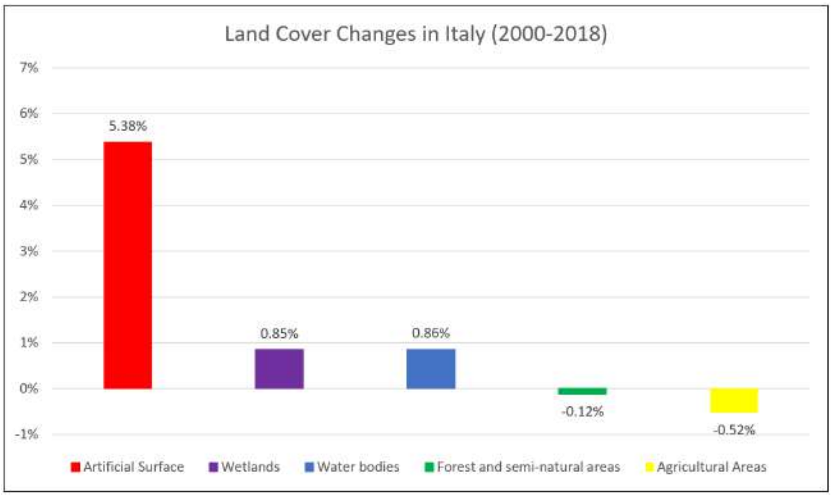

Figure 6. Land cover changes in Italy between 2000 and 2018.

Therefore, a careful analysis of land cover is required to implement really sustainable spatial energy planning. In the case of the Pantelleria Island, the economic and historical fabric is strongly linked to traditional agricultural techniques. The land cover analysis proposed in Figure 7 reports a wide extension of *vineyards*; this is directly linked to the most widespread agricultural sectors on the island.

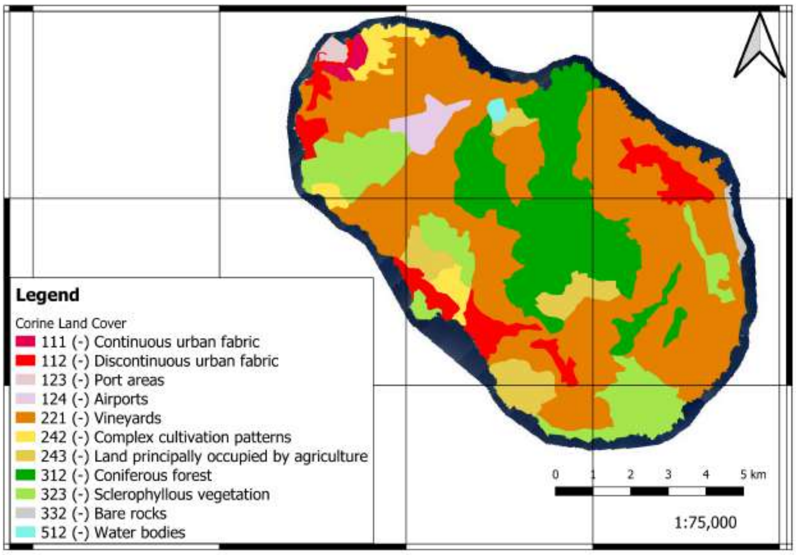

Figure 7. Pantelleria land cover map.

2.3. Spacing from Residential Building

The in-force national regulation prescribes a minimum distance between each wind turbine site and the surrounding residential buildings; up to now this distance is set to be equal to 200 m. This requirement must be taken into account in the early spatial planning phase to ensure a correct identification of the suitable area. Moreover, the layers that report the building footprints are distributed by the local government information systems through an integration in the GIS environment; it is possible to apply a buffer layer of 200 m around each building. Clipping this last from all the identified suitable areas, it is possible to ensure that the distance from residential buildings is respected.

2.4. Wind Technical Potential Assessment

This subsection aims to present the steps followed to elaborate the technical wind potential calculation. The methodology for estimating the technical wind potential provides for the combination of geographic information system QGIS and the software WaSP (Wind Atlas Analysis and Application Program) [26], published by DTU, which allows reliable simulations of wind resource assessment, siting and energy yield calculation [27]. To evaluate effective spatial energy planning (SEP), the average speed, annual energy production (AEP) and power density were calculated.

As shown in Figure 8, the methodology for assessing the technical wind potential consists of five steps:

- Identification of available areas: according to the attention criteria presented before, the methodology identifies eligible areas on QGIS.
- Resource analysis.
- Determination of the technical characteristics of the wind turbine under consideration.
- Micro-site configuration of the wind farms.
- Estimation of the annual outputs.

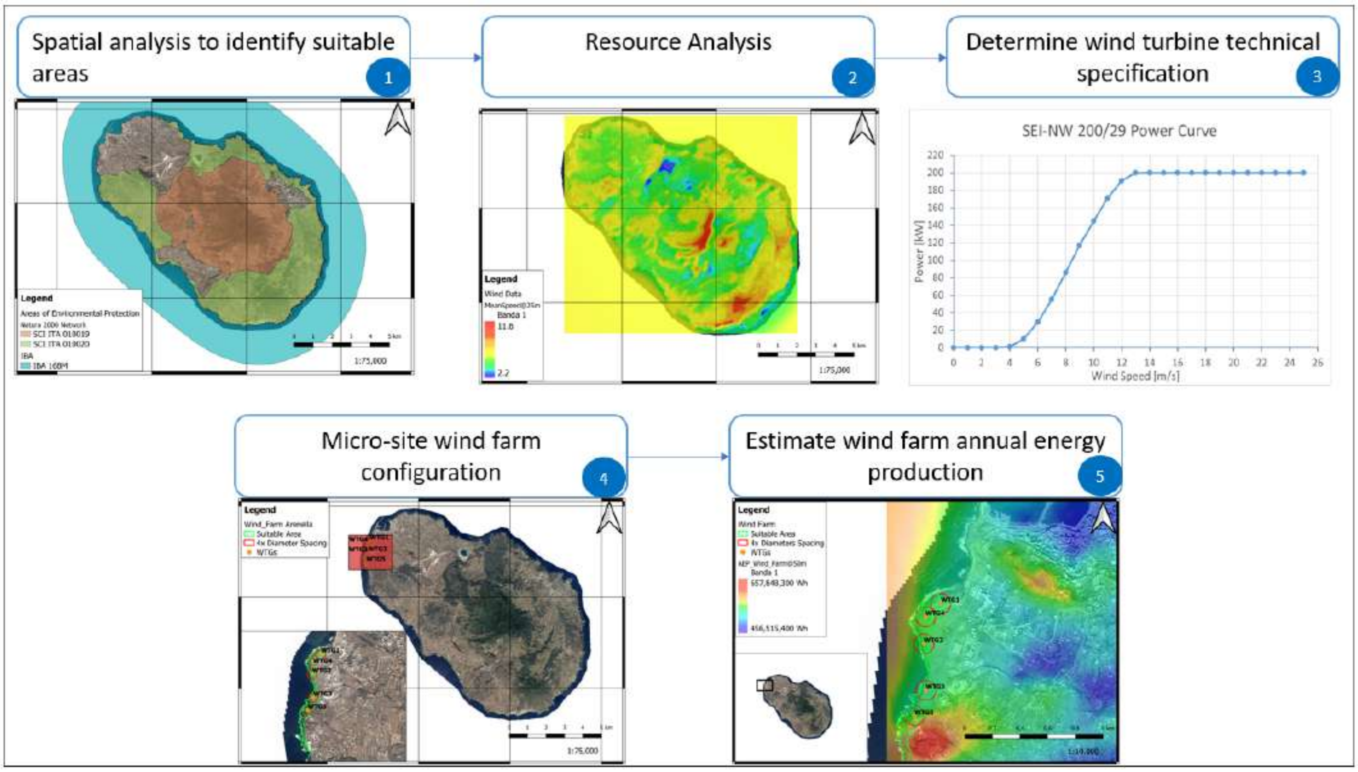

Figure 8. Wind technical potential workflow.

2.4.1. Theoretical and Geographical Wind Potential

In order to perform the resource analysis on a selected area, following the screening criteria exposed in Section 2.2, the WaSP software requires several inputs:

- Latitude, longitude and topological data.
- Wind climate information.
- Orography vector map.
- Roughness vector map.

Most of these data are provided by GWA (Global Wind Atlas) [28], which allows to select a geographical region for which the GWC (Generalised Wind Climate) is obtained by the mesoscale grid cell nearest to the centre of the selected area. The data have a resolution of 30 km^2, but are used to force the mesoscale model to have a resolution of about 3 km^2 [28]. The GWC contains the sectorial frequency of occurrence of the wind (the wind rose) and the frequency distributions of wind speed in the same sectors (as Weibull parameters A and k). The wind climates are given for a range of reference roughness classes and heights above the ground.

The roughness of a terrain model can be parameterised by a roughness length z_0, which is usually defined as the height at which the mean wind speed becomes zero when the wind profile has a logarithmic shape. The relationship between the roughness length and the roughness elements is provided by Lettau [29]:

$$z_0 = 0.5\,\frac{h * s}{S} \tag{1}$$

where z_0 is the effective obstacle height, s is the silhouette area of the average obstacle and S is the specific area measured in the horizontal plane. To obtain the PWC (Predicted Wind Climate), the terrain model in the form of elevation and land cover data must be imported into the suite of GWA. Then, a vector map containing all the terrain information can be used to perform the resource analysis.

2.4.2. Micrositing Assessment

After evaluation of the resource available in the area selected, to obtain the wind technical potential it is needed to perform a careful planning of wind farms on a micro-scale, as shown in Figure 9, that consists in determining the optimal placement of each turbine in a wind farm [30]. Once the areas suitable for wind energy exploitation and the technical requirements and specifications have been determined, the site planning can be carried out according with the rules of thumb for the mutual spacing of the wind turbine generators, which are adequately spaced in order to avoid wake losses.

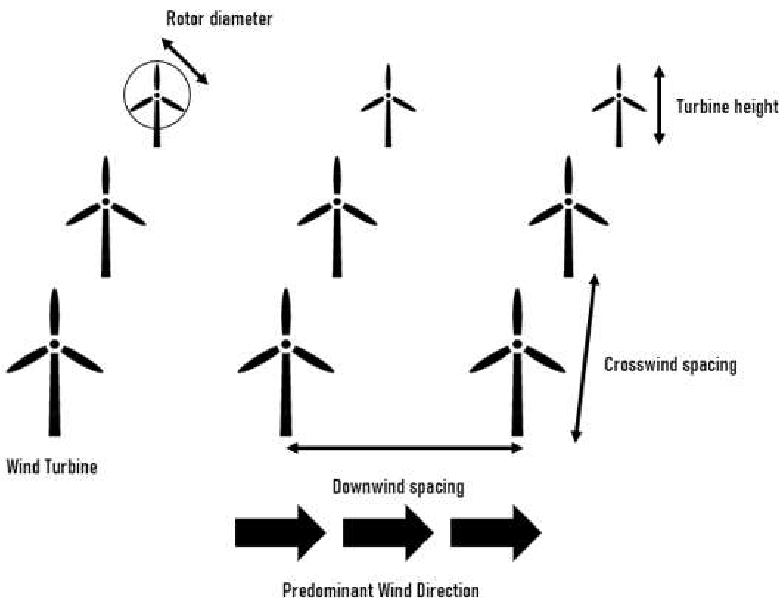

Figure 9. Micro-siting scheme.

Once the site configuration was determined, the WaSP software was used to evaluate the AEP.

2.4.3. Estimation of AEP

The resource network is flexible and adapts to a specific region at a specific resolution. The addition of a wind-turbine model enables AEP estimation. WaSP methodology is complex, and it makes use of models based on the principles of flows in the atmospheric boundary layer, leading to a resolution of simplified Navier–Stokes equations. The software provides the results in an ASCII format that can be imported into QGIS as a georeferenced raster to improve spatial analysis. An example can be found in Figure 10.

For the purposes of this study, three different sizes of wind turbine were investigated:

- Ryse Energy E-20 HAWT (20 kW) [31].
- SEI-NW 200/29 HAWT (200 kW) [32].
- Vestas V100-2.0 MW GridStreamer (2 MW) [33].

This order of magnitude was determined in order to find the most suitable and realistic technical solution for each individual island.

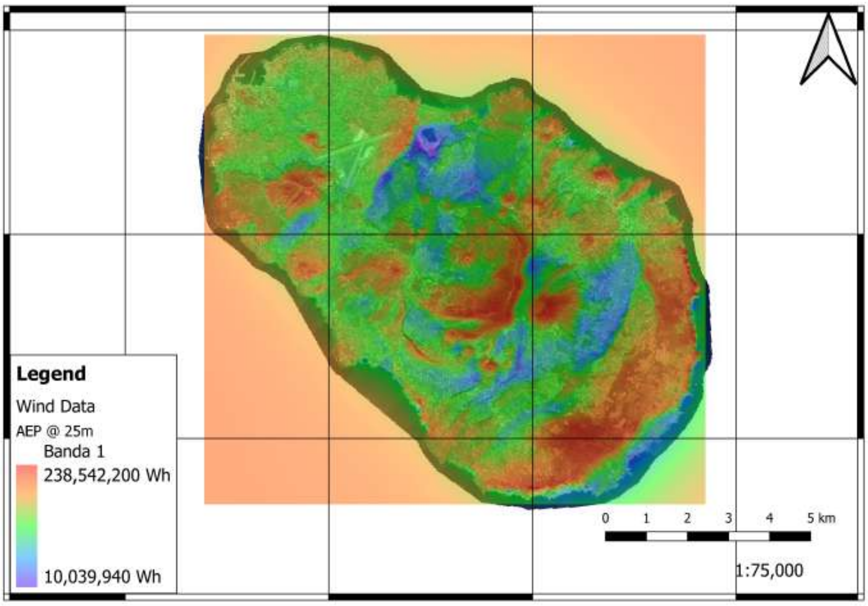

Figure 10. Annual energy production

The resource analysis provides information about the effectiveness of the new RES facility installation, in order to guarantee a cost-effective installation, a Capacity Factor of about 25% was imposed as a minimum threshold.

2.5. Photovoltaic Technical Potential Assessment

The photovoltaic technical potential assessment consists of three steps, as depicted in Figure 11:

- Input data collection and preparation.
- Solar irradiation estimation by means of the UMEP (Urban Multi-scale Environment Predictor) plug-in for QGIS.
- Estimation of the panel area.

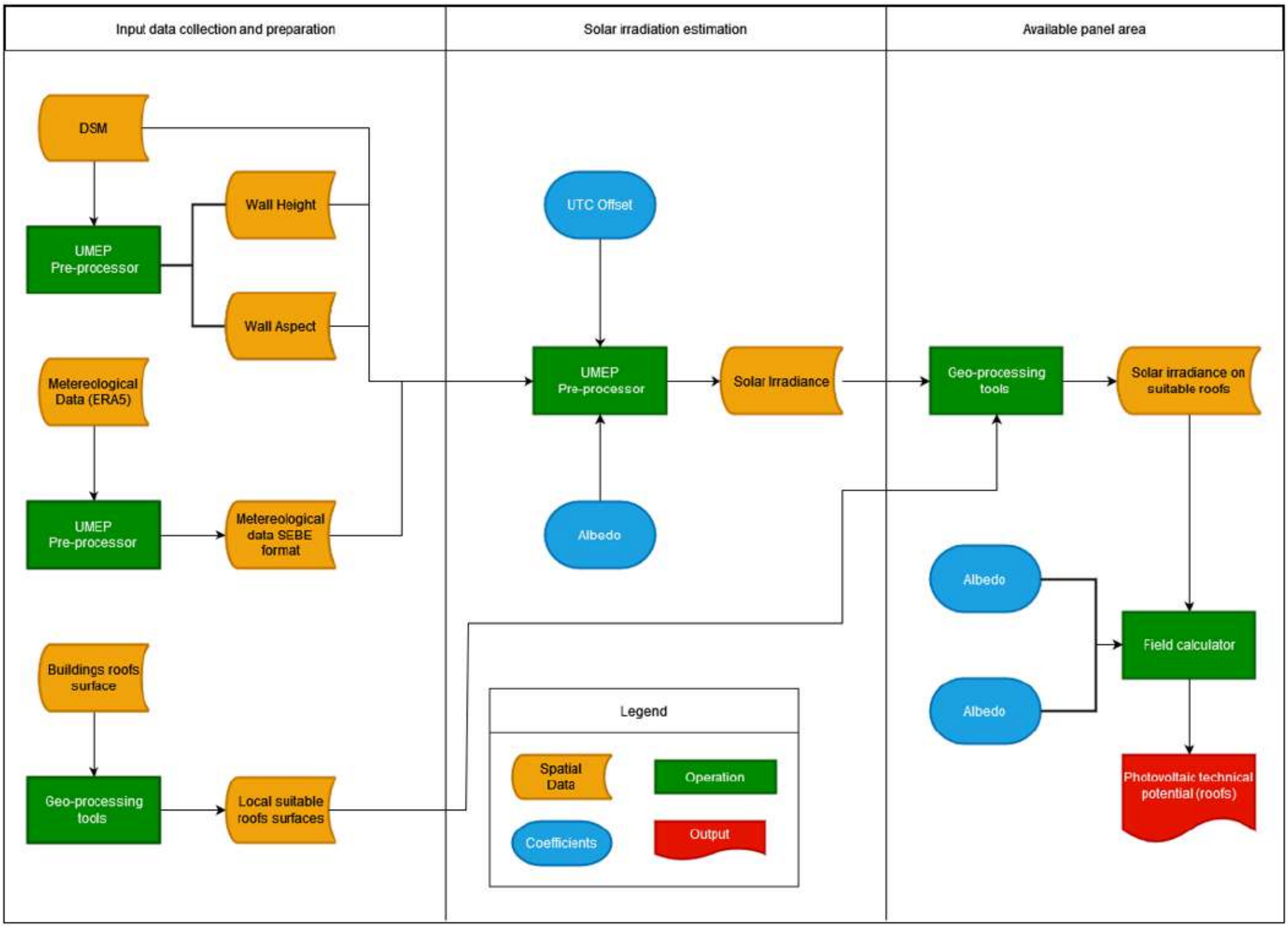

Figure 11. Solar assessment flow.

The core of this approach is based on the extensive use of the Solar Energy on Building Envelopes (SEBE) model [34], which is integrated into UMEP [35]. The SEBE model uses 2D raster modelling to derive 3D irradiance through a high-resolution digital surface model. In addition, SEBE uses observed solar irradiance data to derive highly accurate irradiances for the modelled surfaces [34]. SEBE elaborates a file in GeoTIFF, which gives the total irradiance pixel by pixel in kWh/m^2. The calculated solar irradiance is then used to calculate the technical PV potential on roofs. In order to calculate the solar irradiance on a specific area delimited by the extension of the DSM (digital surface model) used, UMEP requires meteorological data related to a specific time period. It is possible to calculate the irrandiance for a different time period, covering months or years. In this work, the ERA5 dataset provided by the ECMWF (European Centre for Medium-Range Weather Forecasts) was selected. ERA5 provides various atmosphere-, land- and ocean-related climate variables with a resolution of about 30 km. To ensure the best performance of the SEBE, following Lindberg et al. [35], it is recommended to implement the variables below:

- Incoming shortwave irradiance (W/m^2).
- Diffuse shortwave irradiance (W/m^2).
- Direct shortwave irradiance (W/m^2).
- Composed wind speed in (m/s).
- Air temperature at 2 metres above the surface (°C).
- Relative humidity (%).
- Barometric pressure (kPa).
- Precipitation (mm).
- Yearly time.

- Atmosphere transmissivity and Linke turbidity factor (-) [36].

These last variables are not fully provided by ERA5. For example, global shortwave radiation is calculated using the following relationship:

$$G = I \sin(\eta) + G_d \tag{2}$$

where:

- G: global radiation (kWh/m^2/year).
- I: direct radiation (kWh/m^2/year).
- G_d: Diffuse radiation (kWh/m^2/year).
- η: Sun elevation angle (degrees).

In addition, relative humidity can be evaluated separately by estimating saturation pressure (Pa) and real vapour pressure (Pa) derived by correcting Tetens formula [37] provided by [38] for temperatures above 0 °C.

$$e_s = 611e^{\left(\frac{17.27T}{237.7+T}\right)} \tag{3}$$

$$e = 611e^{\left(\frac{17.27T_d}{237.7+T_d}\right)} \tag{4}$$

where:

- T: air temperature (°C).
- T_d: Temperature at the dew point (°C).

The Clausius–Clapeyron relationship can be used to calculate the relative humidity (%):

$$RH = \frac{e}{e_s} \tag{5}$$

However, the variables previously entered must be reordered through a preprocessing phase in the Matlab environment and then through the preprocessing tool provided by UMEP.

2.5.1. Territorial Model

In order to obtain a realistic calculation of solar radiation on a given area of interest, the resolution of the terrain model plays a crucial role. A distinction can be made between two types of terrain models: The DTM (Digital Terrain Model) and the DSM. Both provide information on the orographic features of the area under consideration, but the DTM only contains the ground profile, adding the water bodies, such as rivers and ridges. The DSM, on the other hand, can contain both the natural and anthropogenic terrain features (e.g., buildings, power lines, etc.). Figure 12 reports a simple representation to illustrate the differences.

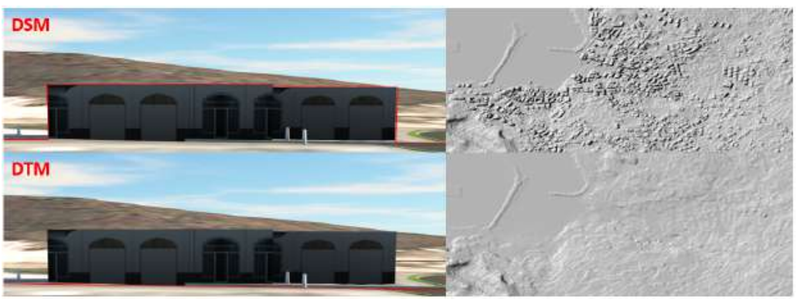

Figure 12. DTM vs. DSM resolution example.

For the purposes of this work, a DSM with a resolution of 2 × 2 m was considered. In addition, in order to evaluate the technical potential of photovoltaics, the proposed method needs information about the area to be evaluated in terms of buildings, vegetation, etc. Usually these layers are available on regional and national information systems and are provided under the Creative Commons Licence in shapefile format [39].

The building layer used in this paper consisted of the following categories: *civil, social and administrative buildings* and *commercial and industrial buildings* as reference buildings for the assessment of the technical potential of solar PV.

2.5.2. Solar Radiation Assessment

According to the SEBE-based method, the total radiation for each pixel (R) on a DSM can be calculated by summing the direct, diffuse and reflected radiation [40] as shown below:

$$R = \sum_{i=0}^{p} [(I\cos(\omega)S + DS + G(1-S)\alpha)]_i \tag{6}$$

where:

- p: number of spots on the hemisphere (-).
- I: incident direct radiation (kWh/m^2/year).
- D: diffuse radiation kWh/m^2/year.
- G: global radiation reflected from the ith field (kWh/m^2/year).
- α: the surface albedo (-).
- ω: sun incidence angle (degree).
- S: the portion of sunlight surface calculated for each pixel (-).

The shadow casting algorithm works using the 'shadow volume' method. This last uses a DSM to generate precise shadow patterns of buildings and greenery as well as ground topography within the model domain [41]. The portion of sunlight surface (S) calculated for each pixel is evaluated as follows:

$$S = S_b - (1 - S_v)(1 - \tau) \tag{7}$$

S_b and S_v are from buildings and vegetation, respectively, and are represented by a Boolean value (presence = 0, absence = 1); τ (-) is the trasmissivity of shortwave radiation due to vegetation.

The SEBE calculation provides a GeoTiff raster containing the pixel-wise total irradiance on the ground and building roofs in (kWh/m^2/year). For a representation in QGIS environment, see Figure 13.

Figure 13. Total irradiance at ground level and on roofs.

The resulting grid, displayed in QGIS Map Canvas, shows the theoretical potential as previously defined.

2.5.3. Photovoltaic Technical Potential Estimation

The assessment of the technical potential includes a preliminary phase focusing on the assessment of the geographical potential as defined in Section 2. Subject to the constraints and procedures set out in national and regional legislation, the technical potential can be assessed by calculating the technological performance of the geographical potential of photovoltaics. In this paper; only the technical potential of roofs is considered, the ground potential is not taken into account.

2.5.4. Evaluation of the Geographical Photovoltaic Potential on Roofs

The available roof area is an essential input for the estimation of the geographical potential. Since, normally, the layers available on local government information systems only indicate the footprint of buildings, an assumption was made about the typology. When considering the typical buildings on the Sicilian minor islands, this study assumes that all roofs are flat. Furthermore, the layers only provide the gross roof area (related to the totality of buildings in the studied area), and according to Yang et al. [42], a double reduction method was applied:

- Absolute reduction: exclusion of buildings that are listed or located in protected areas where the installation of PV systems is prohibited by law.
- Relative reduction: multiplication of the total roof area resulting from the georeferenced layers by various utilisation factors, such as those resulting from orientation, distance between solar modules and other competing uses (solar collectors for water heating).

Using QGIS, these methods can be applied to convert the SEBE output raster into a vector format through a sampling method. By overlaying and clipping the building layer to the global irradiance, it is then possible to obtain the solar irradiance on roofs with a resolution of 4 m^2 (depending on the DSM resolution). An example of the geographical irradiance of roofs on the island of Lampedusa can be found in Figure 14.

Figure 14. Total irradiance on ground and roofs.

In order to obtain an estimate of the potential of solar roofs in terms of cost-effective performance of PV panels, thresholds have been set for the amount of incident energy. For example, a GHI value below 900 kWh/m^2/year is considered insufficient for solar energy generation [40]; furthermore, a range of solar irradiance between 1000 and 1200 kWh/m^2/year corresponds to areas that are not suitable for PV panel installation, such as parapets or interior terraces. For this reason, the threshold was set at 1200 kWh/m^2/year, so pixels with a lower value were filtered out.

Since roofs are considered flat in this study, it is necessary to estimate the actual available area by introducing empirical reduction coefficients based on:

- Mutual shading phenomena.
- Area potentially used by existing PV systems or different technologies.

For PV modules installed free-standing on flat roofs, the phenomenon of mutual shading plays an important role in the evaluation of the energy yield. For the purpose of this study, which is conducted in the Northern Hemisphere, the worst case is assumed to be the winter solstice, which theoretically requires maximum row spacing to avoid mutual shading [42]. However, the distance between rows cannot be determined so easily: it depends on the variation of the sun's altitude during the day and the year. According to [43], the distance between the rows can be calculated as:

$$d = d_1 + d_2 = L \cdot \left(\frac{\sin \beta}{\tan h_0} + \frac{\sin \beta}{\tan \beta} \right) \tag{8}$$

Figure 15 shows the referenced situation.

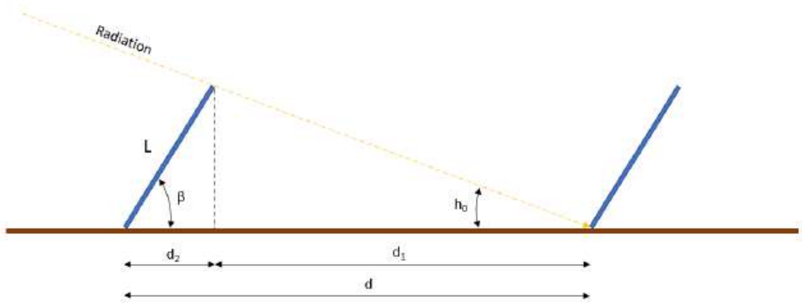

Figure 15. Inter raw spacing.

The solar elevation angle of the day depends on the declination angle δ, the latitude ϕ and the hour angle ω. According to [44], the solar elevation angle for a given latitude and a given day and hour can be calculated as follows:

$$\sin(\alpha_s) = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \tag{9}$$

To calculate the reference tilt angle, a review of the data provided by PVGIS for sample locations was considered, as shown in Table 1.

Table 1. Optimal tilt angle by PVGIS [45].

Location	Latitude	Longitude	Tilt Angle
Pantelleria	36.829°	11.934°	30°
Lampedusa	35.503°	12.611°	34°
Favignana	37.930°	12.329°	41°
Ustica	38.710°	13.193°	39°
Lipari	38.467°	14.954°	39°

Assuming an annual energy use, a value of 36° was used for the further analyses. For the distance between the rows, the physical dimensions of the PV panel under consideration must be known. In this study, a *JinkoSolar Cheetah HC 60 M–325 W* [46] was considered. Knowing the overall dimensions and applying Equations (8) and (9), it is possible to determine the distance between the rows at the winter solstice. An example can be found in Figure 16.

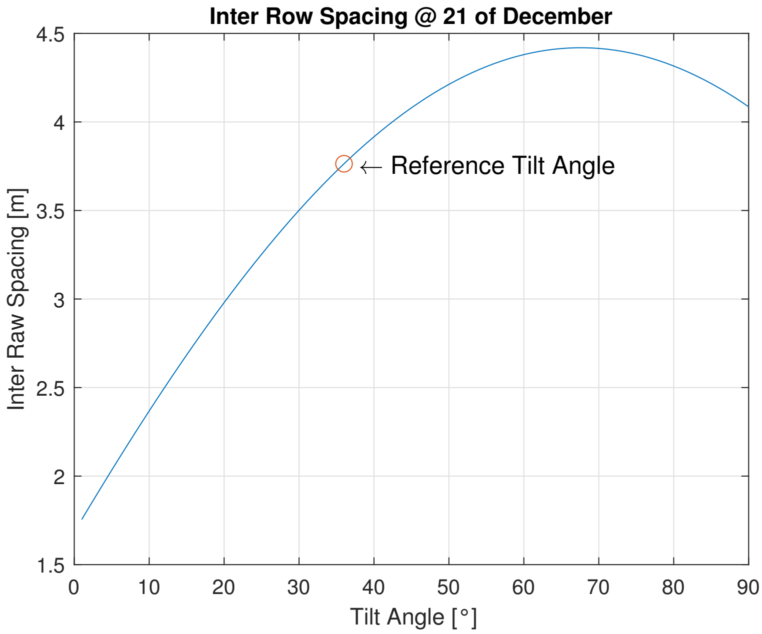

Figure 16. Inter row spacing at winter solstice.

In summary, for a sun angle of about 36° and for the given solar module, the row spacing as defined in Equation (8) is 3.764 m. Knowing the row spacing, one can calculate a coverage index as the ratio between the PV length and the row spacing, as shown in Figure 16 and reported by [47].

$$C_{COV} = \frac{L}{d} = 0.447 \tag{10}$$

However, the assumption that all roofs are available for PV use is not realistic due to the widespread use of solar thermal plants, especially in southern Italy. In addition, roofs may be occupied by chimneys, antennas, roof terraces, heating, ventilation and air conditioning (HVAC) systems or other uses. Following the hypotheses put forward by Bergamasco et al. [48], this study assumes a correction coefficient C_{ST} of 0.9 (i.e., 10% of the roof area occupied by a solar thermal system) and a correction coefficient C_F of 0.7 (i.e., 30% of the roof area unavailable due to other uses). Considering the three factors above mentioned, the reduction factor coefficient C_{RF} can be obtained:

$$C_{RF} = C_{COV} \cdot C_{ST} \cdot C_F = 0.2819 \tag{11}$$

The C_{RF} indicates the percentage of usable roof area for PV installation.

The total roof area can be evaluated using the elementary field statistics function of QGIS, multiplied by the reduction factor as follows:

$$S_{PV} = S_{suitable} \cdot C_{RF} \tag{12}$$

Considering the assumed PV panel model, the space requirement is about 5.11 m^2 for each kWp (i.e., the row spacing has already been considered in C_{RF}); the total PV power is:

$$P_{PV} = \frac{S_{PV}}{5.11} \tag{13}$$

3. Case Study: Minor Non-Interconnected Sicilian Islands

The methodology presented previously has been implemented to evaluate the technical potential of onshore wind and rooftop PV for non-interconnected Sicilian islands. Following the spatial planning approach described above, the suitable areas were identified that comply with national, regional and local regulations. The fourteen islands studied are: the Aeolian Archipelago, the Egadi Archipelago, the Pelagian Archipelago and the islands of Pantelleria and Ustica.

3.1. National Legislation

To meet the challenge of the clean energy transition, Italy has passed several laws regulating RES projects and their integration into the environmental and cultural landscape. In 2003, Italy obtained Directive 2001/77/EC through Legislative Decree No. 387/2003, updated by Legislative Decree No. 28 of 3 March 2011, which emphasises the promotion of a greater share of RESs in electricity production in the Italian and community markets [49,50].

The authorisation procedure and technical requirements for the development of RESs were established by Ministerial Decree of 10 September 2010 No. 219 (D.M 219/2010) [51]. Within the framework of this study, the only guidelines for the distance and safety installation required for the evaluation of the technical potential were adopted. The Decree gives special emphasis to wind turbines and to the minimum requirements for the identification of suitable areas as defined:

- Minimum distance of any wind turbine of 200 m from registered and inhabited residential units.
- The minimum distance required from the inhabited centres must be equal to six times the hub of the wind tower, in compliance with the local urban plan.
- To avoid the increasing of the hydrogeological weakness of the land causing instability phenomena, any new wind farm installation has to demonstrate that it will not trigger further erosion phenomena. This requirement applies in the case of slopes greater than 20%.

D.N. 219/2010 does not pose specific restrictions for the installation of PV systems. Furthermore, it gives to regions the possibility to identify unsuitable areas for specific RES technologies.

3.2. Regional Legislation

In the context of this work, which deals with the fourteen smaller Sicilian islands, the Sicilian Ordinance on the use of RESs has been taken into account. Following the D.M. 219/2010, a detailed classification of unsuitable areas was published by Regional Presidential Decree 10 October 2017 No. 26 (D.P.Reg. 26/2010) [52]. The decree establishes a detailed classification of wind turbines based on rated power:

- E01: Wind turbines with a nominal power < 20 kW.
- E02: Wind turbines with a rated power between 20 kW and 60 kW.
- E03: Wind turbines with a rated power > 60 kW.

Based on the power size, the decree sets specific restrictions on the type of area on which it is wished they be installed. In addition, the decree distinguishes between "unsuitable areas" and "areas of particular importance" for the installation of wind turbines for the production of electrical energy; in particular:

- Unsuitable Areas: Areas where the installation of wind turbines is prohibited (regardless of the size of the power).
- Areas of particular attention: Areas where special precautions or mitigation measures might be required (also depending on the power size).

This study adopts the above classification.

Unsuitable Areas

According to the classification of [52], the unsuitable areas, where any type of installation is prohibited, are zones that have been identified as environmentally and culturally relevant. In particular:

- Site of Community Importance (SCI).

- Special Protection Area (SPA).
- Special Area of Conservation (SAC).
- Important Bird Area (IBA).
- Sicilian Ecological Network.
- Ramsar Site (wetlands) and nature reserves.
- Protected Oasis and Fauna Refuges.
- Geosites.
- Regional and National Parks except those providing for other measures in force at the time of the enactment of the above decree.
- Landscape protection zones and archeological areas and parks as in Art. 134, letters (a), (b) and (c) of the Code of cultural heritage and landscape [53]. In these zones, the construction of individual EO1- and EO2-type wind turbines is allowed to support agricultural activities in areas covered by general regulatory plans under Art. 22 of Regional Law No. 71 of 1978 and subsequent amendments.

  Areas not eligible for plant types EO2 and EO3 are instead:

- The ecological corridors identified on the basis of the maps drawn up to support the management plans of the Natura 2000 sites (SCI, SAC and SPA).
- The areas defined as forests in accordance with Art. 142, paragraph 1, letter (g), of the Code of Cultural Heritage and Landscape.
- Areas classified as "very high" (P4) and "high" (P3) risk in the Hydrogeological Structure Plan.

Therefore, it is clear how, for the addressed case study, the regional legislation introduces significant restrictions to the exploitation of the wind resource.

3.3. Local Legislation

The following paragraphs analyse the local restrictions for the analysed islands on a municipal basis.

3.3.1. Pantelleria

The local urban plan of Pantelleria prohibits any photovoltaic installation within the historic town centre and above the local dwellings called *Dammusi*.

3.3.2. Pelagic Archipelago

The Pelagic Archipelago allows, in line with his local zoning and landscape plan, photovoltaic installation on all the islands. However, the local zoning and landscape plan prescribes measures to mitigate the visibility of PV installations from main roads or certain viewpoints. In addition, the plan prescribes that PV installations must not be located within view of the site, i.e., all parts must exceed parapets. Moreover, the local landscape prescribes a maximum size of 20 kW for wind plant installation.

3.3.3. Eolian Archipelago

There are no specific restrictions for the exploitation of renewable energy facilities.

3.3.4. Egadi Archipelago

There are no specific restrictions for the exploitation of renewable energy facilities.

3.3.5. Ustica

There are no specific restrictions for the exploitation of renewable energy facilities.

4. Results and Discussion

Results on an island basis are presented as follows. A first significant outcome is that all islands except Ustica are completely within IBA, which represents an area not feasible for wind energy exploitation according to D.P.Reg. 26/2010.

The IBA constraint was therefore relaxed, also following discussions and official requests on the matter by some municipalities [54]. This hypothesis stems from the previous considerations about the need to preserve the land for agriculture and other human activities, especially in small contexts such as those of remote islands. Without the use of wind turbines, the self-sufficiency of the non-interconnected islands could seem unattainable.

The following results have been carried out in compliance with the hierarchical flow drafted in Figure 17. The decision process does not regard which technology should be preferred in order to calculate the roof PV technical potential and the onshore wind one; however, it represents the logic flow that has to be followed in order to calculate the potential respecting the regulations in force.

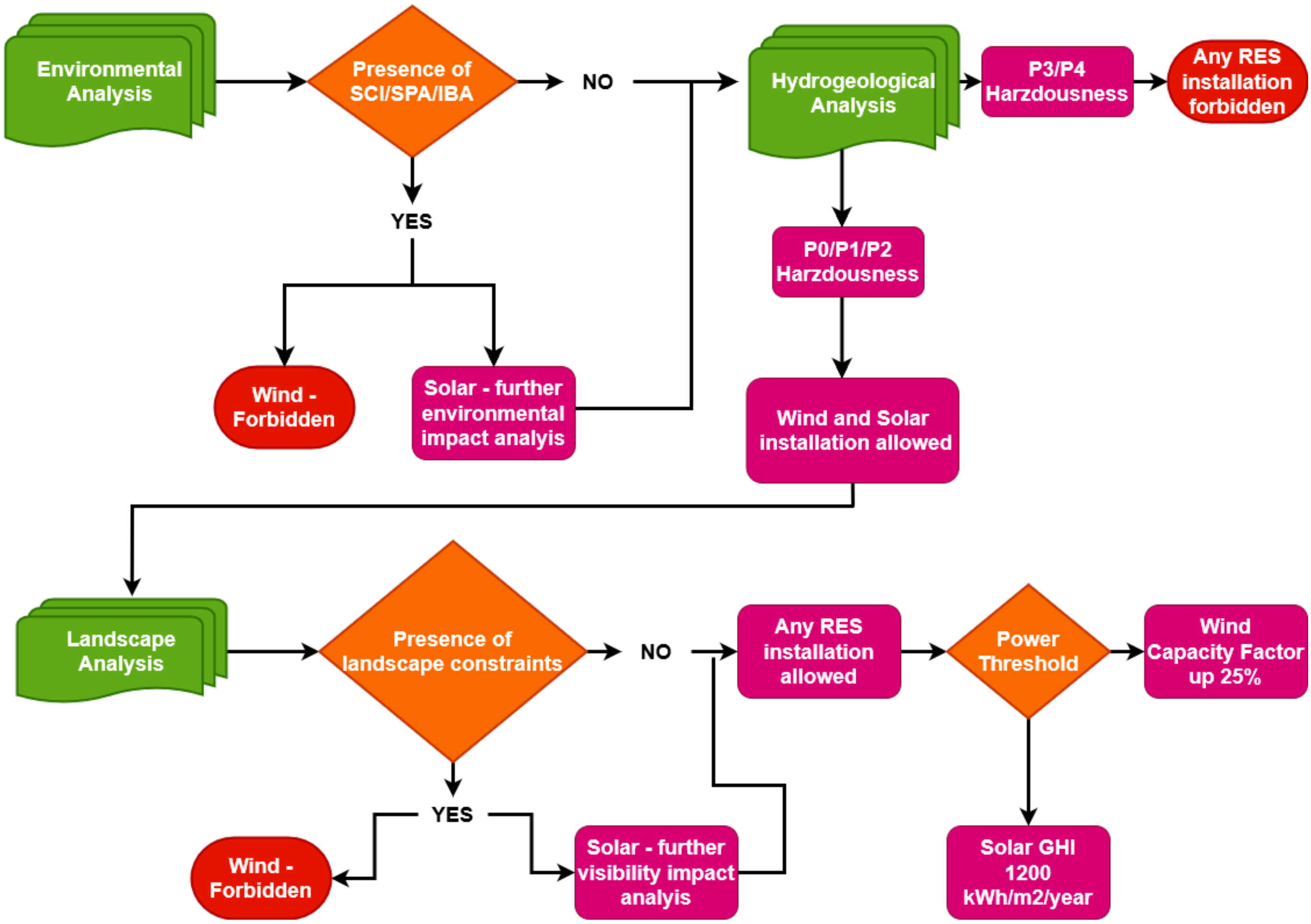

Figure 17. Hierarchical workflow.

4.1. Pantelleria

Pantelleria island is located in the middle of the Strait of Sicily (36.785° latitude, 11.992° longitude). This strategic location contributes to the creation of special meteorological conditions that are extremely favourable for the exploitation of RES. Pantelleria is characterised in particular by a high level of solar radiation throughout the year (i.e., approx. 2000 kWh/m^2) and a marked presence of wind, mostly from the NW, approx. 7 m/s at 25 m above sea level, accordingly with the clean energy transition agenda of Pantelleria [55].

Regarding the technical potential of photovoltaics, the analysis is in line with local regulations. In addition, a regional decree protects the zones outside the town centre. For this reason, the eligible buildings are located within the town centre, as shown in Figure 18.

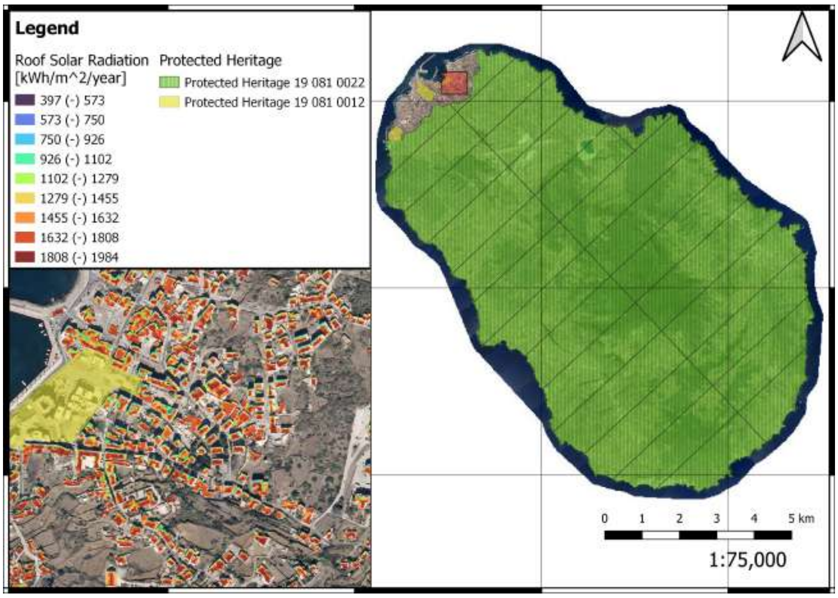

Figure 18. Solar radiation on Pantelleria roofs.

Following the methodology presented up to this point, the technical potential of PV on eligible buildings has been calculated and is reported in Table 2.

Table 2. Pantelleria PV technical potential on roofs.

Suitable Roof Area (m^2)	PV Panel Area (m^2)	PV Technical Potential (MW)
194,342	54,785	10.72

The protected areas on Pantelleria occupy a large part of the territory. Nevertheless, assuming a relaxation of the IBA restriction, a suitable area for the installation of wind turbines has been identified. In particular, an area in the northwest of the island with an area of about 9.36 ha meets the requirements and is suitable for any size and class of wind turbines (i.e., E01, E02, E03). From a resource point of view, Figure 19 reports a mean wind speed of 5.95 m/s at 30m a.s.l. (above sea level).

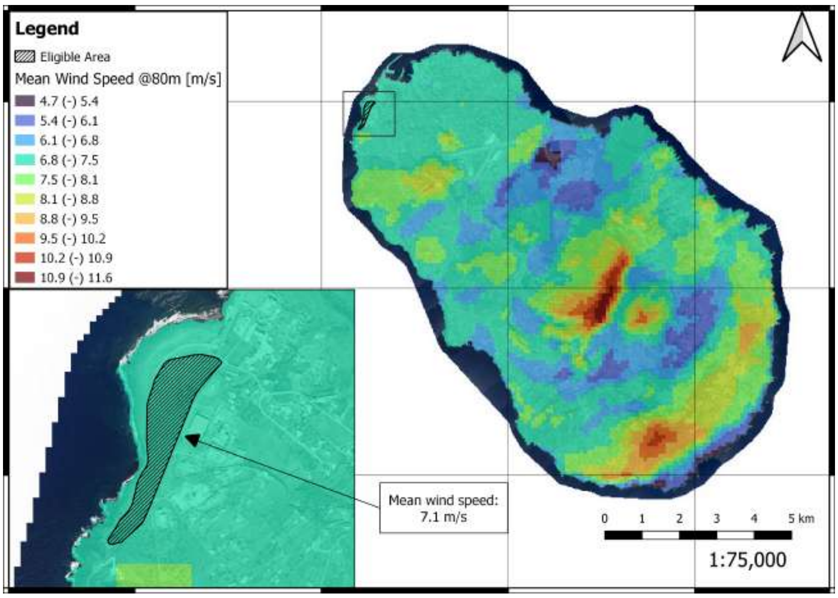

Figure 19. Mean wind speed and suitable area.

Table 3 shows the outputs and productivity of the individual wind turbine types according to the size scale reported previously.

Table 3. Pantelleria wind technical potential.

WTs (kW)	Mean Speed (m/s) at Hub	# WT	Net AEP (MWh/Year)	Wake Losses (%)	Capacity Factor (%)
20	5.45	27	1111	6.68	27.9
200	5.95	7	3043	3.35	25.7
2000	7.1	2	14,404	1.3	41.6

Each layout of each wind turbine size complies with the applicable regulations and crosswind and downwind distances based on the rotor diameter method.

4.2. Pelagic Archipelago

The Pelagic Archipelago includes the islands of Lampedusa and Linosa. This archipelago represents the southernmost area of Italy and Europe (overseas countries and territories are excluded). Lampedusa (35.538 Lat., 12.622 Long.) is the largest island of the archipelago with a total area of 20.2 km^2, while Linosa (35.866 Lat., 12.888 Long.) has an area of 5.4 km^2. Both islands are almost entirely covered by SCI areas (i.e., SCI ITA040002 and SCI ITA040001), which exclude the islands' urban centres. Instead, one IBA area (i.e., 168 and 168 M) completely covers both Lampedusa and Linosa.

As far as local regulations for the installation of PV systems are concerned, there are no specific restrictions. For a detailed illustration of solar radiation on roofs in the city centre of Lampedusa and Linosa, see Figures 20 and 21.

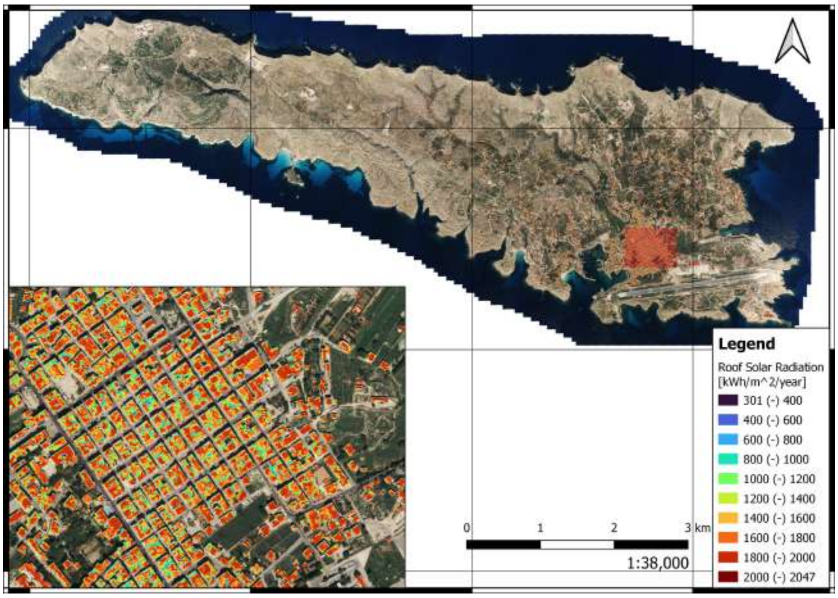

Figure 20. Solar radiation on Lampedusa roofs.

Figure 21. Solar radiation on Linosa roofs.

As the previous images show, the average solar radiation on the Pelagic Archipelago is about 2000 kWh/year, the highest in Italy. For a summary of the technical potential of photovoltaics, see Tables 4 and 5.

Table 4. Lampedusa PV technical potential on roofs.

Suitable Roof Area (m^2)	PV Panel Area (m^2)	PV Technical Potential (MW)
530,367	149,510	29.26

Table 5. Linosa PV technical potential on roofs.

Suitable Roof Area (m^2)	PV Panel Area (m^2)	PV Technical Potential (MW)
60,710	17,114	3.35

Regarding the sites suitable for onshore wind turbines, after relaxing the hypothesis IBA, a suitable area was identified on the island of Lampedusa. Figure 22 shows the mean wind speed on Lampedusa calculated with WaSP and displayed in a QGIS layout. The area identified is an industrial area of almost 2 ha on the NE side of the island, which has a mean wind speed of 5.65 m/s. The wind speed is calculated using WaSP. For this area, the technical wind potential that can be installed is given in Table 6 below.

Table 6. Lampedusa wind technical potential.

WTs (kW)	Mean Speed (m.s) at Hub	# WT	Net AEP (MWh/Year)	Wake Losses (%)	Capacity Factor (%)
20	5.52	8	374	3.87	26.4

As mentioned above, local regulations prohibit the installation of wind turbines with a capacity of more than 20 kW.

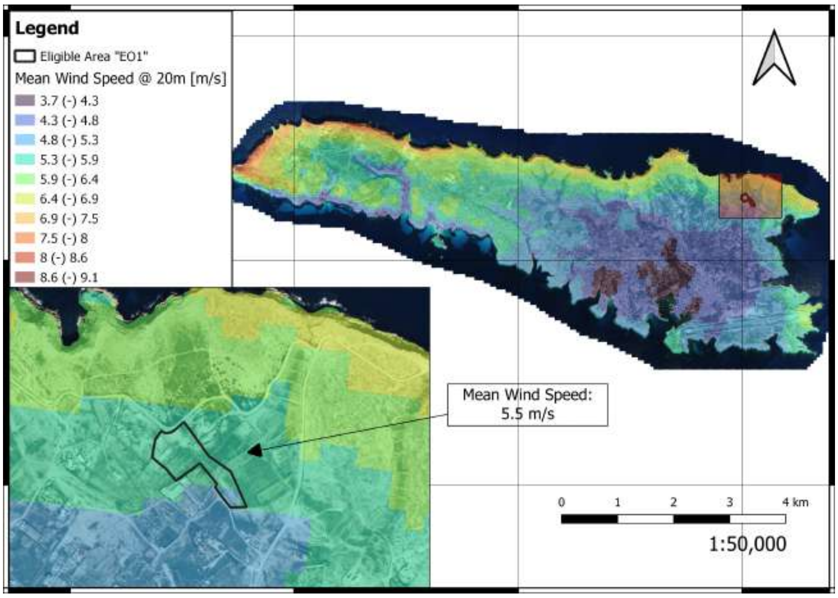

Figure 22. Mean wind speed and suitable areas in Lampedusa

4.3. Eolian Archipelago

The Eolian Archipelago includes seven islands under the jurisdiction of four different municipalities: Alicudi, Filicudi, Vulcano, Panarea, Stromboli and Lipari islands fall under the jurisdiction of the municipality of Lipari, the larger of them. The island of Salina, on the other hand, has three different municipalities: Santa Marina Salina, Leni and Malfa.

The archipelago is located in the southern Tyrrhenian Sea, as shown in Figure 23, and each island is of volcanic origin. This characteristic affects the land extent, four of them have an area of less than 13 km^2, it also affects the morphological nature of the islands, which are characterised by a steep slope of more than 20°. The technical potentials of both wind and solar energy suffer from the effects of the territorial configuration: in fact, it is not possible to install a kW of wind turbines on the entire archipelago, even taking into account the constraints of IBA. The steep slope and the small area reflected in the proximity of feasible wind turbines to urban centres do not allow wind turbines to be installed on the archipelago.

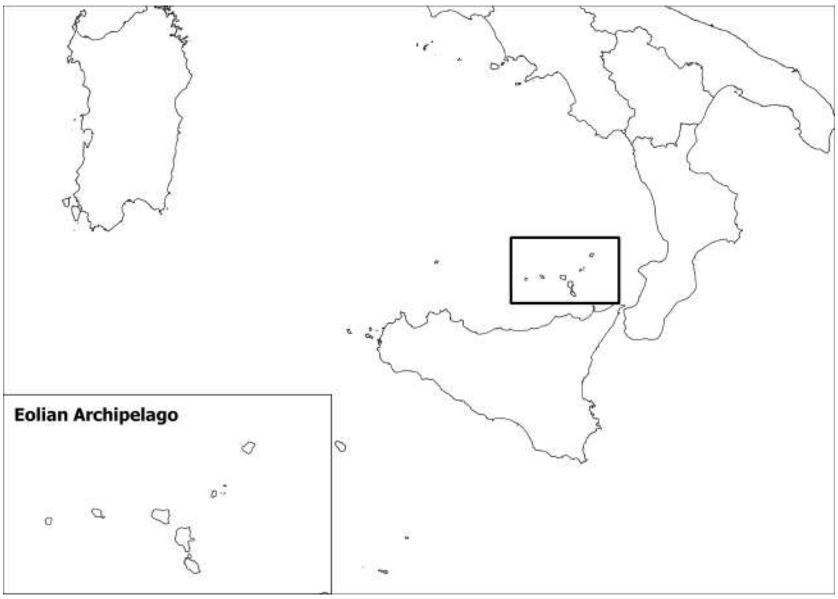

Figure 23. Eolian Archipelago.

In general, the area of Eolian islands is characterised by cultural and ecological beauty. Like the other islands presented, the Eolian archipelago is entirely covered by IBA zones (152 and 152 M) and several SCI areas.

The areas indicated in Table 7 do not cover the urban centres of the islands and the Eolian Archipelago Landscape Plan does not impose any specific restrictions on the use of solar energy on building roofs. For this reason, the analysis included the entire building roofs according to the methodology outlined in Evaluation of geographical photovoltaic potential on roofs . For the sake of clarity and brevity of this article, an example of the technical PV potential on rooftops is given for Salina Island and presented in Figure 24.

Table 7. SCI Areas on Eolian Archipelago.

Island	Type	Code
Alicudi	Land	ITA030023
Filicudi	Land	ITA030024
Panarea	Land	ITA030025
Stromboli	Land	ITA030026
Vulcano	Land	ITA030027
Salina	Land	ITA030028
Salina	Land	ITA030029
Salina	Sea	ITA030041
Lipari	Land	ITA030030

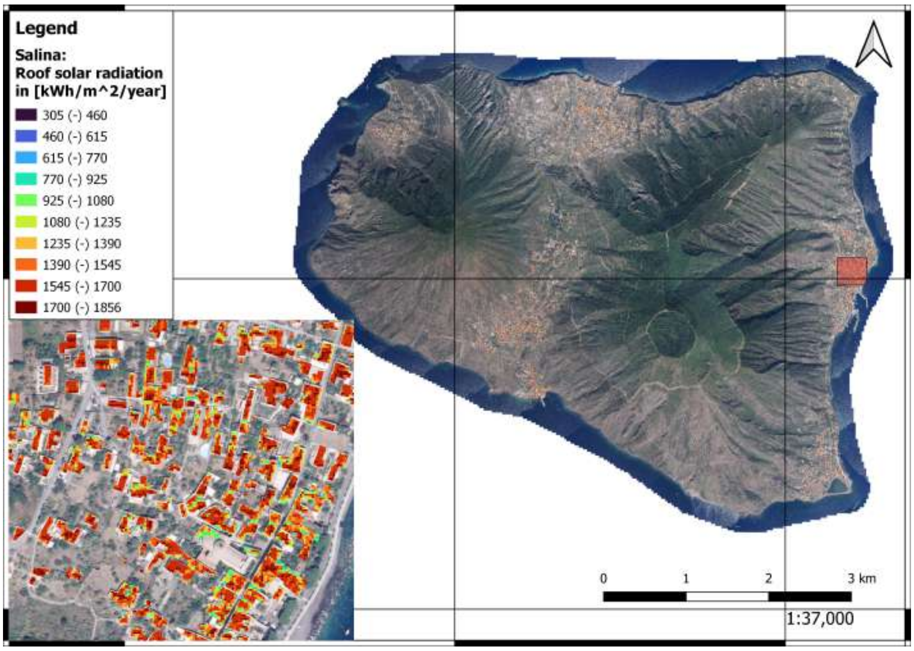

Figure 24. Solar Radiation of the roofs of Santa Marina Salina.

The maximum technical PV potential of roofs for the Eolian Archipelago is given in Table 8 below.

Table 8. Eolian PV technical potential on rooftops.

Island	Suitable Roof Area (m^2)	PV Panel Area (m^2)	PV Technical Potential (MW)
Alicudi	23,874	6730	1.32
Filicudi	65,394	18,434	3.61
Panarea	59,242	16,795	2.40
Stromboli	98,224	27,689	5.42
Vulcano	198,647	55,998	10.96
Salina	269,907	76,086	14.89
Lipari	735,264	207,271	40.56

4.4. Egadi Archipelago

The Egadi Archipelago is a group of three islands in northwestern Sicily, just a few kilometres from it, as shwon in Figure 25. Despite this proximity to the mainland, the islands of Favignana, Levanzo and Marettimo are not connected to Sicily or to each other. Due to their geographical position, renewable-energy sources are abundant: the archipelago has pronounced mistral winds and an average annual solar radiation of about 1950 kWh/m^2. Despite this RES abundance, the use of clean energy must take into account the numerous ecological and cultural beauty parts protected by an IBA area (157 and 157M) that covers the entire extension of the archipelago. In addition, the SCI areas that partially affect the archipelago are listed in Table 9.

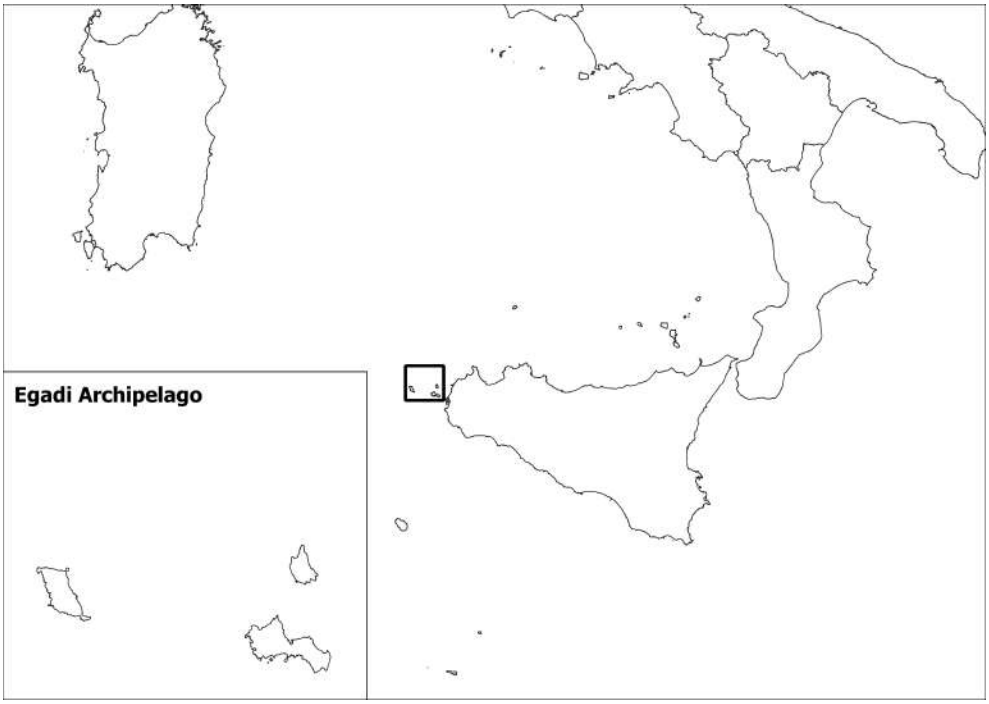

Figure 25. Egadi Archipelago.

Table 9. SCI areas on Egadi Archipelago.

Island	Type	Code
Marettimo	Land	ITA010002
Levanzo	Land	ITA010003
Favignana	Land	ITA010004
All islands	Sea	ITA010024

Under the hypothesis of loosening of the IBA, Favignana may host a certain amount of wind-engineering potential. An area with an extension of 3.5 ha has been identified, located on the SW coast of the island. As shown in Figure 26, the area under consideration is influenced by an average wind speed of 6.6 m/s. However, this area is not free from national restrictions: According to the minimum distance requirements from residential buildings, the maximum allowed size of the wind turbine is 200 kW. In addition, the area is within the 150 m limit from the coast, which theoretically does not allow construction. However, the installation of the wind turbines falls within the scope of a declaration of public interest. This status allows the use of wind energy in this area.

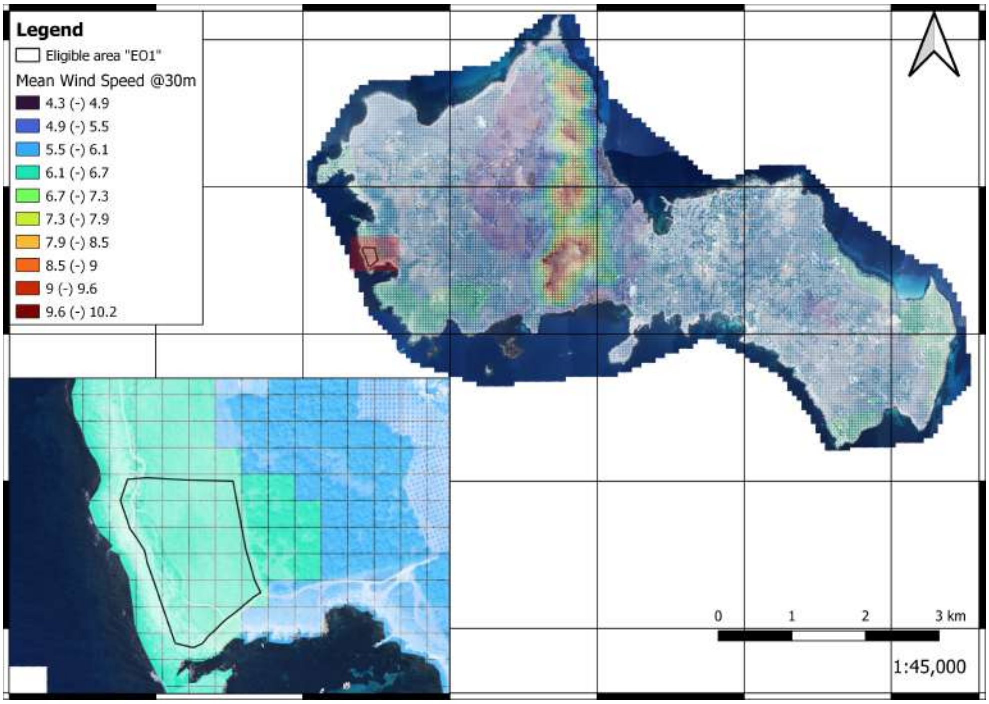

Figure 26. Favignana eligible area and mean wind speed.

The technical wind potential that can be installed in the eligible area is given in Table 10.

Table 10. Favignana wind technical potential.

WTs (kW)	Mean Speed (m.s) at Hub	# WT	Net AEP (MWh/Year)	Wake Losses (%)	Capacity Factor (%)
20	5.8	8	382	4.04	31.5
200	6.14	4	1887	3.03	27.8

In the case of the islands of Levanzo and Marettimo, it is not possible to install wind turbines, despite the relaxation of the IBA restriction. In terms of solar energy, there are no specific restrictions under the current regulations, so all the roofs are eligible for solar energy use. As in the case of the Eolian Archipelago, only one example of solar radiation on roofs has been given in this paragraph, as shown in Figure 27.

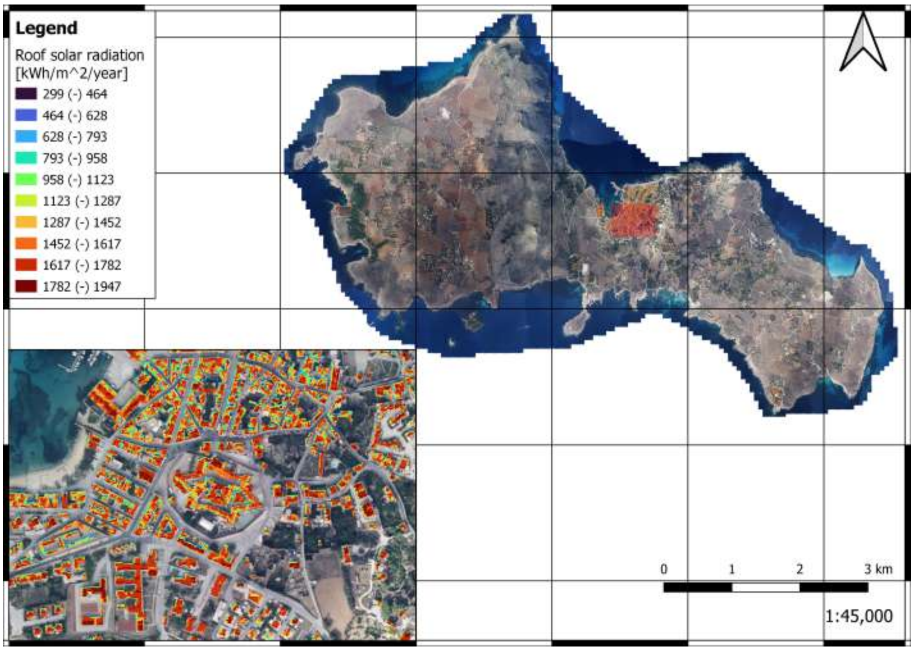

Figure 27. Solar radiation of the city centre of Favignana.

Following the consolidated methodology presented up to this point, the technical potential of rooftop photovoltaics was calculated for each island of the archipelago. The results are presented in Table 11.

Table 11. Egadi PV technical potential on rooftops.

Island	Suitable Roofs Area (m^2)	PV Panel Area (m^2)	PV Technical Potential (MW)
Favignana	303,734	85,622	16.76
Levanzo	18,038	5085	1.00
Marettimo	26,057	7345	1.44

As expected, the technical potential of Favignana is higher than that of the other islands because there are more buildings.

4.5. Ustica

Ustica Island is located in the southern Tyrrhenian Sea (Lat. 38,706, Long. 13,181). Environmental protection is ensured by the establishment of an SCI area (Cod. ITA020010), which does not cover the entire territory of the island. Ustica is the first case in this study of a Sicilian island that is not affected by an IBA area: this feature allows the exploitation of wind resources without any hypothesis.

The estimated area for wind energy exploitation is about 5.43 ha for the typology EO1 WT, which reduces to 2.87 ha for types EO2 and EO3, characterised by a mean wind speed of 5.39 m/s. The eligible area and the relative mean wind speed at 30 m a.s.l. are shown in Figure 28.

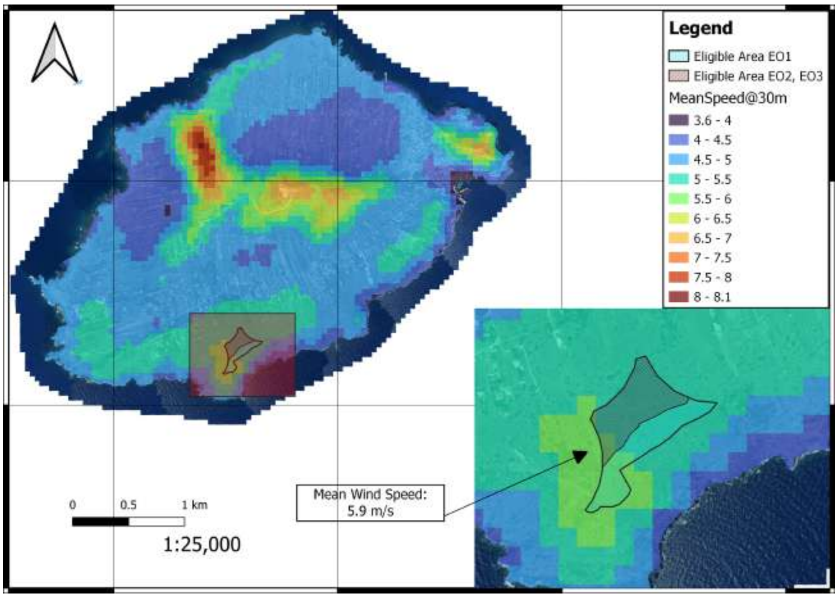

Figure 28. Ustica eligible area and mean wind speed.

Following the current regulations for Ustica, it is possible to evaluate the performance of any size of wind turbine. The results are shown below in Table 12.

Table 12. Ustica wind technical potential.

WTs (kW)	Mean Speed (m.s) at Hub	# WT	Net AEP (MWh/Year)	Wake Losses (%)	Capacity Factor (%)
20	5.07	10	390	2.07	25.3
200	5.93	4	1513	2.67	22.2
2000	5.63	1	5631	0	32.1

As far as the use of rooftop solar energy is concerned, there are no particular restrictions on the island of Ustica, so the presented method is applied to all available building roofs, as shown in Figure 29. Furthermore, the total technical PV potential on roofs is given in Table 13.

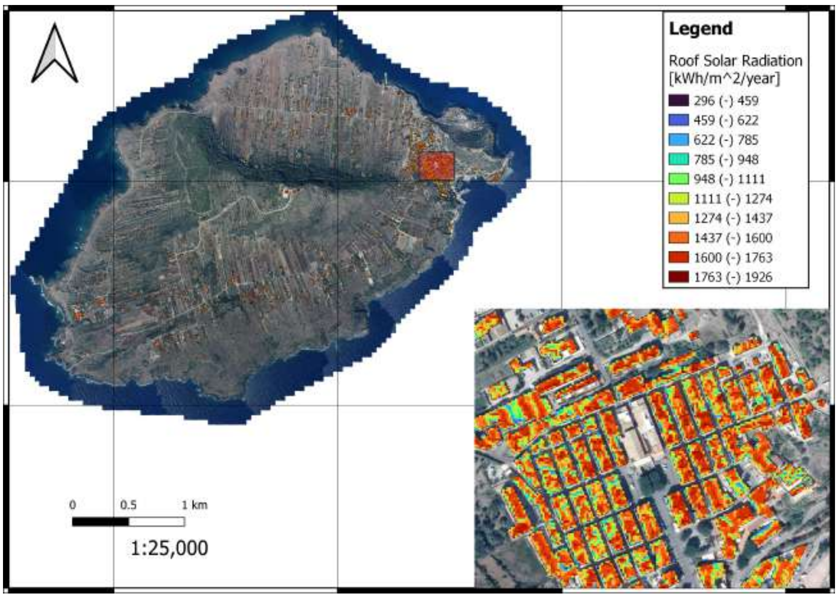

Figure 29. Ustica solar radiation on building roofs.

Table 13. Ustica PV technical potential on rooftops.

Suitable Roof Area (m^2)	PV Panel Surface Area (m^2)	PV Technical Potential (MW)
132,888	37,461	7.33

4.6. Effects on the Annual Electrical Energy Demand

To complete the framework, this paper also aims to provide an overview of the opportunities that these results could offer in achieving self-sufficiency for each island studied. The PVGIS tool was used to calculate the AEP of rooftop PV systems [45]. This choice was necessary because SEBE does not calculate irradiance on sloped surfaces, but only in relation to a given DSM.

As external data, PVGIS requires the performance ratio, i.e., the combination of the various losses that influence the PV system. Many authors assume that PR is about 80% (i.e., without considering the efficiency of the solar cells) [56]; at the same time, PR can be influenced by the cell efficiency [57] or the weather conditions [58]. For an overview of the phenomena affecting PV performance, see [59]. In this study, the PR would like to consider the physical phenomena (i.e., shading or differences with STC) and the electrical (i.e., cable losses, AC–DC conversion), a summary of the different losses is provided in Table 14. Under these hypotheses, the PR could be defined as:

$$PR = \eta_{mis} \cdot \eta_{d-r} \cdot \eta_{wir} \cdot \eta_{temp} \cdot \eta_{shad} \cdot \eta_{CPU} \tag{14}$$

Table 14. Performance Ratio parameters.

Parameter	Definition	Value	Reference
η_{mis}	Tolerance with respect to STC data and mismatch of module current-voltage characteristics	0.97	Spertino et al. [60]
η_{d-r}	Dirt and reflection of the front glass	0.976 [1]	Pavan et. al. [61], A.R.M. Alamoud [62]
η_{wir}	Cable losses	0.994	Ekici et al. [63]
η_{temp}	Overtemperature (or undertemperature) compared to STC	≃0.89 [2]	JinkoSolar [46]
η_{shad}	Shading losses	0.98	Varga et. al. [64]
η_{CPU}	MPP tracker and DC-AC conversion losses	≃0.98 [2]	Huawei [65]

[1] Different results depending on exposure time and climatic conditions, [2] depending on technology.

Assuming a commercial efficiency of PV cells of about $\eta_{STC} = 18\%$, the overall efficiency of the system for converting solar energy into electricity is the same:

$$\eta_{syst} = \eta_{STC} \cdot PR = 0.145 \longrightarrow 14.5\% \tag{15}$$

Based on the above, a PR of 14.5% was assumed. Considering the technical PV potential determined by the method, and maintaining a slope of 36°, the PV AEP was easily determined using PVGIS. The wind AEP results from the analysis of eligible areas carried out with WaSP, which were determined considering a wind turbine of 200 kW. This size seems most suitable in terms of space requirements and visual impact to be placed on a small island. The determined AEPs for both wind and solar energy were compared with the *Conventional Annual Electricity Production* as defined in [66] and presented in Table 15.

Table 15. Summary results and self-sufficiency estimates

Island	Potential Wind AEP (GWh/Year)	Technical Potential Wind Power (MW)	Potential PV AEP (GWh/Year)	Technical Potential PV Power (MW)	Annual Electricity Production from Diesel [1] (GWh_{el}/Year)	Self-Sufficiency Rate (%)
Pantelleria	3.04	1.4	18.47	10.72	44.17	48.69%
Ustica	1.51	0.8	11.45	7.33	4.87	266.21%
Lampedusa	0.374	0.16	49.11	29.26	37.66	131.40%
Linosa	-	-	5.61	3.35	2.80	200.38%
Favignana	0.19	0.8	27.51	16.76	15.47	179.04%
Marettimo	-	-	2.12	1.44	2.04	103.96%
Levanzo	-	-	1.57	1.00	0.60	260.83%
Alicudi	-	-	1.99	1.32	0.40	497.33%
Filicudi	-	-	5.78	3.61	1.40	412.70%
Salina	-	-	22.10	14.89	9.16	241.23%
Lipari	-	-	61.73	40.56	34.80	177.37%
Vulcano	-	-	17.22	10.96	7.28	236.50%
Panarea	-	-	3.50	2.40	3.14	111.40%
Stromboli	-	-	8.00	5.42	3.87	206.68%

[1] Data from Ref. [66]

5. Conclusions

The transition to a low-carbon society requires careful spatial energy planning to protect the environmental and cultural heritage. The methodology presented in this paper combines spatial planning, taking into account the applicable legal framework, and the assessment of renewable-energy sources, with the aim of identifying the technical potential of wind resources and rooftop photovoltaic. The case study addresses Sicilian minor islands, which are characterised by an important environmental and cultural heritage. Thank to a straight application of the hierarchical flow exposed previously, which deals with the analysis of the constraints imposed by the current regulation framework, the paper examined the technical potential of both wind and rooftop photovoltaic for the case study. The environmental analysis highlighted the main limits for the onshore wind installation; in contrast, the landscape constraints study (both on local both at a higher level) completed the framework to find the most suitable areas (and boards) to install RES capacity. Thanks to a very small resolution grid, the method proposed produced results characterised by a high resolution level and totally integrated in the QGIS software for their representation. It was observed that, in compliance with the current regulatory framework, the exploitation of wind energy is possible on just one island (Ustica), while in all other islands the regional regulation prevents it. Except on one island (Pantelleria), the total installable rooftop PV capacity could be sufficient to produce as much energy as is nowadays consumed. Nevertheless, the power supply of insular energy systems cannot rely on only one non-dispatchable renewable-energy source, but rather on a mix of technologies, in order not to overestimate the expense for storage systems [21]. It is therefore recommended to discuss a revision of the current rules on wind energy exploitation, and to invest in the development of offshore renewables (mainly wave energy and offshore wind).

As the authors intend, the developed methodology could be useful for local decision-makers to assess the RES potential, address energy policies and eventually revise current regulation. Future works will focus on the expansion of the work developed for all Italian islands and the presentation of the outcomes on an interactive WebGIS platform.

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Abbreviations

The following abbreviations are used in this manuscript:

IPCC	Intergovernmental Panel on Climate Change
RES	Renewable Energy Source
MCA	Multi Criteria Analysis
NIMBY	Not In My BackYard
CETA	Clean Energy Transition Agenda
WaSP	Wind Atlas Analysis and Application Program
UMEP	Urban Multi-scale Environmental Predictor
GIS	Geographical Information System
IBA	Important Bird Area
EEA	European Environmental Agency
DTU	Danmarks Tekniske Universitet
AEP	Annual Energy Production
WTs	Wind Turbines
GWA	Global Wind Atlas
GWC	Generalised Wind Climate
PWC	Predicted Wind Climate
SEBE	Solar Energy on Building Envelopes
DSM	Digital Surface Model
ECMWF	European Centre for Medium-Range Weather Forecasts)
DTM	Digital Terrain Model
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
TRL	Technology Readiness Level
SCI	Sites of Community Importance

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