POLITECNICO DI TORINO

Master's Degree in Energy and Nuclear Engineering

Master's Degree Thesis

Scalable methodology for wind and photovoltaic energy technical potential assessment: Application to Sicilian minor islands

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Io sono nato in Sicilia
e lì l'uomo nasce isola nell'isola e rimane tale fino alla morte,
anche vivendo lontano dall'aspra terra natìa
circondata dal mare immenso e geloso.

[Luigi Pirandello]

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Abstract

Providing electricity in non-interconnected islands is a big challenge, exacerbated by the high cost of transporting fossil fuels and the non-viability of extending grid connections. Today, the Italian minor islands have an unrepeatable opportunity in front of them to start an effective energy transition process thanks to the fund provided by the national Recovery and Resilience Plan. This plan has allocated, a noteworthy part of the funds, 200 million euros, for the "Green Islands Program" which is aimed at promoting the improvement and strengthening, in environmental and energy terms, of the 19 minor non-interconnected islands.

This thesis aims to set up an original and scalable methodology to determine the technical potential of wind and photovoltaic renewable energy sources in the Italian minor islands' context, to facilitate the proper planning of the energy transition process of these territories. The proposed methodology is based on a spatial energy planning approach, which considers normative constraints, in addition to the technical specifications, to determine the suitable areas for renewable energy exploitation. The wind energy technical potential is evaluated employing the WAsP software suite. This tool is used to place wind farms in relevant regions and simulate their annual energy production, considering the specific terrain characteristics and the technical specifications of the chosen wind turbines. The evaluation of the photovoltaic technical potential is based on the Solar Energy on Building Envelopes model, which estimates shortwave irradiance on ground and roofs that is the main input data for the subsequent calculations. The proposed methodology is implemented on a geographic information system software to perform the geospatial analysis of the unsuitable areas and to visualize the generated resource maps, moreover, it is also created a geodatabase containing all the layers produced.

In this study, the methodology is applied to the fourteen non-interconnected Sicilian minor islands. The preliminary analysis confirms the abundant amount of wind and photovoltaic theoretical potential, in terms of mean wind speed and solar irradiation, reported by previous study. Furthermore, the obtained results disclosed that the on-shore wind and roof photovoltaic technical potential is greater than the diesel generator electricity production on eleven out of fourteen analysed islands. However, the vast majority of the estimated technical potential comes from installing solar panels on the building roofs; while, the wind energy exploitation is totally limited from the actual legislation framework, therefore some assumptions have been made to loosen the restrictions and identify some eligible areas for the wind turbines installation.

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Abbreviations

AGL	Above Ground Level
ARERA	Autorità di Regolazione per Energia Reti e Ambiente
CEMAT	Europe Conference of Ministers responsible for Spatial/Regional Planning
CLC	Corine Land Cover
CTRN	Carta Tecnica Regionale Numerica
DEM	Digital Elevation Model
DOC	Denominazione di Origine Controllata
DOCG	Denominazione di Origine Controllata e Garantita
DOP	Denominazione di Origine Protetta
DSM	Digital Surface Model
DTM	Digital Terrain Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EU	European Union
GHG	Green House Gases
GIS	Geographic Information System
GWA	Global Wind Atlas
GWC	Generalised Wind Climate
HAWT	Horizontal Axis Wind Turbine
IBA	Important Bird Area
IGP	Indicazione Geografica Protetta
ISTAT	Istituto Nazionale di Statistica
LNG	Liquified Natural Gas
MEC	Minor Electrical Company
NGEU	Next Generation European Union
ONR	Oriented Natural Reserves
P2G	Power To Gas
PAI	Piano per l'Assetto Idrogeologico
PTP	Piano Territoriale Paesisitico
PV	Photovoltaic
PWC	Predicted Wind Climate
RES	Renewable Energy Sources
RRF	Device for Recovery and Resilience

SAC	Special Area of Conservation
SCI	Site of Community Interest
SEBE	Solar Energy on Building Envelopes
SEP	Spatial Energy Planning
SITR	Regional Territorial Information System
SPA	Special Protection Area
STG	Specialità Tradizionale Garantita
UMEP	Urban Multi-scale Environmental Predictor
WAsP	Wind Atlas Analysis and Application Program
WT	Wind Turbines

1 Introduction

The energy transition is not an event that can happen in one day, one month and not even in a year, it is a process that evolves during the time, with the aim of eliminating the dependence on fossil sources of energy driven by a recognition that global carbon emissions must be brought to zero to safeguard the health of the planet and therefore of the living beings that inhabit it. For the non-interconnected minor islands, the energy transition towards renewable energy sources (RES) is a necessity of primary importance given their total dependence on the import of fossil fuels from the mainland by sea, in spite of the great local energy potential.

1.1 Research background and motivation

The atmosphere is warming and the climate is changing year after year. One million out of the eight million species on the planet are at risk of extinction, meanwhile forests and oceans are being polluted and destroyed [1]. There is empirical evidence of the unprecedented rate and global scale of impact of human influence on the Earth System [2]. The whole world is called to do whatever it takes to counteract this trend and future catastrophe developments.

The European Union (EU) has responded to these challenges with the European Green Deal, which is defined by the European Commission as [3]: "A new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use". The European Green Deal, pay particular attention to the role of outermost regions taking into account their vulnerability to climate change and natural disasters and their unique assets: biodiversity and renewable energy sources. For this reason, it was established the Clean Energy for EU Islands Initiative to develop a long-term framework to accelerate the clean energy transition on all EU islands. In addition, Europe has programmed several calls in the "Horizon 2020" program to address the specific problems of the minor islands to finance projects aimed at environmental sustainability and energy transition. Among them, the NESOI (New Energy Solution Optimized for Islands) project, which aims to finance 60 promising energy transition projects out of the 2400 inhabited EU islands, mobilizing over 100 million euros of investments and significantly reducing Green House Gases (GHG) emissions by 2023.

In Italy there are more than 70 inhabited minor islands [4] of which 19 are non-interconnected to the national electricity grid [5] (without considering those very small with a few dozen inhabitants). Sicily is the most represented region with 14 out of 19 non-interconnected minor islands. In recent years, several public and private initiatives have been carried out, such as programmatic plans, decree and various funds have been allocated to boost the energy transition of these islands. Unfortunately, Italian minor islands are subjected to restrictive regional regulation which prevented a rapid adoption of renewable energy technologies, so at the moment the RES are not really exploited, except for a few pioneering achievements in the utilization of solar energy [6]. The Politecnico di Torino is contributing with its researcher to the energy transition process of the minor islands working alongside local stakeholders and institutions; for example, it collaborated to the drafting of the Pantelleria island's Agenda for the energy transition.

The pandemic, and the consequent economic crisis, have prompted the EU to formulate a coordinated response with huge economic support packages adopted by individual member states, in particular with the launch in July 2020 of the Next Generation EU (NGEU) program. It is a program of unprecedented scope and ambition, which includes investments and reforms for the ecological and digital transition; improve the training of male and female workers; and acquire greater territorial equity in terms of gender and generations. Italy is the first beneficiary, in absolute value, getting through the device for Recovery and Resilience Facility (RRF) 191,5 billion euros, to be used in the period 2021-2026, of which 68,9 billion are non-repayable grants. On January 2021, the national Recovery and Resilience Plan (RRP) has been approved by the Council of Ministers, defining how these funds will be invested. Just under a third of the RRP, 51,46 billion euros, is earmarked for the green revolution and ecological transition [7].

The Italian minor islands are included in this plan and a part of the funds, 200 million, were allocated to the "Green Islands Program" which is aimed at promoting the improvement and strengthening, in environmental and energy terms, of the 19 minor non-interconnected islands, through the implementation of integrated projects on energy and water efficiency, sustainable mobility, the management of the waste cycle, the circular economy, the production of renewable energy and the various applications for end uses [8]. The target of the decree is to carry out, by 30th June 2026, in each of these islands, at least three of the types of interventions included on the fields mentioned above. To be noticed that they are financed interventions of energy efficiency of public real estate owned by municipalities to reduce energy consumption, construction of renewable energy plants owned by the municipality and interventions on the electricity grid to ensure its continuity and facilitate the integration of energy produced from renewable sources. These initiatives represent a turning point for the energy transition of the Italian minor islands, which could see a long-awaited development that has never materialized.

This master's thesis is placed within the above-mentioned context. It is intended to be a contribution that aims to encourage the definition of the next interventions in the field of energy production from RES, with the assessment of the technical potential from wind and photovoltaic sources. This study can give important insights for the next choices of political decision makers regarding areas that could be better from an energy and legislative point of view to exploit these resources.

1.2 Structure of the thesis

This master's thesis starts with an introduction chapter on the fund deployed by the Recovery and Resilience Plan and the consequent opportunities opened for the energy transition of the Italian minor islands. The first introductory chapter also reports the background and motivation of this work. Chapter 2 gives an overview of the current territorial and energetic framework of the fourteen Sicilian minor islands, highlight the main obstacles for the energy transition process of these territories and provide a brief point of view on the future development scenarios currently planned. Chapter 3 is the core of the thesis and describes the original and scalable methodology that was carried out for the assessment of the technical potential from wind and photovoltaic sources. Firstly, it is introduced the spatial energy planning approach utilized and the geographic information system implemented in the methodology, secondly an analysis of the actual legislation on a national, regional and local scale is performed. The third and fourth sections are focalized on the technical potential assessment of wind and photovoltaic energy respectively. Chapter 4 is dedicated to the application of the methodology on the Sicilian minor islands, taken as a case study, and the numerical results are presented and discussed. Finally, Chapter 5 contains the conclusions of the whole thesis. The results obtained are recalled trying to give a wider view; then, some ideas and suggestions for future improvement of the methodology are given.

2 Energy transition of the Sicilian minor islands: Current status

The minor islands are isolated by definition and for this reason they preserve unique and rare natural characteristics that cannot be easily found in other locations. The environment is the greatest asset they can count on both on identity and economic aspects and for this reason it must be respected and protected. At the same time, to be isolated can cause inconvenience, especially to the people who live in these places, making difficult things that are taken for granted in other contexts.

From the energetic point of view, the minor non-interconnected islands can face problems like the interruption of the electricity supply for several hours or the disruption of fuel supply by ship, used for electricity production and transports, during periods of bad weather and operational costs much higher than the rest of the national territory. These problems could be mitigated or even eliminated changing the actual energetic paradigm based entirely on the import of fossil fuels. Nowadays, there is a wide range of technological solutions to produce electricity from renewable sources that, in the case of Sicilian minor islands, are abundant and of a different nature. It is proven that a single renewable source can not be the solution, therefore it is necessary to develop a strategy that includes an energy mix and so the coexistence of different renewable energy systems among those available: wind, solar, biomass, geothermal, wave energy resource. To do that, in the last years several programs have been designed to promote the energy transition process of the minor islands on different levels: regional, national but also European as the “Clean Energy for EU Islands Secretariat”, an initiative of the European Commission with the aim to support the energy transition path of the European minor islands.

The funds deployed by the Recovery and Resilience Plan for the Italian minor islands are a great opportunity to accelerate the energy transition process and aim for a more sustainable future, but the road to achieve this goal is long and there are several obstacles that are still not easy to overcome. The first thing to do is to understand what the starting point is and what are the constraints and opportunities we face; accordingly, in the next sections the territorial and energetic context of the Sicilian minor islands will be presented, highlighting the points in common and the differences between them; furthermore, a view on the main barriers to the RES exploitation and on the future development scenarios will be discussed.

2.1 Territorial context

The fourteen inhabited and non-interconnected Sicilian minor islands, protagonists of this study, are divided in three archipelagos, with the exception of Pantelleria and Ustica islands as summarized below:

- Eolie archipelago which comprises seven islands: Lipari, Vulcano, Stromboli, Filicudi, Alicudi, Panarea, Salina.
- Egadi archipelago which comprises three islands: Favignana, Marettimo and Levanzo.
- Pelagie Archipelago which comprises two islands: Lampedusa and Linosa.
- Pantelleria island.
- Ustica island.

The fourteen Sicilian minor islands are part of eight municipalities, which can include more than one island with the exception of Salina where the island is divided into three municipalities. The municipal headquarters are: Pantelleria, Ustica, Lipari, S. Marina of Salina, Leni, Malfa, Lampedusa and Linosa, Favignana. A summary of the surfaces and demographic characteristics, divided per municipality, was obtained from the data [9] made available by the Italian national statistic institute (ISTAT), and it is presented in the table 2.1:

Island	Municipality	Province	Archipelago	Surface [km^2]	Population
Pantelleria	Pantelleria	TP	-	83	7.366
Ustica	Ustica	PA	-	8,65	1.271
Lipari	Lipari	ME	Eolie	37,6	12.266
Vulcano				21	
Stromboli				12,6	
Filicudi				9,3	
Alicudi				5,1	
Panarea				3,4	
Salina	Salina - Leni - Malfa			26,2	2.522
Lampedusa	Lampedusa and Linosa	AG	Pelagie	20,2	6.337
Linosa				5,4	
Favignana	Favignana	TP	Egadi	19,3	4.270
Marettimo				12,4	
Levanzo				5,8	
TOTAL				**269,95**	**34032**

Table 2.1: Surface and demographic characteristic of minor Sicilian islands

The biggest island among these is Pantelleria with a surface of 83 km^2, instead the smallest one is Panarea with 3,4 km^2. The total minor Sicilian islands surface is about 269,95 km^2 and the overall inhabitants are 34032 that correspond to about the 0,70% of the entire regional population. The population density is very low for every island but most of the inhabitants are enclosed in small urban centres, with the presence of houses scattered throughout the territory. Transport to and from the islands takes place mainly by ship except in the case of Pantelleria and Lampedusa where the airport is also present.

Each island has its own peculiarities from a cultural and historical perspective, which derive from the different dominations they had suffered, while from the geological classification they can be divided in two main groups: Aeolian archipelago, Ustica, Linosa and Pantelleria islands are of volcanic origin, instead Egadi archipelago and Lampedusa are of calcareous origin. This first classification is useful to understand the potentiality that derives from the origins of the territory, for example the availability of fresh water under the ground or the possibility to exploit different renewable energy resources like geothermal energy for the volcanic islands. In principle, the islands with more than 5000 inhabitants have an economic structure characterized by the development of some local productive activities, although influenced by seasonal tourism, while smaller islands economy is based, almost exclusively, on tourism and fishing [10].

It is possible to recognize some common traits that characterize the Sicilian minor islands and that can be used as starting point for a further analysis:

- Low level of anthropogenic transformation.
- High seasonal variation of the inhabitants due to the tourism flux.
- High annual variation of the energy demand.
- High cost of food and fuel due to the transport by ship.
- Little penetration of energy production by RES.
- Limited freshwater resource.
- Problems in waste management and transportations.

It is clear that the points in common are the result of insularity and they affect mostly the local population and the environment. The peaks of summer tourism put a strain on local organization and especially on the management of resources such as fresh water, energy or waste disposal.

Fresh water is imported from the mainland by ship in nearly every case and this practice is characterized by high procurement costs, in the order of 10-14 €/m^3. Today only five out of fourteen Sicily’s remote islands can meet the local freshwater demand autonomously, thanks to the presence of more or less efficient desalters, they are: Pantelleria, Ustica, Lampedusa, Linosa and Lipari. The latter one has a highly efficient reverse osmosis desalter partially powered by photovoltaics, which has an energy consumption of 5 kWh/m^3, instead of 15 kWh/m^3 of the old mechanical vapor compression technology [6]. To be noticed that on Vulcano and Favignana islands desalters are present, but in the periods of the year with greater tourist affluence the local freshwater production is not sufficient, so they recur to the procurement by ship or, in the case of Favignana, by the submarine pipelines connected to Trapani [11].

One of the biggest issues, common to all the minor islands, is the electrical power production that to date is entirely based on fossil fuels. It is crucial to understand the criticalities of this system and the needs of the local realities to act towards a more sustainable future; for this reason, in the next section the current electrical energy production scenario will be discussed.

2.2 Current energy supply

The electricity system of the Sicilian Minor Islands is an isolated system, where the generation is entrusted to small thermoelectric power plants made up of several production units fuelled by diesel, while the distribution is realized through medium and low voltage networks, characterized by very limited extension. For 8 out of 14 islands all the services related to electricity: production, selling, distribution and measurement, are carried out with a monopolistic concession from, the so called, Minor Electrical Companies (MEC) and for the remaining six the services are provided by the Italian company, Enel Produzione S.P.A.

The current energy scenario poses various problems related to this method of electricity generation and distribution, which causes a consequent increase in operating costs. In particular, the generation from diesel groups is penalized by low efficiency, high fuel procurement costs, the necessity to foresee additional reserves to cope with refuelling delays in case of bad weather and commodity price change. Consequently, the costs of the necessary activities to provide these services are much higher than the national average, due to the particular complexity of the context. Hence, to ensure the economic survival of these companies and to avoid an unsustainable electricity price to end users, the Italian Regulatory Authority for Energy, Networks and the Environment (ARERA) has established that the island's end customers pay the energy at the average national price, “Prezzo Unico Nazionale”, and that the MECs are subjected to a regime of remuneration of the net assets and reinstatement of the costs incurred for the provision of the services (minus the profits derived from the energy selling) [12].

In table 2.2 is presented a summary of the local electrical services provider and the annual production of electricity generated by the thermoelectric plant for each Sicilian Island, taken from a study of the observatory on smaller Italian islands referred to 2021 [11]:

Island	Annual electricity production from diesel [MWh_{el}/y]	Electricity company
Pantelleria	39.000	S.MED.E Pantelleria
Ustica	4.870	Impresa Elettrica D’Anna e Bonaccorsi
Lipari	34.800	SEL SNC Lipari
Vulcano	7.280	ENEL Produzione
Stromboli	3.870	ENEL Produzione
Filicudi	1.400	ENEL Produzione
Alicudi	400	ENEL Produzione
Panarea	3.140	ENEL Produzione
Salina	9.160	ENEL Produzione
Lampedusa	37.660	S.EL.I.S. Lampedusa
Linosa	2.800	S.EL.I.S. Linosa
Favignana	15.470	SEA (Società Elettrica Favignana)
Marettimo	2.040	S.EL.I.S. Marettimo
Levanzo	600	I.C.EL.

Table 2.2: Thermoelectric plant production and ownership

It is clear that the annual power production is relatively low for almost every island except for the most inhabited like Pantelleria, Lampedusa and Lipari. Nevertheless, the diesel generator power installed is widely over-dimensioned to assure the reliability of the network and to cover the seasonal peak of energy demand that for the minor islands can reach two times the energy demand of winter months [13]. In fact, the biggest challenge is not to meet the annual production of electricity, but rather to do it in an efficient, reliable and sustainable way exploiting local resources aiming to the energy self-sufficiency.

In 2017, a big step forward was taken by the institutions to boost the production of energy from RES on the Italian minor islands, with the issuing of a ministerial decree by the minister of economic development, named “Minor Islands Decree”. This decree identifies the provisions for the progressive coverage of the needs of non-interconnected Italian minor islands through energy from renewable sources and, in particular, establishes [5]:

- The quantitative objectives of the islands' energy need to be covered through production from renewable sources.
- The time objectives for the process of gradual development of production from renewable sources.

- The methods of supporting the investments necessary to pursue the aforementioned objectives.

The decree refers both to the production of thermal energy and electricity from RES and establishes the minimum development goals for the use of renewable energy sources to be achieved by 31 December 2020. The situation at that date for the Sicilian minor islands is summarized in the table 2.3 [11]:

<table>
<tr><th>Island</th><th>Photovoltaic power installed</th><th>Wind power installed</th><th>Electricity needs covered by RES</th><th>RES power 2020 objective</th></tr>
<tr><th>[-]</th><th>[kW]</th><th>[kW]</th><th>[%]</th><th>[kW]</th></tr>
<tr><td>Pantelleria</td><td>840,3</td><td>32</td><td>3,13%</td><td>2.720</td></tr>
<tr><td>Ustica</td><td>432,6</td><td>0</td><td>11,99%</td><td>280</td></tr>
<tr><td>Lipari</td><td rowspan="7">508,9</td><td rowspan="7">0</td><td rowspan="7">1,35%</td><td rowspan="7">2.860</td></tr>
<tr><td>Vulcano</td></tr>
<tr><td>Stromboli</td></tr>
<tr><td>Filicudi</td></tr>
<tr><td>Alicudi</td></tr>
<tr><td>Panarea</td></tr>
<tr><td>Salina</td></tr>
<tr><td>Lampedusa</td><td rowspan="2">605,1</td><td rowspan="2">0</td><td rowspan="2">2,25%</td><td rowspan="2">2.310</td></tr>
<tr><td>Linosa</td></tr>
<tr><td>Favignana</td><td rowspan="3">404,1</td><td rowspan="3">0</td><td rowspan="3">3,01%</td><td rowspan="3">1.060</td></tr>
<tr><td>Marettimo</td></tr>
<tr><td>Levanzo</td></tr>
</table>

Table 2.3: Power production from RES and 2020 objectives

It is clear that the objectives by 2020 have not been reached by any island, with the exception of Ustica. It has reached, and exceeded, the power installed of about 55% and has achieved a self-production of 12% as regards electricity. The coverage of electricity needs from RES was calculated dividing the theoretical producibility of electricity RES with the annual production from fossil sources.

To understand what were the causes that led to the non-satisfaction of the objectives set and that can counteract the energy transition project, it is necessary to analyse the obstacles that have arisen in more detail. It will be essential to overcome these barriers in order to take advantage of the opportunities and money offered by the PNRR. For this reason, the next section is dedicated to the discussion of the main obstacles for the energy transition of the Sicilian minor islands.

2.3 Main obstacles for the energy transition of the minor islands

In order to achieve the ambitious objective of the Sicilian minor islands energy transition, it is necessary to analyse the constraints and obstacles that, until now, have not allowed an adequate development of RES. They should not be understood as conditions surrounding the energy transition process, but as obstacles and technological challenges to be faced. The main obstacles can be divided in three main areas [10]:

1. **Energy:** It is important to study the variation in energy demand in relation to the availability of RES under different time scales. From the point of view of seasonal variation, the Sicilian minor islands have daily demands for electricity in the summer months up to 2 times higher than in winter, as highlighted in the previous section and a low base load. This obstacle can be mitigated through an accurate analysis of the electricity demand and the availability of RES on a case-by-case basis, sizing the plants for the exploitation of the various renewable resources to maximize useful production.
2. **Technological:** A high penetration of RES involves problems in the dispatching service, or in the instant-by-instant balance between the demand and the supply of electricity. Problems in the energy demand coverage can be limited, identifying adequate deferrable loads and introducing storage systems at various levels of the system to ensure storage during periods of excess production from RES and release during periods of low production. Nevertheless, initially the contribution of "conventional" plants will be essential to provide the grid with "aggregate inertia" for the purposes of primary frequency control, but alternative solutions - such as flywheels and power batteries - must be tested, to open the way for future diffusion.
3. **Regulatory:** Many of the Minor Islands have particular constraints that limit the diffusion of technologies for the exploitation of RES. In general, these constraints are linked to the presence of woods and forests, Sites of Community Interest (SCI), Special Protection Areas (SPA) and Oriented Natural Reserves (ONR). All the rules must be analysed case by case, trying to identify the available areas and possible requests for the relaxation of specific restrictions zones for the installation of the different devices.

Finally, the use of land is one of the most important disadvantages related to the development of technologies to produce energy from renewable sources; it takes on even greater importance on the minor islands, where the space to be dedicated to human activities is more limited. Renewable sources are in fact characterized by energy densities that are decidedly lower than those of fossil fuels, and the plants for RES necessarily occupy larger spaces than the diesel generators widespread on the smaller islands. In any case, the different technologies for the exploitation of RES have different land uses: they range from a very high use of land for photovoltaic panels and concentrated solar power to lower values for on-shore wind; marine sources, on the other hand, have no use of land, and do not subtract space from anthropic activities on land, for these reasons the interest for off-shore wind and wave energy converters is growing fast.

To avoid unwanted environmental impacts, such as the excessive use of land by one or more RES technologies, it is essential to plan the future energy mix of each island right away in a conscious manner, also by analysing the current environmental constraints and relaxing those deemed too stringent. With this in mind, the next section talks about the future development scenarios, focusing on energy transition projects that have already been presented in recent years by the Sicilian minor islands in collaboration with various entities.

2.4 Future development scenarios

The path that the Sicilian minor islands are trying to undertake sees, as protagonists, new renewable energy production systems based on an energy mix of RES present in the territories, so it is necessary to identify which technologies are currently most convenient and which are the most interesting to experiment in such peculiar contexts.

2.4.1 Renewable energy sources exploitability

Photovoltaic panels and on-shore wind turbines represent mature technologies with high reliability; in addition, a further breakthrough is expected within the next decade for photovoltaics, which will see the emergence of new highly efficient technologies. These two technologies are already economically convenient and technically ready to be used, but as explained in the previous paragraph there are several obstacles that limit their diffusion on the minor islands. One of the most promising solutions for wind turbines is the off-shore installation which would avoid using the scant land available on the minor islands, but which presents critical issues such as the depth of the seabed. Traditional installations, with the towers planted on the seabed, are feasible up to depths of approximately 50 meters: these values are reached a few hundred meters from the coast of many of the minor islands, limiting the main advantages associated with the sea installations. An alternative, which is also spreading in the northern seas, is that of wind turbines on floating platforms: since the turbines are no longer planted on the bottom but anchored, they can be installed on much deeper bottoms. This solution is still expensive but will greatly expand the technical potential for exploiting the wind resource. As far as wave motion converters are concerned, there is a large number of devices with more or less high stages of development that could ensure a considerable production of energy also for the Mediterranean Sea application, as an example the Inertial Sea Wave Energy Converter (ISWEC) of the Politecnico di Torino; the main obstacle in this case is of an economic type, as these technologies still have very high costs, difficult to compare with those of wind and photovoltaics [10].

2.4.2 Agendas for the energy transition

The European Commission, in cooperation with the European Parliament, in 2018 set up a Secretariat to deliver the objectives of the Clean Energy for EU Islands initiative. The Secretariat acts as a platform of exchange of best practice for islands' stakeholders and provides dedicated capacity building and advisory services as the "Island Clean Energy Transition Agenda", which is a strategic roadmap for the transition process towards clean energy. It is designed by the local community, for the local community developing a shared understanding for the transition to a future-proof clean energy system will allow you to progress in the following three areas [14] :

1. **Community engagement:** Creating awareness and increasing involvement of local stakeholders to support a governance system that clearly defines the responsibilities and ensures local ownership of the island's transition activities.
2. **Decarbonisation plan:** The development of a decarbonisation plan which links the community's vision with concrete actions for its realization.
3. **Financing concept:** Increasing the island's capacity to benefit from existing and new funding opportunities by developing a clear financing concept.

To date, the Italian minor islands that have presented the energy transition agenda are two, both Sicilian: Pantelleria and Linosa, but others will be added shortly. These two islands will be an inspiration to the others that will soon begin the energy transition process and for this reason it is important to underline some of the key points of their agendas.

Salina's vision is clear: "In the future Salina is a sustainable island with an energy generation system based on renewables. Transport is decarbonised and all buildings are energy efficient. The local community uses resources efficiently and the island's natural features are respected" [15]. Among the strategic objectives to pursue this ambitious vision, there is that of increasing awareness among the population, through targeted actions to raise understanding of the efficient use of resources. The energy generation systems in Salina will be progressively decarbonised, based on the use of renewable sources, biofuels, hydrogen and liquified natural gas (LNG), with accumulations also of the power to gas (P2G) type. The internal mobility sector will be totally electric and 100% clean and maritime transport to reach the island will be decarbonised. All buildings and installations on the island will have high energy efficiency and therefore low energy requirements. The energy transition will promote sustainable development also from a social point of view, with economic and employment repercussions on the territory, in harmony with the landscape, geo-morphological and naturalistic characteristics (marine, forest, agricultural and Mediterranean scrub) of the island. In figure 2.1 the transition pathways of the Salina Island are graphically summarized:

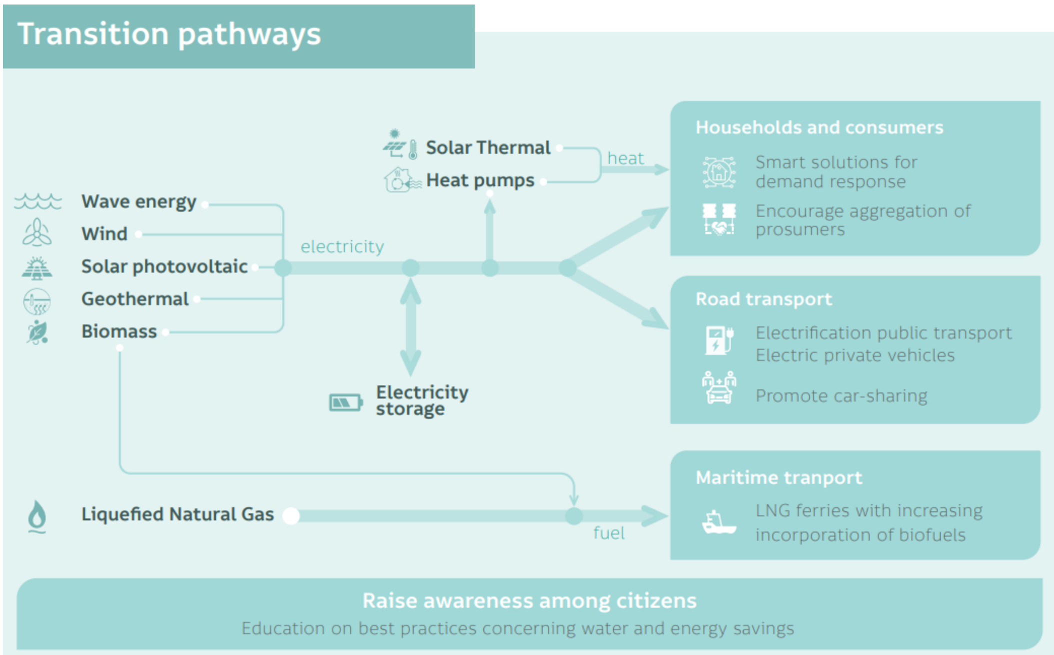


Figure 2.1: Transition pathways proposed for Salina Island

The island of Pantelleria fully agrees with this vision and it focuses on 5 fundamental pillars, to which is added the zero-pillar linked to energy efficiency and the reduction of consumption, which is transversal to the various areas, to make it a reality [13]:

a. **Generation of electricity from RES:**
   Production of electricity from wind, solar and wave sources. Definition of circumscribed areas for the exploitation of wind and solar sources with medium and large size plants. Exploitation of marine sources (off-shore wind and wave motion).
b. **Self-sufficiency of buildings and distributed production:**

Achievement of high self-sufficiency values in the residential sector and maximization of self-production in all sectors. Coverage of the thermal consumption of buildings through solar and biomass sources.

c. **Sustainability of transports on the island:**
Electrification of motorized transport on the island and use of locally produced biogas for a part of the vehicles. Installation of photovoltaic shelters compatible with the rural nature of the area for electricity generation and vehicle recharging.

d. **Energy storage and deferrable loads:**
Centralized storage systems to support grid stability. Distributed storage systems to support the self-consumption of residential buildings and economic activities. Vehicles and desalters as deferred loads for the full exploitation of renewable plants.

e. **Pantelleria energy community:**
Creation of one or more energy communities on the island's territory. Maximization of community self-consumption, exchange of energy flows. Co-ownership of medium and large production plants by citizens, public bodies and the private sector.

This vision and the pillars described above are important starting points for proceeding towards the energy transition of the smaller islands, not only of Pantelleria and Salina but also of those that will be added in the coming months or years and will be able to take inspiration from what has already been done. As mentioned in the introductory chapter, the “Green Islands Decree” is a great opportunity and will give very important financial support to speed up the path launched by the previous program and to undertake new ones, that can transform small islands into examples to follow with innovative and economically sustainable solutions on networks, production plants and users, with the aim of identifying the conditions for making renewable sources the main axis of the energy system of the islands, and to obtain useful information also for the future national system.

In the next chapter the methodology followed to assess the technical energy potential from wind and photovoltaic resources is presented. The focus is on the instruments used for the simulation of the energy potential and on the actual legislation, which limits the exploitation of RES on the Sicilian minor islands.

3 Methodology

This chapter is the core of the thesis and presents an original methodology to estimate the technical potential from wind and photovoltaic energy sources on the fourteen Sicilian minor islands as a case study. In line with [16] the term ‘potential’ is commonly distinguished into five categories, namely: theoretical, geographical, technical, economic and feasible potential. These terms can be defined as follows:

- **Theoretical/physical potential:** the physically usable amount of energy within a certain region and time.
- **Geographical potential:** the area that is available for the generation of energy, considering restrictions such as nature reservation areas and other land uses such as urban fabric and traffic routes.
- **Technical potential:** the usable amount of energy under technical constraints within a specified region and time. In this case the technical potential is the amount of energy generated by on-shore wind turbines and photovoltaic panels installed on building roofs in the available area on the fourteen Sicilian minor islands, whilst accounting for technical specifications such as conversion efficiencies, spacing requirements and wake or shading effects.
- **Economic potential:** the technical potential that can be realized economically within a certain region and time. It strongly depends on the perspective taken, i.e., whether assessed from a private investor’s or society’s perspective, as well as the economic criteria employed, i.e., payback period, net present value, internal rate of return etc. In addition, the determination of the economic potential can be difficult for contexts with a particular market design like minor islands. As a consequence, the assessment of the technical potential, in terms of economic feasibility, implies complex case by case decisions, so it is not evaluated in this study.
- **Feasible potential:** the actual achievable economic potential, taking into account also market, organizational and social barriers, which mean that, in practice, the economic potential is not fully realized.

In the present study the focus is on the technical potential, with the addition to identify the suitable areas, where to install a certain technology with defined technical specifications, considering also non-technical aspects, as constraints resulting from the national, regional and municipal legislation in environmental and landscape safeguard. Under these conditions, the usable annual amount of energy that can be generated from wind and photovoltaic technologies is evaluated. The proposed methodology is implemented on the open-source software QGIS and applied at the local spatial planning scale. To do that, an integrated spatial energy planning approach is introduced.

3.1 Spatial energy planning approach

An official definition of spatial planning, adopted by the European Conference of Ministers responsible for Regional Planning (CEMAT), is reported [17]: "Regional/spatial planning gives geographical expression to the economic, social, cultural and ecological policies of society. It is at the same time a scientific discipline, an administrative technique and a policy developed as an interdisciplinary and comprehensive approach directed towards a balanced regional development and the physical organisation of space according to an overall strategy."

In practice, spatial planning systems refers to the methods and approaches used by the public and private sector to influence the distribution of people and activities in spaces of various scales. The aim is to create a more rational territorial organization of land use and the linkages between them, to balance demands for development with the need to protect the environment, and to achieve social and economic objectives [18]. Spatial planning is, therefore, an important function for promoting sustainable development and improving quality of life.

Applying the spatial planning approach to the energy sector, the environmental and landscape impacts can be considered during the early stages of a project, like the identification of suitable areas where to install the renewable energy plants. In this way, the chance that projects are approved increases or, as in this case, it is possible to give a more accurate estimation of the energy potential available in a certain area.

3.1.1 Why spatial energy planning

Spatial Energy Planning (SEP) is a tool based on the land-use planning process, with the objective to develop sustainable energy supply solutions for communities, including the widest possible use of local renewable resources as well as energy efficiency [19].

Despite the fact that some renewable energy (as wind and photovoltaic) technologies are already techno-economically viable, there are still strong constraints like spatial low-density that cause a large land use, environmental, social, and landscape impacts. Another crucial obstacle is the integration into energy systems, which is exasperated for the islands' context. These barriers are related not only to the usual "developer" vs. "local population" syndrome, but also to the conflict between energy policy and land use planning processes. Consequently, when integrating RES technologies into energy systems, synergies and trade-offs with other sustainability concerns should be considered, such as water and land use, landscape impacts, and socio-economic aspects. However, most energy planning approaches are centralized on energy modelling tools that focus exclusively on techno-economic aspects. Actually, to understand the energy, social, and spatial dynamics at the local level has become an important issue in the literature on RES development [20].

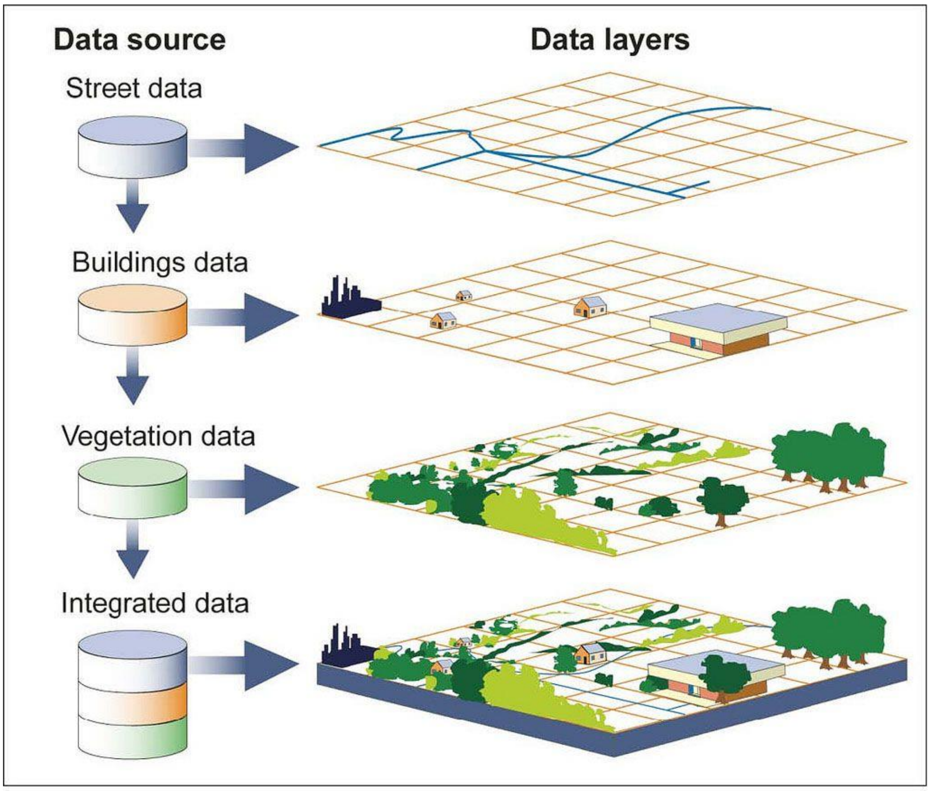
For this reason, the objective of this study is to determine the technical potential of wind and photovoltaic sources exploitable, under specific realistic hypotheses, with a systematic approach carried out following many of the SEP principles. Along this line, they were considered aspects beyond the techno-economic ones, taking into account also normative constraints mainly about environment and landscape safeguard. Local normative aspects, mainly about environment and landscape safeguard are considered, since municipal law better reflect the intrinsic aspects of the territories, which in this case are geographically delimited and spatially limited. The constraint analysis, the calculations relating to the energy potential and the graphic visualization of the results was made by means of the QGIS software, which is presented in the next paragraph.

It is thought that this type of approach has the capability, during the planning process, to prevent conflicts when integrating RES technologies into the isolated electric systems of the minor islands. This would be useful for decision-makers to be aware of the unexplored renewable technical potential and to plan further actions to accelerate a sustainable energy transition.

3.1.2 Geographic Information System for spatial energy planning

The Geographic Information System (GIS) plays a significant role in energy planning, from exploring renewable resources and combining them with the existing system to identifying a suitable site for the system installation. A GIS can be defined as an information system that is designed to work with data referenced by spatial or geographic coordinates. In other words, a GIS is both a database system with specific capabilities for spatially referenced data, as well as a set of operations for working with data [21]. The distinction must be made between a singular geographic information system and a GIS software. The first one is a single installation of software and data for a particular use, along with associated hardware, staff, and institutions (i.e., the GIS for a particular city government). The second one is a general-purpose application program that is intended to be used in many individual geographic information systems in a variety of application domains.

GIS can show many different kinds of data on one map, such as streets, buildings, and vegetation. This enables people to see, analyse, and understand patterns and relationships more easily [22].



Source: GAO.

Figure 3.1: Illustration of GIS data source and layers

GIS are used for the storage, management, analysis and display of geographically referenced data, being valuable tools for assisting planning and decision making in multiple contexts in which geo-referenced information plays a relevant role. In this study the methodology was implemented with the QGIS software, which is a free and open-source desktop geographic information system application that provides for viewing, editing and analysis of geospatial data. QGIS supports a wide variety of formats, but it is necessary to distinguish between the two most used for this work: raster data, which use the GeoTIFF extension and vector data, which utilize the shapefile extension. Raster data are a simple type of continuous spatial data that consists of a matrix of cells (the single cell is called pixel) organized into rows and columns in which each cell represents specific information, as an example temperature, air pressure, elevation, etc. On the contrary, vector data is a complex type of spatial data used for storing information that has discrete boundaries, such as administrative borders, roads, rivers, etc. [23].

Actually, the local database, containing all the data from this study, contains data in geopackage format. The geopackage is a recent universal format which allows to store and share both vector and raster data in just one file. It also presents various advantages [24]:

- It is an open and compact format independent from platform or application, so it is interoperable in all corporate and personal computer environments.
- It contains all the information in a single file with the extension ".gpkg".
- It is designed to store complex and voluminous data.
- The style of the vectors can also be stored in the Geopackage.
- Almost all GIS software can read Geopackage files, and it is the default format for QGIS.

To manipulate the spatial data is used a GIS operation named geoprocessing. A typical geoprocessing operation takes an input dataset, performs an operation on that dataset, and returns the result of the operation as an output dataset. Common geoprocessing operations include: geographic feature overlay, feature selection and analysis, topology processing, raster processing and data conversion. Geoprocessing allows, by definition, management, and analysis of information used to form decisions [21]. Thanks to QGIS it is possible to perform a terrain analysis of the islands surfaces that consists in creating derivative datasets that represent a specific aspect of the surface (i.e., slope and aspect of the terrain, hydrological modelling, viewshed analysis, etc.) starting from a Digital Elevation Model (DEM). A DEM is a 3D computer graphics representation of elevation data to represent terrain, commonly produced in raster format by associating the attribute relating to the absolute dimension to each pixel.

Using GIS in energy planning may help to avoid the sensitive areas that can cause adverse environmental and social impacts. In this study QGIS software was used to several purposes as find the suitable locations where to install RES plants for the assessment of the technical potential mapping out the existing environmental and landscape constraints, as well as distances from residential zones; in the case of photovoltaic resource, it is used to calculate the renewable resource availability with a proper plug-in and all the resource maps created are reported on the QGIS georeferenced environment for a graphic visualization of the energy potential.

3.2 Legislation

This section analyses the current constraint system that concerns the fourteen Sicilian minor islands, considering the different areas of environmental and landscape protection. The focus is on existing restrictions on the installation of wind and photovoltaic technologies on a national, regional and local scale. The analysis carried out recognize the main laws that limit the exploitation of wind and photovoltaic energy, in order to take them into account when identifying suitable areas where to install RES technologies. The objective is to understand the range of action of the constraints imposed to locate eligible areas for RES projects and, consequently, to give a more accurate estimation of the technical potential from wind and photovoltaic resources.

3.2.1 National legislation

The need to change the current world energy paradigm from a system based on fossil fuels to one based on renewable energy resources has been clear for decades. In fact, many nations are planning and implementing energy transition plans which provide a progressive increase in the production of energy from renewable sources. For the European Union this is by far one of the priorities. Therefore, to promote the energy production from RES, the Directive 2001/77/EC of the European Parliament and of the Council on the promotion of electricity from renewable energy sources in the internal electricity market has been issued in 2001 [25]. Italy has implemented this directive by means of the Legislative Decree n. 387 of the 29th December 2003, which is intended to promote a greater contribution of renewable energy sources to the production of electricity in the Italian and Community market, measures for the pursuit of national indicative targets and to encourage the development of electrical micro-generation plants powered by renewable sources. The aforementioned decree provides the approval of guidelines for carrying out the authorization procedure for plants powered by renewable sources and in particular to ensure correct insertion of the plants in the landscape, with specific regard to wind farms [26].

Consequently, the Ministerial Decree n. 219 of the 10th September 2010, "Linee guida per l'autorizzazione degli impianti alimentati da fonti rinnovabili", concerning the guidelines for the authorization procedure for plants powered by renewable sources, has been enacted. It has the objective to facilitate the reconciliation between the needs of economic and social development with those of environmental protection and conservation of natural and cultural resources in regional planning and administrative activities. The administrative measures and technical criteria referred to these guidelines are applied to the procedures for the construction, operations, interventions of modification, enhancement, total or partial refurbishment and reactivation, as well as for the related works and infrastructures indispensable for the construction and operation of the RES plants on the mainland. For the purposes of this study, only the guidelines considered for the determination of the technical potential from wind and photovoltaic sources are reported [27]:

- Minimum distance of 200 meters of each wind turbine from residential units, regularly registered and permanently inhabited.
- Minimum distance of six times the maximum height of the wind turbine, of each wind turbine, from the inhabited centres identified by the urban planning instruments.
- Attention must be paid to the stability of the slopes avoiding slopes where erosion phenomena can be triggered. In the case of slopes greater than 20% it must be demonstrated that the construction of wind farms will not produce further erosion processes and hydrogeological instability phenomena.
- Make use of existing access routes if technically possible and adaptation of new ones that may be necessary to existing types.

These indications are applied to the wind power plants projects and are identified in the legal document as mitigation measures, but they are a fundamental prerequisite for the approval of the projects, and for this reason they have been considered in identifying the suitable sites where to install wind turbines. For what concerns photovoltaic panels, no stringent constraints have been identified by these guidelines, but the roof surface above which the photovoltaic panels will be potentially installed has been taken as the maximum limit for the plant surface, as prescribed by the law, to access the simplified procedures to start the projects.

All these restrictions, that influence the available surface on the islands for the exploitation of wind and photovoltaic resources, are implemented on the QGIS software environment, through which were created georeferenced layers whereby is possible to visualize the constrained areas, such as buffer distances from residential zones or slopes greater than 20 degrees, and it is also possible to make spatial calculations excluding those areas.

The abovementioned decree also says that only the Regions and the Autonomous Provinces may proceed to indicate specific areas and sites that are not suitable for the installation of specific types of plants powered by renewable energy. The attachment number three of the decree specifies that the identification of unsuitable areas must take into account the following specifications:

a. It must be based exclusively on objective technical criteria linked to aspects of environmental protection, landscape and artistic-cultural heritage, connected to the intrinsic characteristics of the territory and the site.
b. It must distinguish between the diverse renewable sources and the different plant sizes.
c. Areas classified as agricultural by current urban plans cannot be generically considered unsuitable areas and sites.
d. It must not concern significant portions of the territory or areas generically subject to protection of the environment, landscape and historical-artistic heritage, nor result in the identification of respect bands of not justified dimensions by specific and reasonable protection needs.
e. It has to indicate as unsuitable areas and sites for the installation of specific types of systems, the areas that are particularly sensitive and / or vulnerable to territorial or landscape transformations, in line with the protection and management tools provided by the regulations in force and taking into account the development potential of the different types of plants.

Therefore, it is crucial to focalize the attention also on the regional legislation, in particular, the Sicilian region has a specific rule which explicitly identifies areas not suitable for the installation of wind turbines.

3.2.2 Regional legislation

According to the Ministerial Decree n. 219 of the 2010, the Sicilian region has issued the Presidential Decree n. 29 of the 20th November 2015, “Norme in materia di tutela delle aree caratterizzate da vulnerabilità ambientale e valenze ambientali e paesaggistiche”, which establishes the criteria and identifies the areas unsuitable for the construction of wind power generation plants with a size exceeding 20 kW of nominal power. In order to speed up the authorization process for the construction and operation of the electricity production plants powered by renewable wind source, the regional councillor for energy and public services proposed a redefinition of the criteria and an updated identification of unsuitable areas, which was accepted by the regional council. Hence, the legislation currently in force, which is being considered for this study, is the Presidential Decree of the 10th October 2017, “Definizione dei criteri ed individuazione delle aree non idonee alla realizzazione di impianti di produzione di energia elettrica da fonte eolica […]”.

This decree identifies the unsuitable areas for the installation of wind turbines (WT) on the regional territory, including the minor islands, distinguishing between three different categories of wind turbines depending on their nominal power [28]:

1. “EO1”: WT nominal power $\leq$ 20 kW.
2. “EO2”: WT nominal power $>$ 20 kW and $\leq$ 60 kW.
3. “EO3”: WT nominal power $>$ 60 kW.

On the basis of the size of power, specific limitations are established related to the type of territory on which they have to be located. Furthermore, this decree makes a clear distinction between "unsuitable areas" and "areas of particular attention" for the installation of wind power plants for the production of electricity:

- **Unsuitable areas:** areas in which it is impossible to install or submit projects for the installation of wind turbines.
- **Areas of particular attention:** areas in which particular precautions or mitigation measures may be prescribed as part of the authorization procedure.

3.2.2.1 Unsuitable areas

Pursuant to the decree, the zones identified as areas of particular environmental value are deemed unsuitable for all three types of system: EO1, EO2 and EO3. These areas are:

a. Site of Community Importance (SCI);
b. Special Protection Area (SPA);
c. Special Area of Conservation (SAC);
d. Important Bird Area (IBA), including the nesting and transit areas of migratory or protected birds;
e. Sicilian Ecological Network;
f. Ramsar sites (wetlands) and natural reserves;
g. Protection oasis and fauna refuge;
h. Geosites;
i. Regional and national parks with the with the exception of those that provide for different measures in force on the date of issue of the abovementioned decree;
j. The landscape assets and the archaeological areas and parks referred to art. 134, lett. a), b) and c) of the Code of cultural heritage and landscape. For these zones, it is allowed the construction of plants consisting of single EO1 and EO2 type wind turbines to support activities related to agriculture in areas individuated by general

regulatory plans pursuant to art. 22 of the regional law n. 71 and subsequent amendments.

While the unsuitable areas for EO2 and EO3 types of system are:

- The ecological corridors that are identified on the basis of the maps drawn up in support of the Management Plans of Natura 2000 sites (SCI, SAC and SPA).
- The areas defined as woods, pursuant to art. 142, paragraph 1, lett. g), of the Code of cultural heritage and landscape.
- Areas identified as "very high" (P4) and "high" (P3) danger in the “Piano per l’Assetto Idrogeologico” (PAI), which is the plan for the defence from the hydrogeological risk of the territory.

3.2.2.2 Areas of particular attention

As mentioned before, the decree identifies also the "areas of particular attention" for the installation of wind power plants, they are intended as those areas characterized by a sensitivity to the transformations of the territory and the landscape, for which they can be requested in the authorization phase further mitigation works or specific precautions by the administrations involved. These areas also depend on the WT size and they are:

- The ecological corridors that are identified on the basis of the maps drawn up in support of the Management Plans of Natura 2000 sites (SCI, SAC and SPA). These areas affect the construction of EO1 type plants.
- Areas identified as "very high" (P4) and "high" (P3) danger in the PAI, which is the plan for the defence from the hydrogeological risk of the territory. These areas affect the construction of EO1 type plants.
- Areas identified as “medium” (P2), “moderate” (P1) and “low“ (P0) hazard in the PAI. These areas affect the construction of EO1, EO2, EO3 type plants.
- Areas characterized by environmental vulnerabilities with hydrogeological constraints pursuant to the Royal Decree n. 3267 of the 30th December 1923. These areas affect the construction of EO1, EO2, EO3 type plants.
- Areas subject to interventions for the construction of EO1, EO2 and EO3 wind power plants in view of the areas indicated in art. 134, paragraph 1, lett. a) and c) of the Cultural Heritage and Landscape Code or near the buildings listed in the art. 136, paragraph 1, lett. a) and b). In the coastal buffer zone referred to lett. a) of art. 142 of the aforementioned Code, the construction of plants is permitted exclusively in areas

intended for production activities subject to the landscape-environmental recovery regime in accordance with the landscape plans.

- Areas of agricultural value and beneficiaries of contributions and areas of landscape value as a testimony of the agricultural tradition of the Region. They affect the construction of EO1, EO2 and EO3 type plants and specifically are:
  - Organic productions;
  - “Denominazione di Origine Controllata “ (DOC) productions;
  - “Denominazione di Origine Controllata e Garantita” (DOCG) productions;
  - “Denominazione di Origine Protetta” (DOP) productions;
  - “Indicazione Geografica Protetta” (IGP) productions;
  - Traditional and “Specialità Tradizionale Garantita” (STG) productions.

The areas of particular attention do not limit the technical potential, since they are not intended to be constraints but areas to be aware of when preparing a feasibility study to prevent undesired transformations of the territory and the landscape.

All the areas referred to this decree are geo-referenced, in the GIS environment, and can be found in the regional geoportal, named Regional Territorial Information System (SITR) managed by the Regional Department of Urban Planning. For the estimation of the technical potential from wind resource, these areas were taken as reference for the identification of suitable area on the Sicilian minor islands’ territories making use of the geo-referenced layers available on the SITR geoportal or creating proper layers that were not accessible yet.

For what concerns solar energy exploitation, the regional law requires a meticulous environmental assessment to receive the permission to build, named “Autorizzazione Unica”. For the Sicilian territory this authorization is issued by the Sicilian region for PV plants greater than 1 MW, instead in the case of smaller PV plants the authorization is simplified and the responsible are the municipalities [29]. Moreover, the local regulation provides additional constraints related to photovoltaic exploitation, whose analysis is reported in the next paragraph.

3.2.3 Local legislation

The territory of the individual municipalities is subjected to landscape constraints by means of the territorial landscape plan, named “Piano Territoriale Paesistico” (PTP), which is an urban planning tool provided by the Region jointly with the Ministry of Heritage, Cultural Activities and Tourism. The landscape plans, with reference to the territory considered, recognize its peculiar aspects and characters, as well as the landscape characteristics, and delimit the relative areas. For each area, the landscape plans define specific prescriptions and forecasts aimed at the conservation and restoration of landscape values, the redevelopment of compromised or degraded areas, the safeguarding of landscape characteristics and the identification of urban and building development lines, compatible with the different recognized and protected landscape values. For the Sicilian minor islands, it was necessary to redact plans for each archipelago, or individual islands, as the minor islands are geographically delimited and have unique characteristics.

The PTPs are provided by the Sicilian Region, on the basis of the indications expressed by the Guidelines of the Regional Landscape Plan, approved in the year 1999, and pursuant to the Legislative Decree n. 42 of the 22nd January 2004, "Codice dei beni culturali e del paesaggio, […]", which is the Cultural Heritage and Landscape Code mentioned in the previous paragraph. More precisely, the landscape plan is a tool that allows the identification and protection of landscape assets and the contents of the PTP are identified by Article 143 of the Code abovementioned. Since the PTP affect the suitable areas for the installation of renewable energy systems, a summary of the main principles is reported [30]:

- On the basis of the natural and historical characteristics and in relation to the level of relevance and integrity of the landscape values, the plan divides the territory into homogeneous areas, from those of high landscape value to those significantly compromised or degraded.
- Depending on the different recognized levels of landscape value, the plan assigns corresponding landscape quality objectives to each area. The landscape quality objectives include in particular:
    - The preservation of the characteristics, the constituent elements and the morphologies, taking into account also the architectural typologies, as well as the construction techniques and materials.
    - The provision of urban and building development lines compatible with the different levels of recognized value and they have not to diminish the landscape value of the area, with particular attention to the protection of sites included in the UNESCO World Heritage List and agricultural areas.
    - The recovery and renovation of compromised or degraded buildings and areas subject to protection, in order to reintegrate the pre-existing values or to create new landscape values that are coherent and integrated with the context.

- The landscape plan, considering the different types of works and interventions of transformation of the territory, identifies: the areas in which their realization is allowed on the basis of the verification of compliance with the requirements, measures and management criteria established in the landscape plan, pursuant to paragraph 3, letters d), e), f) and g), and those areas for which the landscape plan defines constraints for the specific provisions to be introduced in the urban planning instruments in the context of conformation and adaptation, pursuant to article 145 of the Code.

The landscape plans include constraints concerning renewable energy exploitation at a local scale, for example areas not suitable for wind farms or buildings above which it is not possible to install photovoltaic panels as the traditional house of the Pantelleria island, named “Dammuso”. Therefore, for the estimation of the technical potential have been taken into account also the landscape plans of the individual islands or archipelagos to consider the suitable areas. A more in-depth analysis, island by island, will be presented in the next chapter, where the technical potential from wind and photovoltaic sources of each island is evaluated.

3.3 On-shore wind technical potential assessment

The proposed methodology is implemented using the geographic information system software, QGIS, and it is applied at the municipal spatial energy planning scale. For this part, it is essential to make use of the WaSP (Wind Atlas Analysis and Application Program) software suite, which is the industry-standard for wind resource assessment, siting and energy yield calculation for wind turbines and wind farms [31]. Thanks to this software it is possible to calculate the mean speed, the power density and the Annual Energy Production (AEP) on the entire islands' surface for each type of wind turbine, taking into account the different meteorological and territorial characteristics.

The methodology consists of four distinct stages:

1. Identifying appropriate areas to site on-shore wind farms by means of spatial analysis approach based on specific assessment criteria.
2. Determining the principal technical specifications of the three different on-shore wind turbines under consideration.
3. Micro-siting configuration of on-shore wind farms considering the turbine type, wind direction and wake effects.
4. Estimating the total annual energy production of each on-shore wind farm, on the most suitable sites.

An overview of the methodology is shown in figure 3.2:

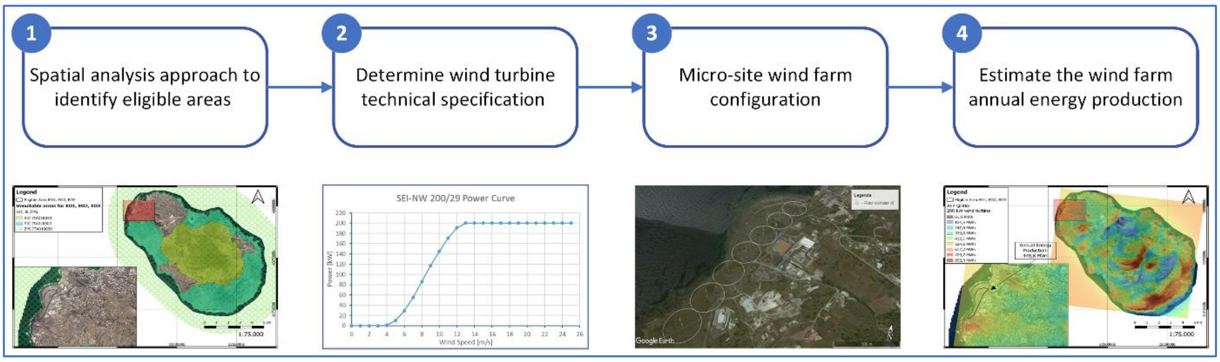


Figure 3.2: Methodology overview for wind technical potential assessment

In the first stage, territorial constraints, such as landscape aesthetical and environmental aspects, are considered and spatial planning rules, such as separation distances from residential areas or between wind farms, are implemented. Then, the wind generator technical specifications, such as power curve and thrust coefficient, are introduced as they will be considered for the evaluation of the following points. Once the suitable areas are individuated and the technical specifications are specified, it is possible to properly site the on-shore wind farm. It is done by means of the WAsP spatial view which provides the visualization of the terrain characteristics and of the wind climate; moreover, it is possible to set the distance between the single wind turbines to limit the wake effects. The fourth and last stage consists of the simulation of the prepared wind farm. The calculations are performed by means of the WAsP software too. In this section, each of the four steps is described in details.

The final outcome of the proposed methodology is the wind energy technical potential, calculated for the three different wind turbines under consideration on the suitable areas found from the spatial planning study at municipal scale.

3.3.1 Identification of suitable areas

This analysis can be intended as the evaluation of the geographical potential, i.e. the area that is available for the generation of energy. In this case, the suitable area is evaluated considering the normative restrictions, until local scale, presented in section 3.2. The geographic information system software, QGIS, is used to identify the suitable areas for wind turbine installation in the Sicilian minor islands. The georeferenced layers representing the unsuitable areas for the installation of wind energy plants, individuated by the Sicilian region, pursuant the Presidential Decree of the 10th October 2017, are taken from the regional geoportal, SITR. Though, the layers, provided by the SITR, regard the whole Sicilian region, they are in shapefile format, so it was simple to cut out the surfaces involved by this study, thanks to the vector geoprocessing tool "Clip" of the QGIS software. The layers have also been organized into groups and sub-groups, according to the normative requirements. An example of the layer's visualization, on the Pantelleria island territory, is reported in figure 3.2:

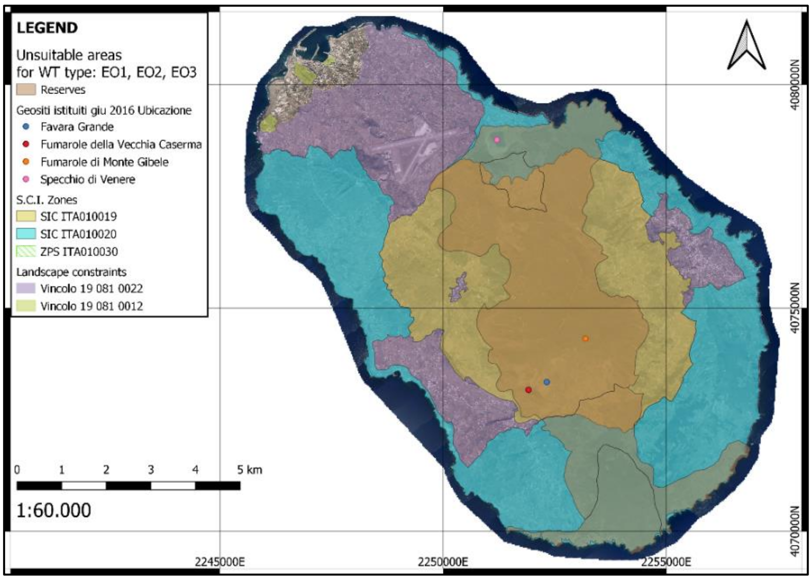


Figure 3.3: Example of unsuitable areas layers visualization of Pantelleria island

In this way, the layers containing the georeferenced spatial constraints are overlayed to identify the areas suitable for wind energy generation. In figure 3.2 are shown just a few layers concerning the unsuitable areas for wind turbines installation, but there are many others; specifically, for the purpose of this study the considered constraints were derived from the analysis of the regulation made in the previous chapter. Summarizing, the total surface of the islands is reduced considering the following unsuitable areas:

- SCI and SPA zones;
- Reserves;

- Geosites;
- Landscape constraints;
- Woodland;
- PAI sites;
- Buffer area of six times the maximum height of the wind turbine considered from the inhabited centres identified by the urban planning instruments.

It is important to notice, that for the application of this methodology to the Sicilian minor islands two constraints are not considered:

- The Important Bird Area, since it regards the whole surface of all the islands, except Ustica. If it is considered, it wouldn't be possible to install any kind of wind turbine on the Sicilian minor islands' territory, so the suitable area would be zero.
- The buffer area of 200 meters of each wind turbine from residential units, regularly registered and permanently inhabited, because it is not possible to identify which houses are permanently inhabited with the tools available.

Starting from the total islands' surface, the above mentioned unsuitable areas are subtracted and the suitable areas are obtained. In those areas the wind farms are located and, by means of the Wasp software, the technical energy potential is evaluated. For some islands, the smallest one, it is not possible to find any suitable areas. In those cases, it is reported the annual energy production of the single turbine for each type of turbine chosen to give an overview of the unexploitable energy potential of the wind technology.

3.3.2 Wind turbines technical specifications

For the purpose of this study the most common type of wind turbines is chosen, i.e. the horizontal axis wind turbine (HAWT) with 3 blades [32]. Three different commercial wind turbines characterized by different sizes in terms of nominal power are considered: 20 kW, 200 kW and 2 MW. The first HAWT has a nominal power equal to the upper limit of the EO1 category, while the other two are included in the EO3 category. There is not a representative turbine of the EO2 category because the unsuitable areas for EO2 and EO3 do not differ so much and for the Sicilian minor islands they coincide. Thus, two EO3 wind turbines are chosen for distinct reasons. The 200 kW wind turbine is considered the most suitable size for the application of this study, in particular for the trade off between AEP and hub height with the consequent buffer zone from residential settlements. The 2 MW one is close to the Italian average power rating installed in 2019, which is between 2 and 3 MW [33], so it is possible to compare the results of the AEP with other existing wind farms, even if it does not satisfy some normative requirements.

Since, the amount of energy generated by a wind turbine at a specific site depends on many factors, for example wind speed conditions at the location, as well as on the characteristics of the wind turbine generator itself [34], it is important to introduce the main technical characteristics of the chosen wind turbines.

3.3.2.1 Ryse Energy E-20 HAWT (20 kW)

The first wind turbine introduced is the model “E-20” of the Ryse Energy company. It is a 20 kW HAWT for on-grid and off-grid power systems. The technical parameters are summarized in table 3.1 [35]:

Generator	Type	Permanent magnet
	Maximum Power	20 kW
	Rated Power	18 kW
Rotor	Configuration	Horizontal axis
	No. of Blades	3
	Blade Material	Glass fibre
	Blade Length	4,5 m
	Rotor Diameter	9,8 m
	Swept Area	75,4 m^2
	Nominal Rotor Speed	120 rpm
	Pitch/Yaw	Downwind active pitch with assisted yaw
Wind	Cut-in Speed	2 m/s
	Rated Wind Speed	11 m/s
	Cut-Out Speed	30 m/s
	Survival Speed	70 m/s
Towers	Lattice	15 – 36 m
	Monopole	18 – 27 m
	Tilt-up	18 – 27 m
Design Parameters	Turbine Design Class	IEC 61400-2 Class 1
	Temperature Range	-20°C to 50°C
	Lifespan & Servicing	20 years, subject to regular maintenance

Table 3.1: E-20 wind turbine datasheet

To properly calculate the annual energy production, the Wasp software requires the power curve of the wind turbine, which give the power output corresponding to each value of wind speed. Therefore, the E-20 power curve, based on the standard air density equal to 1,225 kg/m^3, is reported in fig. 3.3:

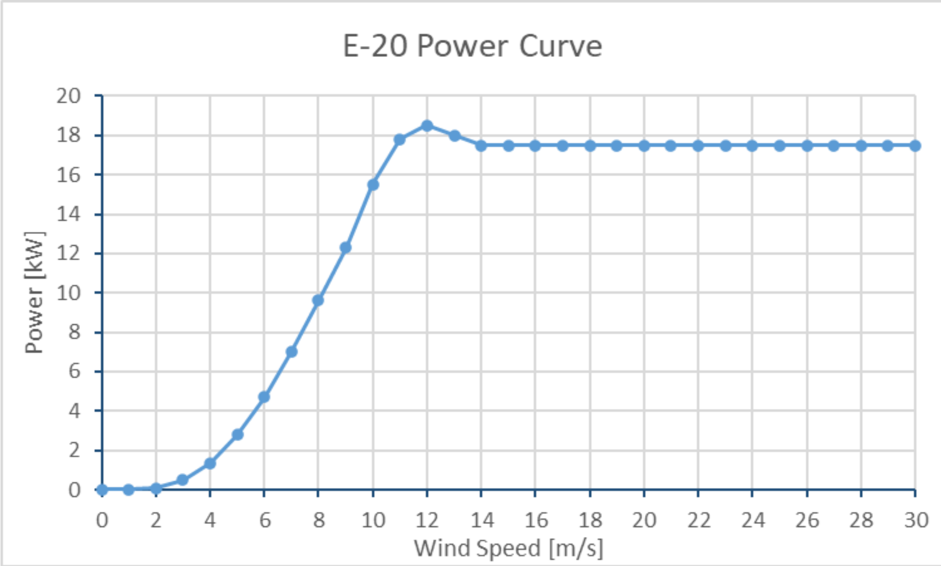


Figure 3.4: Power Curve of E-20 wind turbine

3.3.2.2 SEI-NW 200/29 HAWT (200 kW)

The 200 kW wind turbine taken as reference for this study is the model “SEI-NW 200/29” of the Italian company named Società Elettrica Italiana. The datasheet is reported in Table 3.2 [36]:

Generator	Type	Three-phase 4-pole asynchronous
	Maximum Power	225 kW
	Rated Power	200 kW
Rotor	Configuration	Horizontal axis
	No. of Blades	3
	Blade Material	Glass fibre
	Blade Length	13,4 m
	Rotor Diameter	29 m
	Swept Area	660,5 m^2
	Nominal Rotor Speed	38 rpm
	Pitch/Yaw	Fixed Pitch / Fixed Tilt
Wind	Cut-in Speed	4 m/s
	Rated Wind Speed	13 m/s
	Cut-Out Speed	25 m/s
	Survival Speed	67 m/s
Tower	Galvanized Steel	30 m
Design Parameters	Turbine Design Class	IEC 61400-2 Class 1
	Lifespan & Servicing	20 years, subject to regular maintenance

Table 3.2: SEI-NW 200/29 wind turbine datasheet

In figure 3.4, it is also reported the WT power curve, based on the standard air density of 1,225 kg/m^3, which is used for the evaluation of the annual energy production:

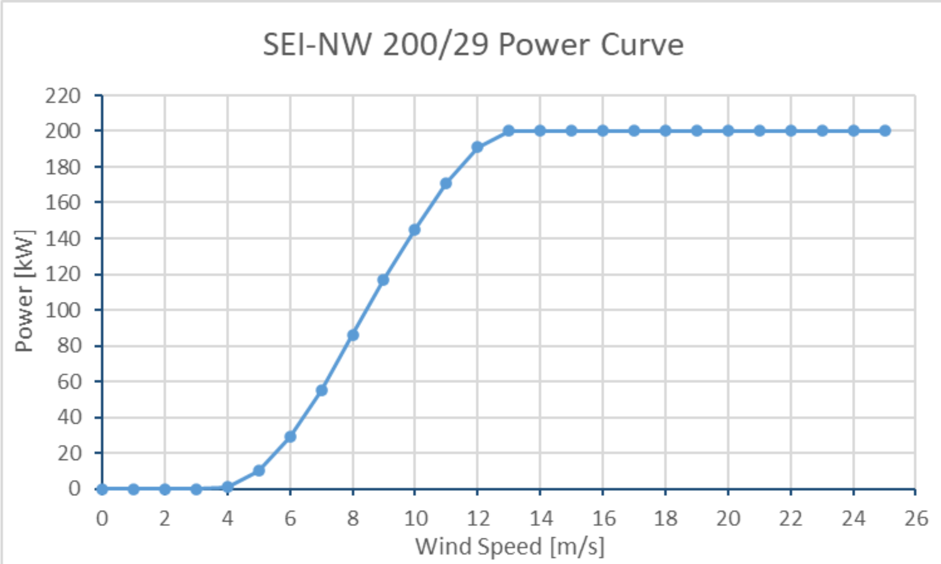


Figure 3.5: Power curve of SEI-NW 200/29 wind turbine

3.3.2.3 V100-2.0 MW GridStreamer (2MW)

The reference HAWT for the 2 MW size is the model "V100-2.0 MW GridStreamer" of the global leader company, Vestas. The main technical specifications of this turbine are summarized in table 3.3 [37]:

Generator	Type	4-pole (50 Hz) doubly fed generator, slip rings
	Rated Power	2.000 kW
Rotor	Configuration	Horizontal axis
	No. of Blades	3
	Blade Material	Glass fibre
	Blade Length	49 m
	Rotor Diameter	100 m
	Swept Area	7.854 m^2
	Nominal Rotor Speed	1550 rpm
	Pitch/Yaw	Pitch regulated with variable speed
Wind	Cut-in Speed	3 m/s
	Rated Wind Speed	12,5 m/s
	Cut-Out Speed	20 m/s
Tower	Tubular Steel Tower	80 m
Design Parameters	Turbine Design Class	IEC IIB
	Temperature Range	-20°C to 40°C

Table 3.3: V100-2.0 MW GridStreamer wind turbine datasheet

In figure 3.5 is reported the power curve of the presented WT, based on the standard air density of 1,225 kg/m^3:

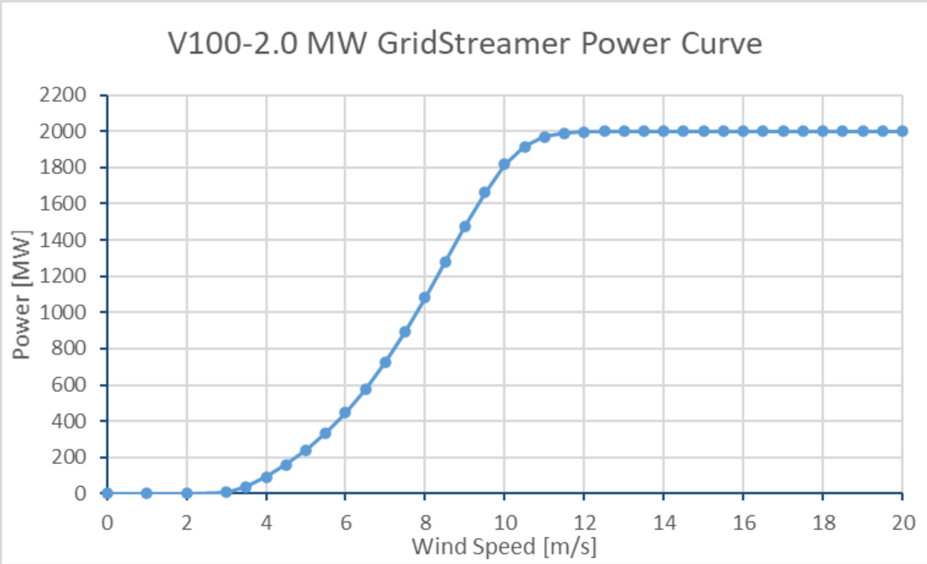


Figure 3.6: Power curve of V100-2.0 MW GridStreamer wind turbine

The presented power curves are implemented on the WAsP software by means of the "WAsP Turbine Editor" application. The tool allows to create the dataset, containing all the technical specifications of the wind turbine and the power curve, which are used as input data for AEP calculation. In the next paragraph the micro-siting of these WTs considering their technical characteristics is presented.

3.3.3 Micro-siting configuration of wind farms

The micro-siting of wind farms consists in determining the optimal placement and arrangement of individual turbines in a wind farm [38]. Once the suitable areas for the exploitation of the wind potential energy are identified and the technical parameters of the WTs are defined, it is possible to site the wind turbines. For this methodology are taken into account the rules of thumb for the reciprocal spacing of WTs, which are based on the rotor diameter length, as showed in figure 3.6:

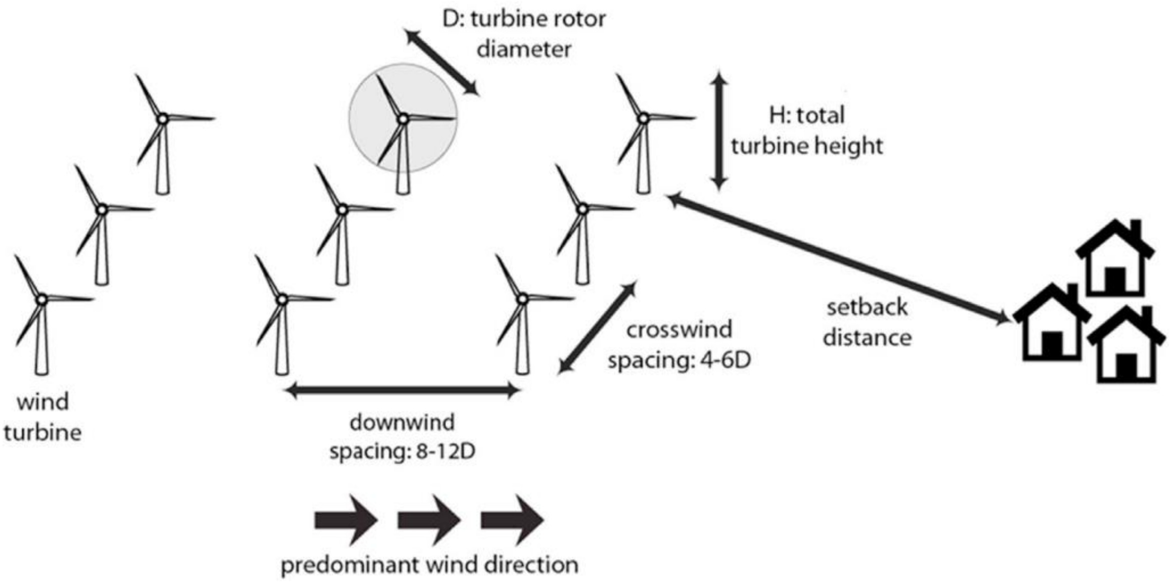


Figure 3.7: Schematic of wind farm layout showing typical spacing [39]

In this study is applied the distance of five times the turbine rotor diameter (5D) for the crosswind spacing, while it is considered eight times the turbine rotor diameter (8D) for the downwind spacing. The setback distance from the residential zones is calculated as six times the total turbine height as provided by the Italian law. Even if the 20 kW HAWT has a total turbine height of 24,5 m the setback distance from the residential zones considered is equal to 200 m, since it is the minimum distance from a single residential house provided by the national law. Regarding the other two HAWTs the calculated setback distance is 255 m and 750 m respectively.

The setback distances have already been considered on the identification of suitable areas, so for the micro-siting configuration of wind farms only downwind and crosswind distances are considered. These distances are adjusted on the vector map in WAsP environment, visualizing the proper rotor diameter extension. By means of the Google Earth application, it is possible to synchronize the vector map view with the virtual globe to better understand the exact positions of the WTs and the interaction with the real environment that surrounds them. An example of the 200 kW WTs located in Pantelleria is shown in figure 3.7:

Figure 3.8: Micro-siting of 200 kW WTs in Pantelleria island

The circles in the figure have a diameter equal to five times the WT rotor diameter since the WTs are positioned crosswind with respect to the predominant wind direction, that in this case is northwest.

3.3.4 Wind farm annual energy production estimation

The estimation of the annual energy production of the proposed wind farms represents the practical result of this thesis. The AEP is calculated by means of the reliable WAsP software; thus, the focus is not on the mathematical model used by the software, but on the procedure to follow to carry out the wind energy potential analysis. To assess the productivity of a wind farm over a certain region it requires several input data that are:

- Coordinates and topological data;
- Wind climate data;
- Orography map;
- Roughness map;
- Wind turbine technical specifications.

The coordinates and the topological data of the case study locations are taken together with the wind climate data from the Global Wind Atlas (GWA) database. The GWA is a free, web-based application developed to help policymakers, planners, and investors identify high-wind areas for wind power generation virtually anywhere in the world, and then perform preliminary calculations [40]. On the GWA website it is displayed a georeferenced map of the entire globe and it is possible to visualize different layers reporting, for example, the wind speed or characteristics of the terrain, such as orography and roughness. Selecting a specific area it is possible to download the Generalized Wind Climate (GWC) which is derived from the mesoscale grid cell closest to the centre of the selected area. The GWC file is intended for use in microscale modelling software such as WAsP, in fact the file format is the WAsP lib-file. The GWC file contains the sector-wise frequency of occurrence of the wind (the wind rose) as well as the wind speed frequency distributions in the same sectors (as Weibull A and k parameters). The wind climates are specified for a number of reference roughness classes and heights above ground level. It is needed to add the GWC file in the WAsP workspace to visualize the information contained inside, which are represented as shown in figure 3.8:

	R-class 1 (0,000 m)	R-class 2 (0,030 m)	R-class 3 (0,100 m)	R-class 4 (0,400 m)	R-class 5 (1,500 m)
Height 1 (10,0 m a.g.l.)	U = 6,19 m/s	4,34 m/s	3,83 m/s	3,04 m/s	2,03 m/s
Height 2 (50,0 m a.g.l.)	7,33 m/s	6,04 m/s	5,57 m/s	4,86 m/s	3,97 m/s
Height 3 (100,0 m a.g.l.)	7,98 m/s	7,19 m/s	6,67 m/s	5,91 m/s	5,01 m/s
Height 4 (150,0 m a.g.l.)	8,24 m/s	7,94 m/s	7,30 m/s	6,48 m/s	5,58 m/s
Height 5 (200,0 m a.g.l.)	8,41 m/s	8,45 m/s	7,77 m/s	6,93 m/s	6,00 m/s

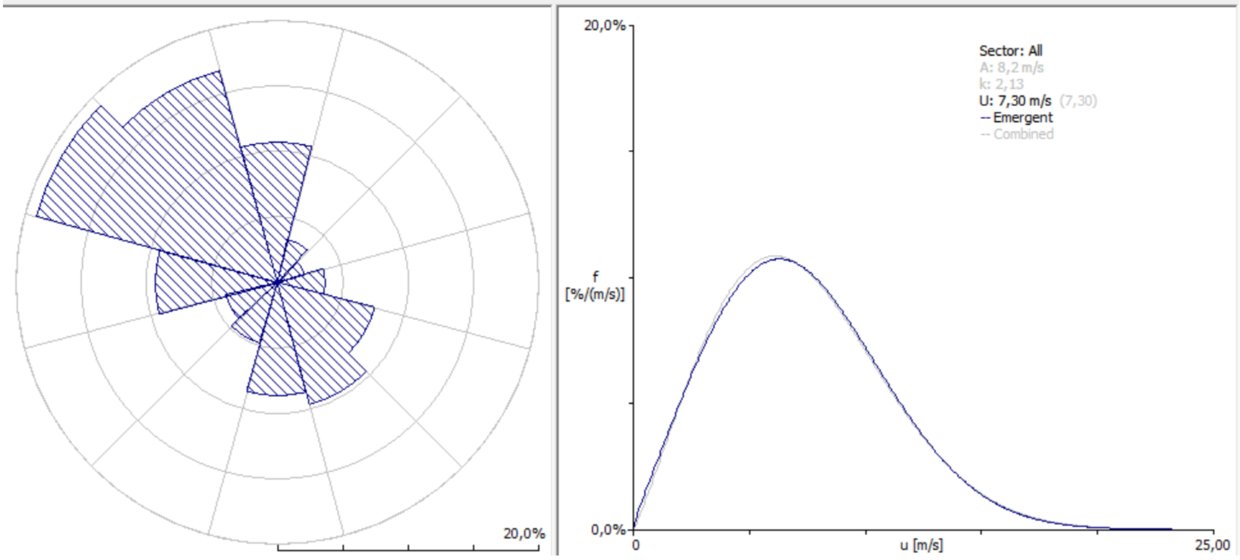


Figure 3.9: Wind rose and wind frequencies distribution for R-class 3 and 150 m a.g.l.

In the figure are shown, as an example, the wind rose and the wind frequencies distribution for the roughness class 3, which means a roughness of 0,100 m, and for a height of 150 m a.g.l. (above ground level) in the case of Pantelleria island. By definition, The GWC is the hypothetical wind climate for an ideal, featureless and completely flat terrain with a uniform surface roughness, assuming the same overall atmospheric conditions as those of the measuring position. Therefore, it is needed to add the terrain information to obtain a Predicted Wind Climate (PWC) which respects the specification of the area under study.

To do that a terrain analysis is performed using the WAsP Map Editor tool. It allows to import elevation and land cover data, of the selected area, from the WGA to create the roughness and orography maps. Then, it is possible to join them and create a vector map, which can be used on WAsP to add the terrain analysis to the GWC. The vector map of Pantelleria is shown in figure 3.9:

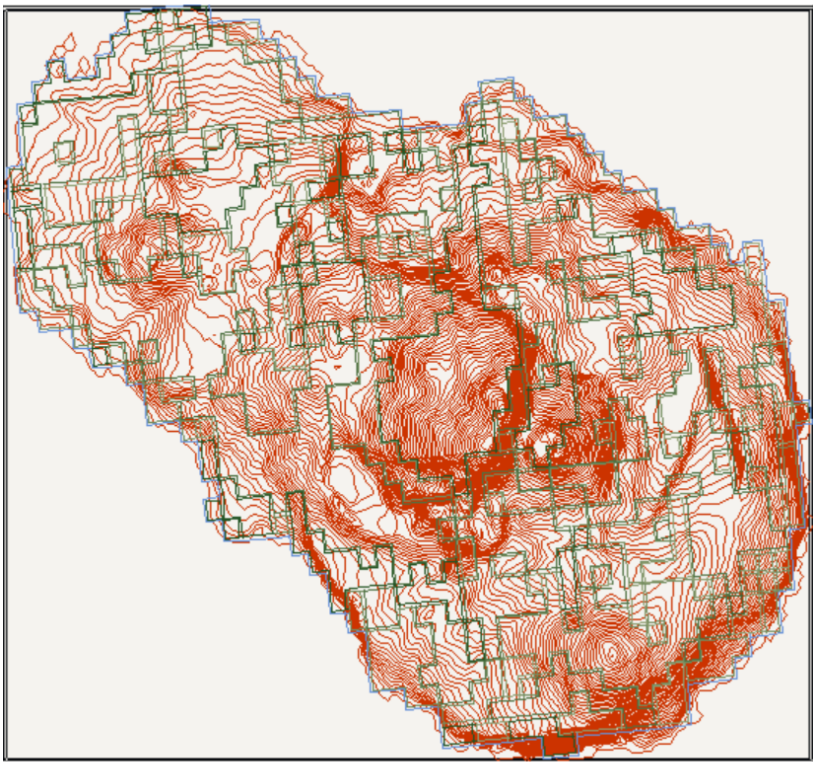


Figure 3.10: Pantelleria vector map (roughness and orography)

The red lines represent the contour line along which the elevation is constant, while the green and blue lines represent the roughness change vector where the roughness class varies.

At this point, knowing the GWC and the terrain analysis, it is possible to introduce a resource grid that permits to manage a rectangular set of points for which summary predicted wind climate data are calculated. On the resource grid are stored and displayed the main parameters of the wind resource assessment, such as the mean wind speed and the mean power density [41]. The resource grid is characterized by an extension, that for this study is the surface of the islands, by a resolution, which is the size of the pixel side and the height value above the ground level at which the calculations are performed. All these parameters can be easily set to the desired value.

After the resource grid calculations performed by the WAsP software, it is possible to visualize all the results in a table format or graphically on the vector map. The maps created can be also exported in a file format usable in QGIS. An example of the resource grid visualization reporting the mean wind speed of Pantelleria island's surface is shown in figure 3.10:

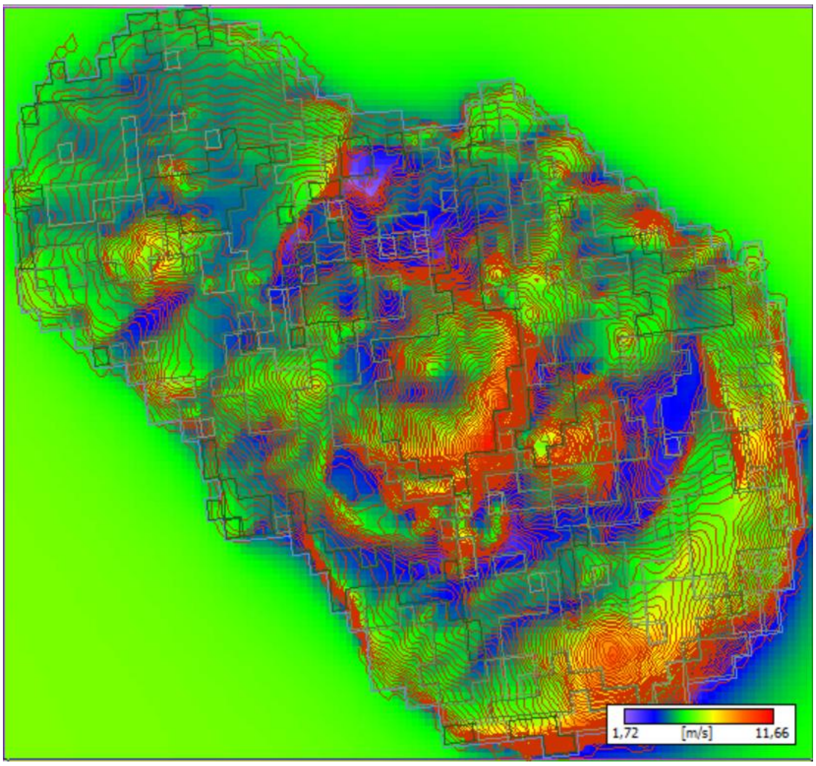


Figure 3.11: Mean wind speed map of Pantelleria island's surface

The map covers the entire Pantelleria island's surface and the resolution is 100 m. The map shows the mean wind speed for each point in the grid, but WAsP also calculates the elevation, the mean power density and the Weibull parameters. Furthermore, the annual energy production is calculated if a wind turbine generator is associated.

The wind turbine generator is added from the file prepared with the Wasp Turbine Editor tool as introduced in the paragraph 3.3.2. Given the technical specification and the power curve of the selected wind turbine, Wasp is able to calculate the annual energy production over the entire surface indicated in the resource grid. Therefore, every point of the map is characterized by an AEP value relating to the climatic conditions and the terrain of the chosen area and to the type of turbine selected.

At this point, a wind farm is added to the WAsP project. To properly define the wind farm is needed to specify the wind turbine generator to utilize and the exact locations of the turbine sites. The wind farm is positioned in the suitable areas identified as explained in paragraph 3.3.1, not necessarily points with more wind resource. An example of the AEP visualization on the vector map with a wind farm positioned on the suitable area of the Pantelleria island is shown in figure 3.11:

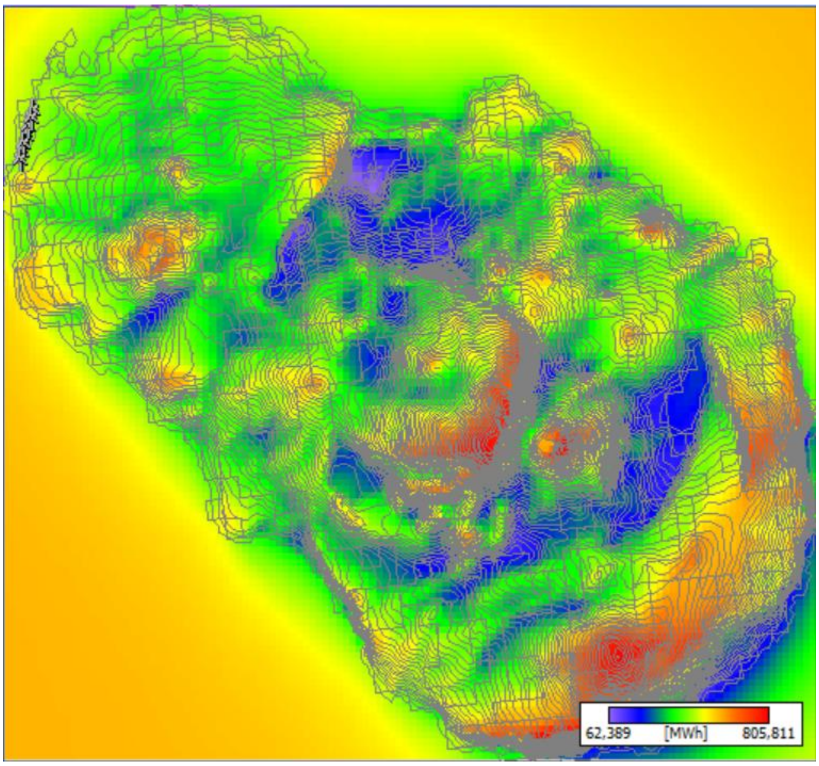


Figure 3.12: AEP map and wind farm site visualization of Pantelleria island

Given the power and thrust coefficient curves, contained in the wind turbine generator file, and the wind farm layout, WAsP can finally estimate the wake losses for each turbine and, thereby, the net annual energy production of each wind turbine and of the entire farm, i.e., the gross production minus the wake losses. The wind farm results are shown on WAsP in a table format, reporting:

- Total gross AEP in [MWh] or [GWh];
- Total net AEP in [MWh] or [GWh];
- Proportional wake losses in [%];
- Capacity factor in [%];
- Mean wind speed in [m/s] ;
- Mean wind speed (wake reduced) in [m/s];
- Air density in [kg/m^3];
- Power density in [W/m^2].

The final results of the wind farm annual energy production are reported and discussed, island by island, in the next chapter. The resulting maps reporting the mean wind speed, the mean power density and the annual energy production are exported from WAsP in a raster format and imported in QGIS. Then, these maps are converted in vector format to be manipulated and visualized in the QGIS environment to improve spatial analysis.

3.4 Photovoltaic technical potential assessment

The estimated photovoltaic (PV) technical potential is achieved proceeding through an original and scalable methodology. The assessment requires the evaluation of the useful solar radiation (physical potential), suitable surface (geographical potential) and PV system efficiency (technical potential). For this study is used a GIS-based approach implemented in the QGIS software and using the Urban Multi-scale Environmental Predictor (UMEP) plug-in.

The methodology is divided in three fundamental stages:

1. Collecting the geospatial input data from the several public geoportal and data sources.
2. Estimating the solar irradiation on roofs and ground surface, making use of high-resolution digital surface models (DSMs).
3. Estimating the technical PV potential on defined suitable areas considering the PV system technical specifications.

The summary workflow for the photovoltaic technical potential assessment is shown in figure 3.12:

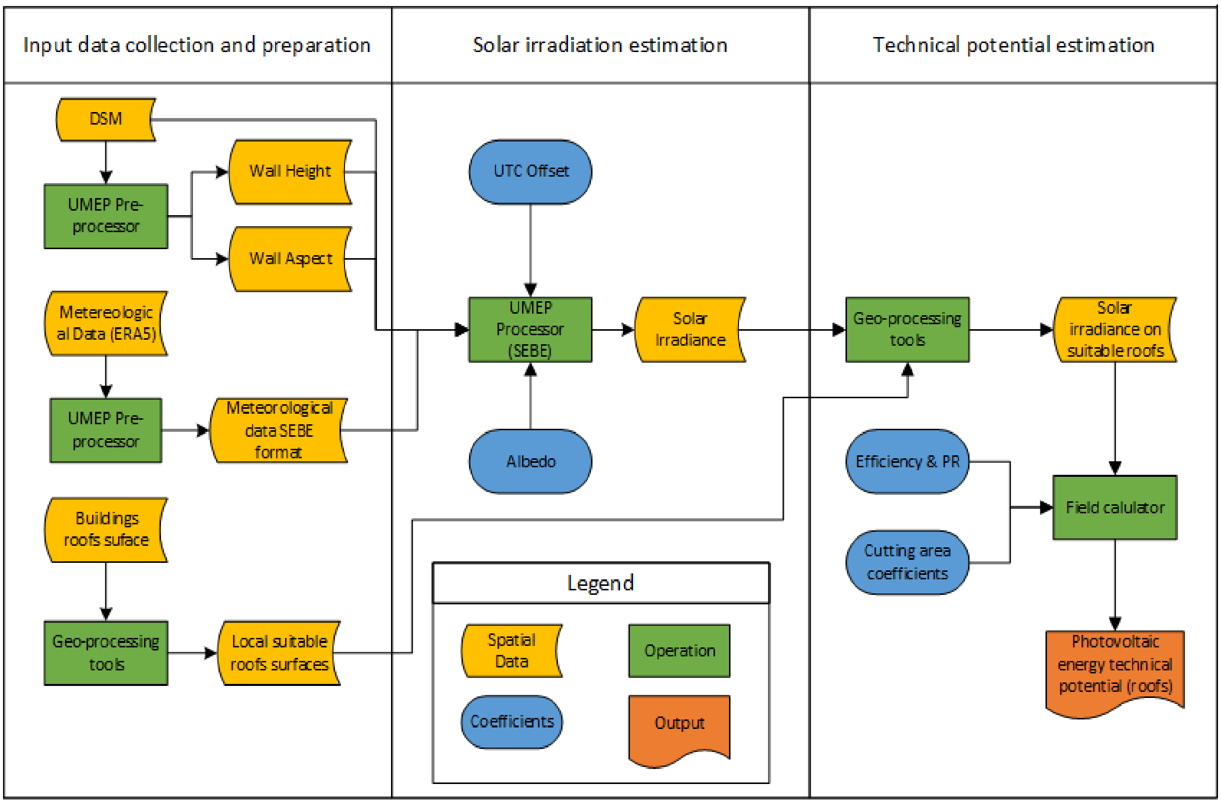


Figure 3.13: Photovoltaic technical potential assessment workflow

The core of this methodology is the Solar Energy on Building Envelopes (SEBE) model, incorporated in UMEP, which adopts a 2D raster modelling approach to derive 3D irradiance information, which makes it possible to compute extensive areas up to city scale. High resolution digital surface models are used to describe the urban geometries. In addition, SEBE utilizes observed solar radiation data with the purpose of deriving highly accurate irradiances for the surfaces modelled [42]. The output of the SEBE model is a file, in GeoTIFF format, that shows pixel wise total irradiance in kWh/m^2. Then, the solar irradiance calculated is used for the estimation of the PV technical potential on the suitable roofs' areas. All the data analysis and mathematical calculations are performed by means of the open-source GIS software, QGIS, introduced in the paragraph 3.1.2.

3.4.1 Preliminary data collection and preparation

The initial stage of the analysis corresponds to the collection of the various data, which is of fundamental importance, as the accuracy of the final results depends in great measure on the precision of the original data. For the purpose of this assessment, two main groups of input data can be distinguished: the meteorological data and the territorial data. This information is properly prepared in the QGIS environment to be used as input for the SEBE model and for the spatial analysis of the available areas for the exploitation of the photovoltaic resource.

3.4.1.1 Meteorological data

To obtain a detailed description of input forcing conditions, the SEBE model utilizes observed hourly data of shortwave radiation, at least one year in length, as meteorological input information. It has been decided to refer to the ERA5 datasets provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), freely available for public use. ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables covering the Earth on a 30km grid [43].

It is chosen the 2020 year as reference for the input meteorological data. The meteorological variables required by SEBE to perform the calculation are:

- Incoming/global shortwave radiation in [W/m^2];
- Diffuse shortwave radiation [W/m^2];
- Direct shortwave radiation [W/m^2];
- Wind Speed in [m/s];
- Air temperature in [°C];
- Relative humidity [%];

- Barometric pressure in [kPa];
- Rainfall in [mm];
- Time related variable: year, days of the year, hours, minutes.

All this information is provided by the ERA5 datasets, but they have to be specifically formatted to be used with SEBE. This specific format can be created using the UMEP pre-processing tool that provides a guided process.

3.4.1.2 Territorial data

To correctly calculate the PV technical potential, it is needed to rely on high quality territorial GIS data. For the Italian territory there are a lot of public geoportals at national, regional and municipal level which provide geospatial data even at high resolutions. This methodology needs in particular two kind of territorial data that are:

- Numerical Technical Regional Map (CTRN);
- High resolution Digital Surface Models.

The first map is available on the regional geoportal of the Sicilian region, SITR, and are provided in shapefile format. The CTRN consists of information layers, grouped by logical affinity in 10 categories, such as vegetation, communication systems, etc. [44]. For this study it is needed only the "buildings and other structure" category, which is downloaded from the SITR on a scale of 1:10.000. The layer represents the building footprints, which in a first approximation can be considered equal to the building roof area. The buildings are divided in several categories depending on the use, but for this study are considered only two categories: the "civil, social and administrative buildings" and the "commercial and industrial buildings". In the technical potential, corrective coefficients are also introduced to consider the differences between the building footprints and the available area for the PV panels installation on the roofs. The extension of the layers downloaded includes the entire regional territory, so it is necessary to export the areas of interest, in this case the Sicilian minor islands, using the geoprocessing tool. In particular, it is used the "clip" function overlaying to the regional maps the islands surface extension.

The high-resolution DSMs are essential for estimating accurate values of the solar radiation on the roofs and ground surfaces. They contain buildings and ground heights which are the main inputs for the SEBE model simulation. Firstly, it is important to distinguish between a DSM and a DTM (Digital Terrain Model). Both are digital elevation model, but the DTM retains only features of the bare-earth terrain, such as rivers and ridges, instead, the DSM captures both the environment's natural terrain features and the artificial one, such as the tops of buildings, trees, powerlines, and any other objects.

Figure 3.13 provide a representation to better understand the concept:

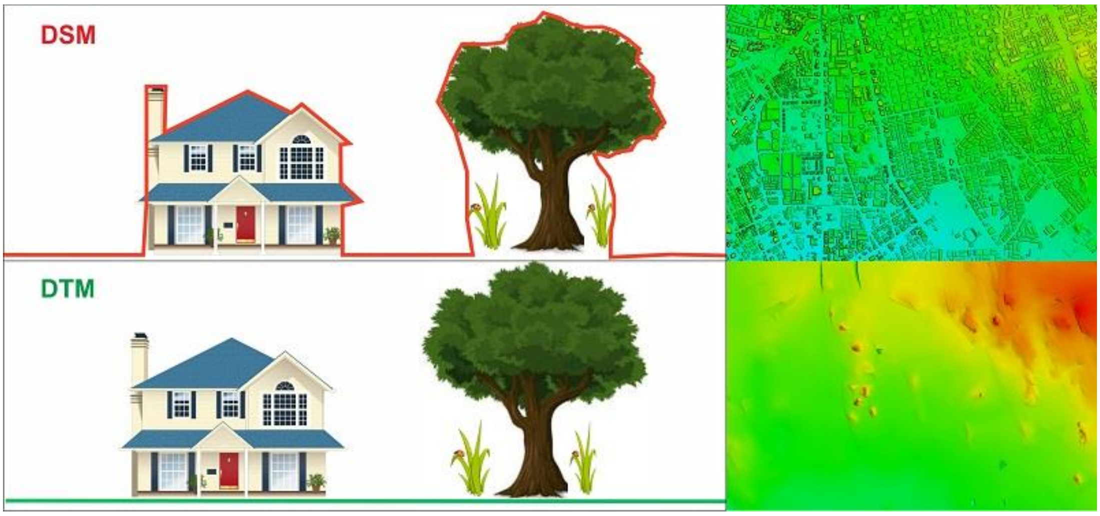


Figure 3.14: Representation of the DSM and DTM features [45]

The high-resolution DSMs are not available on the SITR geodatabase but can be found on the national geoportal managed by the Italian Ministry of Ecological Transition. For the purpose of this study, it is used a DSM grid resolution of 2 meter, so a pixel size of 2x2 meter. To have a higher accuracy, it is possible to use the grid resolution of 1 meter, but it would increase by far the execution time of the SEBE model that can last days for each island. It is thought that the 2-meter grid resolution is the best compromise between accuracy and simulation time for this study application. Therefore, to download these DSMs it is needed to make a formal request to the Ministry by mail and wait for the credential to use for the download of the data. The surveyed territory is organized in sheets which represent small land portions, and each island is characterized by several distinct DSMs. Thus, it is needed to merge the single DSMs with the raster function "merge" to obtain the complete DSM representative of the total island's surface to be used as input of the SEBE model.

Two raster datasets of the same size and extent as the ground and building DSM, containing wall heights and wall aspects are needed to calculate irradiance on building walls. They are generated, starting from the complete DSM, using the "Wall Height and Aspect" function located at the urban geometry tool on the UMEP pre-processor plug-in.

3.4.2 Solar irradiance estimation

The proposed methodology uses the SEBE model to estimate the solar irradiance on ground surfaces and building roofs. SEBE is incorporated in UMEP, a plugin for QGIS, and it is classified as a 2.5-dimensional model which makes use of high-resolution ground and building digital surface models to calculate pixel wise potential solar energy [42].

The total irradiance for a roof pixel (R) on a DSM is calculated by summing the direct, diffuse and reflected radiation. The reference equation is [46]:

$$R = \sum_{i=0}^{p} [(I\omega S + DS + G(1 - S)\alpha)] \tag{3.1}$$

Where:

- p is the number of patches on the hemisphere;
- I is the incidence direct radiation;
- D is diffuse radiation;
- G is the global radiation originating from the i^{th} patch;
- α is the surface albedo;
- ω is the sun incidence angle;
- S is the shadow calculated for each pixel.

The first and second term represents the direct and diffuse irradiance respectively, whereas the third term accounts for reflected irradiance.

An essential feature of the model is the shadow casting algorithm, which uses sequential computation of ‘shadow volumes’ with a DSM to generate accurate shadow patterns from buildings and vegetation as well as ground topography within the model domain [47].

The shadow (S) calculated for each pixel is evaluated as:

$$S = S_b - (1 - S_v)(1 - \tau) \tag{3.2}$$

Where S_b and S_v are shadows from buildings and vegetation, respectively represented by a Boolean value (presence = 0 or absence = 1) and τ is the transmissivity of shortwave radiation through vegetation. Since just one image of shadow patterns represents a 60-min period in the evaluation process, a pixel is either in the shade or exposed to the sun for a full hour, which might not be the case in reality. Actually, a location could be shaded for 40 min and then exposed to sunlight during the remaining 20 min. SEBE calculates this location as if it is shaded for the entire hour, even if it is not the reality. This may result in underestimation or overestimation of the shortwave radiation fluxes [42].

To do the calculation the model requires various inputs to be inserted in the SEBE dialog box on QGIS, which is reported in figure 3.14:

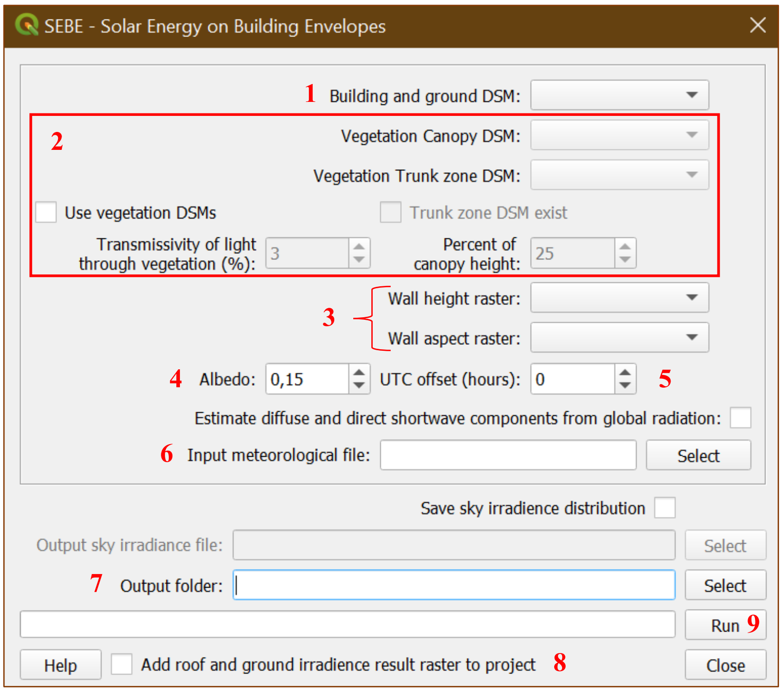


Figure 3.15: SEBE dialog box on QGIS

The dialog box is divided in two main parts: the top section where input data are introduced (1-6) and the bottom section for specifying the output folder and for running the calculations (7-9). It is necessary to explain the meaning of each section and how they are used [46]:

1. **Building and ground DSM:** In the first drop-down menu is selected the DSM consisting of ground and building heights. This dataset also decides the latitude and longitude used for the calculation of the Sun position.
2. **Use vegetation DSMs:** When it is ticked, two vegetation DSMs are required. The first one to describe the top of the vegetation (Vegetation Canopy DSM) and the second one to describe the bottom, underneath the canopies (Vegetation Trunk Zone DSM). The vegetation input data are optional and for this study are not considered. This assumption causes a slight overestimation of the solar irradiance, since the vegetation can shadow ground, walls and roofs reducing the potential solar energy production.
3. **Wall height and Wall aspect raster:** They are two raster files prepared starting from the high-resolution DSM, containing wall heights and wall aspects of the buildings. They have to be specified to calculate irradiance on building walls.

4. **Albedo:** This parameter specifies the reflectivity of shortwave radiation of all surfaces (ground, roofs, walls and vegetation). It should be a value between 0 and 1. The albedo is set to 0,15 [42] and it is an average value used for all surfaces.
5. **UTC offset (hours):** It is needed to accurately estimate the sun position. The UTC is related to the meteorological forcing data so if ERA5 data is used, UTC is equal to zero.
6. **Input meteorological file**: The meteorological file, specifically formatted to be used in UMEP, needs to be specified in this section. A dataset with hourly time resolution should be used for SEBE, at least one year in length. Multiple years can also be used to improve the model outcome.
7. **Output folder:** A specified folder where results are saved should be specified in this space. One raster showing irradiance on ground and building roofs is saved as well as a text file reporting wall irradiance.
8. **Add roof and ground irradiance result raster to the project:** If it is ticked, the result is automatically added to the QGIS map canvas after the process run.
9. **Run:** It starts the calculations which is computationally intensive, so can last a lot of time depending on the DSMs resolution and extension. For the application of this study, the model is run one time for each island with an extension equal to the islands' surface. The only exception is Pantelleria, which is the biggest Sicilian minor island and it is divided in four sectors to reduce the execution time of the model, so four simulations are needed.

As mentioned earlier, three mandatory datasets are saved if the model runs successfully:

- The GeoTIFF file "Energyyearroof.tif" that contains pixel wise total irradiance on ground and building roofs in kWh/m^2/year.
- The text file "Energyyearwall.txt" contains total wall irradiance for each wall column.
- The additional text file "Vegetationdata.txt" including information of vegetation height and location Energyyearwall.txt if the vegetation DSMs were added. For this study the third file is not present.

Example of the output total irradiance raster, visualized on QGIS, is presented in figure 3.15:

Figure 3.16: Example of SEBE output solar radiation visualization (Lampedusa)

The resulting raster added to the QGIS map canvas reports the horizontal radiation on the ground and roof surfaces. The SEBE output represents the physical potential which is indicative of the maximum energy limit, without considering the geographical and normative restrictions and the technical specifications of the PV technology.

3.4.3 Technical potential estimation

The hierarchy used in this study for the photovoltaic technical potential estimation comprises three levels:

1. The physical potential calculation, which encompasses the total amount of energy received from the Sun in the area of study and it is assessed in the previous paragraph.
2. The geographic potential, which restricts the locations where this energy can be captured considering the normative constraints introduced in the legislation section and geographical restrictions such as shaded locations with low solar energy potential.
3. The technical potential, which further takes into account the technical characteristics (including performance) of the technology used for transforming the solar resource into electrical energy.

It is decided to distinguish between technical potential on the ground and technical potential on the building roofs, because the process to assess the geographical potential is different for the two contexts. Moreover, this differentiation can be useful for future energy planning process, since the photovoltaic plants on the ground can be different from that one on the roofs regarding the size and the public’s or private’s interest and investments. In this study is presented a methodology to evaluate the technical potential only on the building roofs.

3.4.3.1 Roof-top photovoltaic geographical potential

The roof area estimation is a fundamental input for the knowledge of the solar thermal potential in building. Several considerations must be made in order to compute the roof area available. The identification of the buildings and the construction typologies influence the built-up surface area. As presented before, the reference data that identify each single building and its footprint are downloaded by the Sicilian geoportal and manipulated on QGIS. This dataset provides the geometries of all the buildings present on the Sicilian region divided in categories. For this study are considered only the civil, social and administrative buildings, as well as the commercial and industrial ones. The lack of information on the roofing properties indeed, imposes the assumption of a representative roofing typology and its empirical analysis based on the visual inspection of Google Earth images. For the Sicilian minor islands, it can be noticed that the most employed roof typology is, by far, the flat roof, so for this study it is assumed that all the building roofs are flat.

The geographical potential for solar photovoltaic installation is defined as the usable roof area that receives the solar radiation for the PV facility. In order to reduce the gross surface area to the realistic available surface area for solar PV systems, both absolute reductions and relative reductions are made. These reductions are defined as follow [48]:

- Absolute reduction consists in excluding the buildings that are protected for their special purposes (for example, cultural-heritage values) or because they are built on protected areas where it is not permitted, by the law, to install PV panels.
- Relative reduction consists in multiplying the total roof area, derived by the georeferenced layers, by different utilization factors, such as those due to orientation, inter-array distance and other competing uses (solar collectors for domestic hot water).

By means of the QGIS field calculator, these reductions are applied for each pixel, which are characterized by a specific solar irradiance and by a maximum extension of 4 m^2. To do that, the SEBE raster output, previously calculated, containing the pixel wise total irradiance on ground and building roofs in kWh/m^2/year is converted in vector format to be properly manipulated. Then, the building vector layer is overlapped to the output raster, utilizing the "clip" function, in order to single out the building footprints of the appropriate building categories individuated before.

A zoom of the result layer of the Lampedusa island urban centre is shown in figure 3.16:

Figure 3.17: Solar radiation on Lampedusa urban centre roofs

The building roofs surface is further reduced considering that the amount of energy received by the roofs needs to be cost effective. Irradiance values below 900 kWh/m^2/year are considered too low for solar energy production [46]; moreover, solar radiation in the range 1000-1200 kWh/m^2/year correspond to areas not suitable for the installation of solar panels, such as parapets or internal terraces, therefore the pixels characterized by a solar radiation lower than 1200 kWh/m^2/year are filtered. The total roof surface area is computed through the elementary field statistics function of the vector analysis tool. The evaluation of effective available roofs area, however, requires the introduction of empirically found cutting coefficients.

For PV modules that are free-standing on flat roofs, determining the appropriate spacing between each row of PV modules is important, since the electricity yield can be affected by mutual-shading. For the application of this methodology, solar modules mounted facing south are considered, for which mutual-shading is caused by the preceding row of PV modules, affecting all rows except the first one. In the northern hemisphere, on the winter solstice solar radiation is at its minimum, which requires a theoretically maximum inter-row distance, to avoid mutual shading. On the other hand, on summer solstice solar radiation is at its maximum, which requires a theoretically minimum inter-row distance, as illustrated in figure 3.16 [48]:

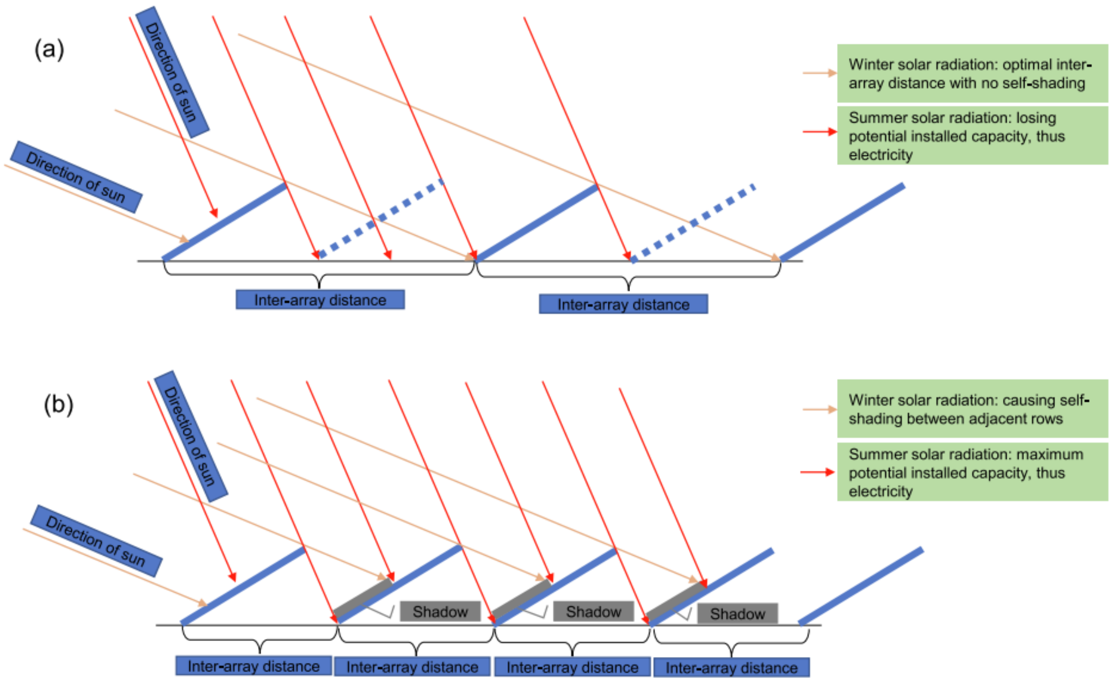


Figure 3.18: Inter-row distance designs and mutual-shading effect during winter (a) and summer season (b)

In this study, all the building roofs are considered flat roofs, so the mutual-shading effect is considered. The design of the inter-array distance is not trivial and depends on many factors that can easily change on a case-by-case basis. In order to take into account these gaps, it is introduced the covering index coefficient C_{COV}, that is assumed to be equal to 0,45, which represents the ratio of module surface divided by the total roof surface available [49].

In the Sicilian minor islands there are already a fair amount of solar collectors on the roofs that continue to increase as they are highly efficient and economically convenient at that latitude. For this reason, it is considered that 10% of the roof surface may not be available because of potentially occupied by solar-thermal systems. Therefore, it is introduced the corrective solar-thermal coefficient C_{ST} assumed equal to 0,9. Precautionary, it is considered also that 30% of the roofs area is already occupied by chimneys, aerials, roof terraces, Heating Ventilation and Air Conditioning Systems (HVAC) or other uses. Hence, it is introduced the corrective feature coefficient, C_F, equal to 0,7 [49]. Considering all the above-mentioned coefficients, their product yields the total corrective coefficient for roof-top PV plants, C_{RF}, which is finally calculated by the following equation:

$$C_{RF} = C_{COV} \cdot C_{ST} \cdot C_F = 0{,}45 \cdot 0{,}9 \cdot 0{,}7 = 0{,}2835 \qquad (3.3)$$

C_{RF} indicates what fraction of the roof's area can be covered by solar panels, so it reduces the available total roof area, reducing the total PV geographical potential.

3.4.3.2 Solar energy conversion

The annual potential of solar electricity generation, at a selected site can be estimated based on the calculated annual solar radiation per unit surface, the total suitable area, and the efficiency of the PV technology. Eq. 3.4 is used to estimate the yearly photovoltaic energy technical potential [50]:

$$E_{AC} = H_g \cdot S_{PV} \cdot \eta_{STC} \cdot PR \tag{3.4}$$

where:

- H_g is the global in-plane solar irradiation in [kWh/m^2/year].
- S_{PV} is the total area available for the PV electricity generation.
- η_{STC} rated efficiency of PV modules at Standard Test Condition (STC)
- PR stands for "Performance Ratio". It is the ratio of the final system yield to the reference yield, and compares the energy actually generated with what is produced under the same amount of irradiation, but under ideal no-loss conditions.

Inside the PR different losses (or rarely gains) are included. It can be evaluated by multiplying seven different efficiencies, as reported in eq. (3.5):

$$PR = \eta_{mis} \cdot \eta_{d-r} \cdot \eta_{AM} \cdot \eta_{wir} \cdot \eta_{temp} \cdot \eta_{shad} \cdot \eta_{PCU} \tag{3.5}$$

These seven efficiencies represent [50]:

1. Tolerance with respect to STC data and intrinsic mismatch of modules current-voltage characteristics.
2. Dirt and reflection of the frontal glass.
3. Different air mass compared to the STC air mass (AM_{STC} = 1,5).
4. Wiring, blocking diodes, fuses and breakers;
5. Over-temperature (or under-temperature) compared to STC (T_{STC} = 25°C);
6. Non-uniform illumination on all modules (shading effect);
7. MPP tracker and DC-AC conversion of the inverter.

The actual design values of PR are in the range 0.65-0.85, depending on the presence of the previous losses. For the Sicilian minor islands application, it is chosen to assume a conservative PR equal to 0,75.

At today, the most employed low concentrated PV module technologies are essentially three [51]:

- The mono-crystalline, also called single-crystalline, silicon is the oldest and more expensive production technique since it is manufactured from the purest silicon. However, it is actually the most efficient sunlight conversion technology available with an actual efficiency range of 20 – 27 %.
- The poly-crystalline, also called multi-crystalline, silicon has a slightly lower conversion efficiency compared to the mono-crystalline, but the manufacturing costs are also lower. The actual efficiency range is 15 – 22 %.
- The thin film, also called amorphous silicon, is obtained by vaporization and deposition of the silicon on glass or stainless steel. The production cost of this last technology is lower than any other method, but the conversion efficiency is also low. Nowadays, the efficiency gap is shortened, and the thin film efficiencies are in the range 15 – 21%

Though researchers have developed PV cells with efficiencies approaching 50%, most commercial panels have efficiencies from 15% to 20%. Generally the PV module manufacturers provide the nominal peak power at Standard Test Conditions (STC), which means at 1000 W/m^2 solar irradiance, a module temperature of 25°C and with an air mass equal to 1,5. Nowadays, the PV module market is extremely dynamic, there is a wide range of technologies and a multiplicity of nominal efficiencies declared by manufacturers for the various module typologies [49]. For the purpose of the present study, it has been decided to assume a representative value of PV panel efficiency in STC equal to 0,18 ($\eta_{STC} = 0{,}18$) . It is needed to specify that in this study the efficiency worsening along the module lifetime is neglected.

Therefore, multiplying the PR with the PV panel efficiency assumed it is possible to quantify the total system efficiency for the conversion of solar energy in electricity, which is:

$$\eta_{syst} = \eta_{STC} \cdot PR = 0{,}18 \cdot 0{,}75 = 0{,}135 \rightarrow 13{,}5\% \qquad (3.6)$$

This means that only 13,5% of the incoming solar radiation on a certain area is converted into usable electricity by the PV system technology.

Another parameter that is useful to know when it is talking about technical potential is the nominal power that has to be installed to generate the estimated energy. Following the methodology utilized until now it is decided to evaluate the PV power starting from the suitable area for the PV panels installation, which is the sum of the areas of the single filtered pixels that characterize the identified roofs. The total roofs area is evaluated by means of the elementary field statistics function on QGIS, then it is multiplied by the C_{RF} to obtain the actual area covered by PV panels as follows:

$$S_{PV} = S_{suitable} \cdot C_{RF} \quad (3.7)$$

Considering that it is needed 7 m^2 for every kW_p, without considering the spacing which is already included in C_{RF}, the total PV power is calculated as:

$$P_{PV} = \frac{S_{PV}}{7} \quad (3.8)$$

In the next section this methodology is applied to the fourteen Sicilian minor islands and the final results are presented. To sum up, the resulting PV technical potential is calculated starting from the physical potential, which is evaluated by multiplying pixel-by-pixel the solar radiation, given by the SEBE model, and the roofs available area for the solar energy exploitation. The area is properly reduced to give a more accurate estimation of the geographical potential. Finally, the PV system technical specifications are introduced, which further reduce the physical potential providing the estimation of the electricity that can be produced from the solar energy, i.e., the PV technical potential.

4 Results and discussion

In this Chapter, the presented methodology is applied to the fourteen Sicilian minor islands to estimate the technical potential of wind and solar photovoltaic resources, which are recognized as the most commercially convenient renewable technologies. The fourteen islands are divided in five paragraphs representing the three archipelagos: Pelagie, Egadi and Eolie, and the two single islands; Pantelleria and Ustica. Following the methodology, it is possible to estimate for each island the amount of electricity potentially generated by the on-shore wind turbines and photovoltaic panels installed on roofs. It is also provided an estimation of the nominal power to install to produce the calculated potential energy.

The numerical results are shown, island by island, by means of tables. For the islands where it is not possible to install wind turbines the average values of wind speed, power density and AEP are reported to provide an overview of the potentiality. Moreover, wind and photovoltaic energy potential resource maps are produced concerning the entire islands' surface. The normative constraints considered for the identification of the suitable areas are highlighted in the maps reported in the cartography appendix. The available areas are identified overlapping the georeferenced layers downloaded or produced considering the actual national, regional and local legislation, and accounting for technical specifications. The graphic visualization of the resource maps, as well as the normative constraints cartography, are prepared by means of the QGIS software.

4.1 Pantelleria

Pantelleria is the largest Sicilian minor island and the fifth Italian island for extension. It is closer to Africa (70 km) than Sicily (110 km). The total surface is equal to 83 km^2 and the perimeter is 51,5 km. The 7366 inhabitants are called “Panteschi”. The island is of volcanic origin and it belongs to the Province of Trapani [52]. Pantelleria is characterized by a great abundance of RES: an annual global solar radiation exceeding 2000 kWh/m^2, an average wind speed greater than 7 m/s at 25 m a.g.l., a wave motion energy potential equal to 6,7 kW/m of wave front, and diffuse secondary volcanic phenomena [13].

The territory is characterized by wide areas subject to environmental and landscape constraints such as two SCI and one SPA zones, a natural reserve and an IBA which for this study is neglected. These areas cover most of the island limiting the potential exploitation of RES, in particular the wind technologies, which have a great impact on the landscape. The layers, representing the normative constraints, utilized to define the eligible area are reported in the appendix dedicated to the cartography.

The estimated area in Pantelleria for wind energy exploitation is about 93.665 m^2 (9,36 ha). The eligible area and the relative mean wind speed at 30m a.g.l. are presented in figure 4.1:

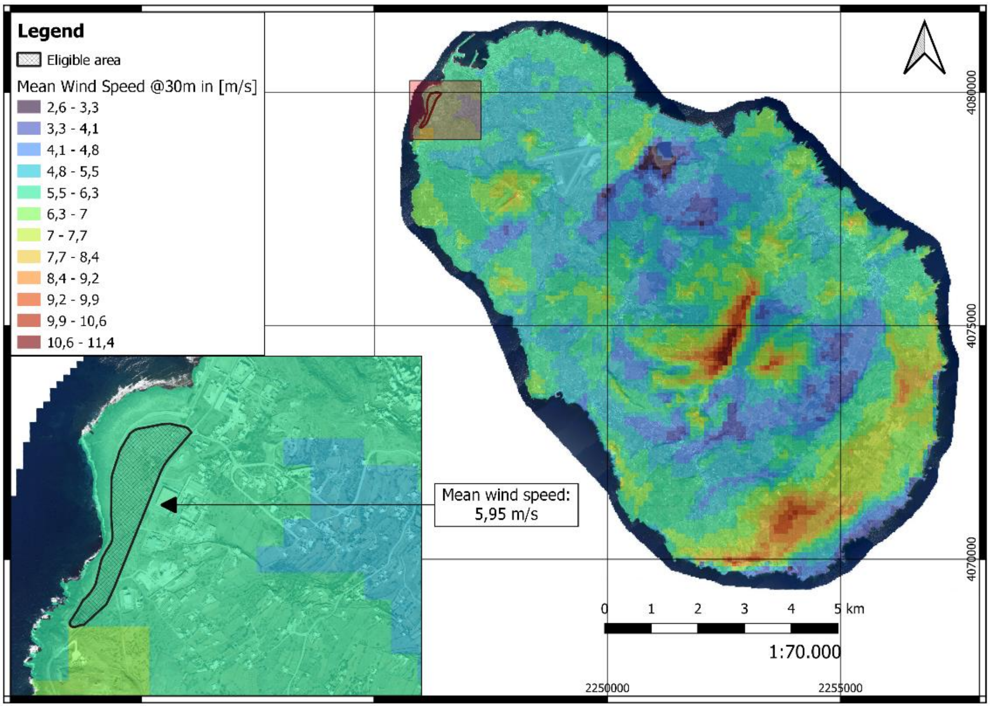


Figure 4.1: Pantelleria eligible area and mean wind speed

The eligible area is within 150 m from the line cost, but it is possible to install WTs if they are identified as "public works or declared to be of pre-eminent public interest".

Under the assumption of neglecting the IBA, the individuated area is suitable for each WT category EO1, EO2 and EO3 but not for any size. For the purpose of this study the 20 kW and 200 kW wind generators can be placed in that area; instead, the 2 MW can not, because it is necessary to consider a longer distance from the inhabited centres which exclude also that portion of terrain. The wind farm configuration, for the three WT considered, are simulated using the WAsP software and the results are reported in table 4.1:

WTs P_n	Hub height	Mean wind speed	Wind farm	Net AEP	Wake losses	Capacity factor	Self-Sufficiency
[kW]	[m a.g.l.]	[m/s]	[N. WT]	[MWh/year]	[%]	[%]	[%]
20	20	5,45	27	1.111	6,68	27,9	2,9
200	30	5,95	7	3.043	3,35	25,7	7,8
2000	80	7,1	2	14.404	1,3	41,6	36,9

Table 4.1: Wind technical potential results for Pantelleria island

The table includes the 2 MW wind generator to give an overview of the technical potential achievable with that turbine size, but the available technical wind potential is referred to the 200 kW wind generator. The self-sufficiency parameter indicates what is the percentage of the island’s annual electricity demand covered by the wind farm. It is important to note that a wind farm with seven 200 kW wind generators can be feasible, relaxing the restrictions about IBA, and can potentially cover around 8% of the annual demand of electricity of the entire island reducing the greenhouse gases (GHG) emissions and the dependence from fossil fuels. It is clear that considering the normative constraints it is not possible to harvest the huge wind energy potential of the island, for this reason it is necessary to include other renewable energy technologies in the future energy mix.

For what concerns the photovoltaic energy technical potential, in this study it is evaluated only on the suitable building roofs. The roof-top photovoltaic technical potential is evaluated using the methodology based on the SEBE model, explained in the previous chapter. The territorial landscape plan of Pantelleria limits the installation of PV panels on any building roof outside the main city centre and its peripheral areas. Moreover, it is not possible to install PV panels on the roofs of the traditional house, named “Dammuso”, which has an important historical, cultural and landscape value. The Dammuso is characterized by domed roofs and it is distributed throughout the island with the exception of the main urban centre where there are few. It is not possible to distinguish the houses typology from the territorial data utilized, so it is assumed that all the buildings in the main urban centre and on its peripheral areas are not protected.

In figure 4.2, the landscape restrictions and the roofs solar radiation are shown; moreover, it is highlighted a portion of the area where it is possible to install PV panels:

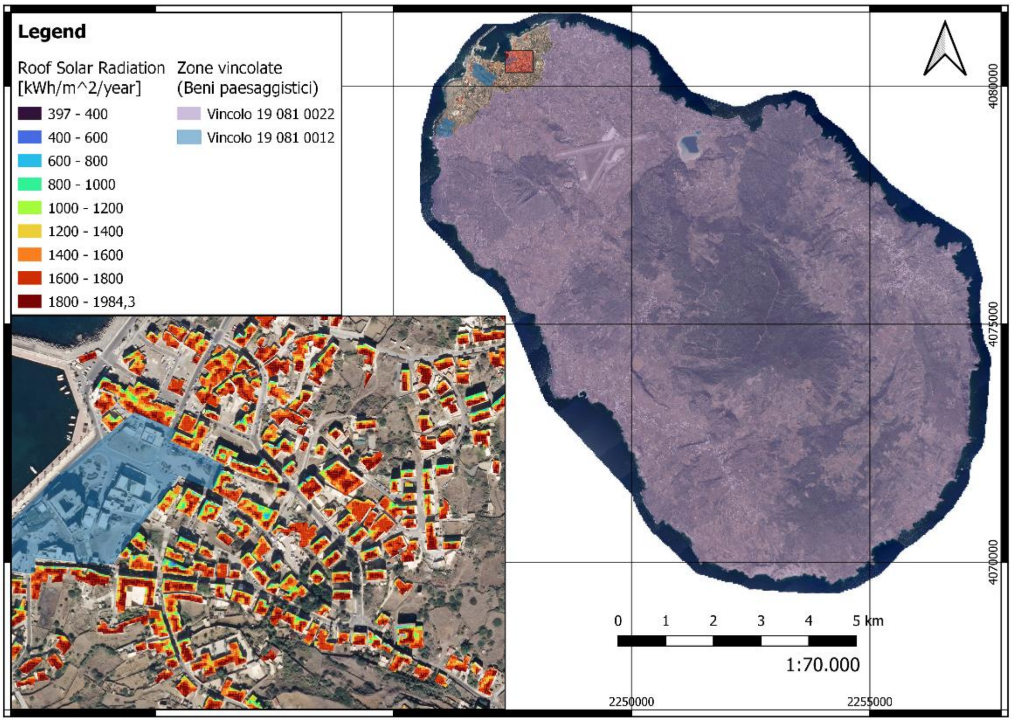


Figure 4.2: Pantelleria solar radiation on urban centre roof and restrictions

The photovoltaic technical potential of PV panels installed on the unrestricted buildings roof in Pantelleria is calculated by multiplying, for each pixel, the annual solar irradiance by the pixel area by the two corrective coefficients introduced in the previous chapter, C_{RF} and η_{syst}. The main out parameters of the photovoltaic technical potential assessment are reported in table 4.2:

Suitable roofs area	PV panels surface	Electricity Production	Potential PV power	Self-Sufficiency
[m^2]	**[m^2]**	**[GWh/year]**	**[MW]**	**[%]**
193.342	55.095	12,53	7,87	32,12

Table 4.2 Photovoltaic technical potential on Pantelleria roofs

The total suitable roofs area for PV panels installation is about 0,2 km^2 and the photovoltaic technical potential is 12,53 GWh/year. It corresponds to about 32% of the annual electricity demand of the island. The value of self-sufficiency is not as much as for the other islands due to the restriction regarding the “Dammuso”, which limits most of the roof’s area. This type of constraint is certainly understandable, given the great historical and cultural importance of the Dammuso; therefore, Pantelleria has the necessity to focus also on the solar potential on the ground or on other renewable energy resources such as wind but also the most recent technologies to exploit the wave energy potential or the geothermal resource.

4.2 Ustica

The island of Ustica is located in the southern Tyrrhenian Sea and belongs to the Province of Palermo. The island is of volcanic origin and is characterized by a surface of 8.65 km^2 and a population of 1.271 inhabitants. It is the Sicilian minor island with the highest value of electricity needs covered by RES, which is around 12%, thanks to the presence of 432,6 kW of PV power installed by 2020 [11]. The territory is characterized by areas of particular environmental value, such as SCI, SPA and natural reserve, furthermore, Ustica is the only Sicilian minor island that does not fall under the IBA constraint.

The estimated area for wind energy exploitation is about 54.373 m^2 (5,43 ha) for the EO1 WT typology, which is reduced to 28.687 m^2 (2,87 ha) for EO2 and EO3 types. The eligible area and the relative mean wind speed at 30m a.g.l. are presented in figure 4.3:

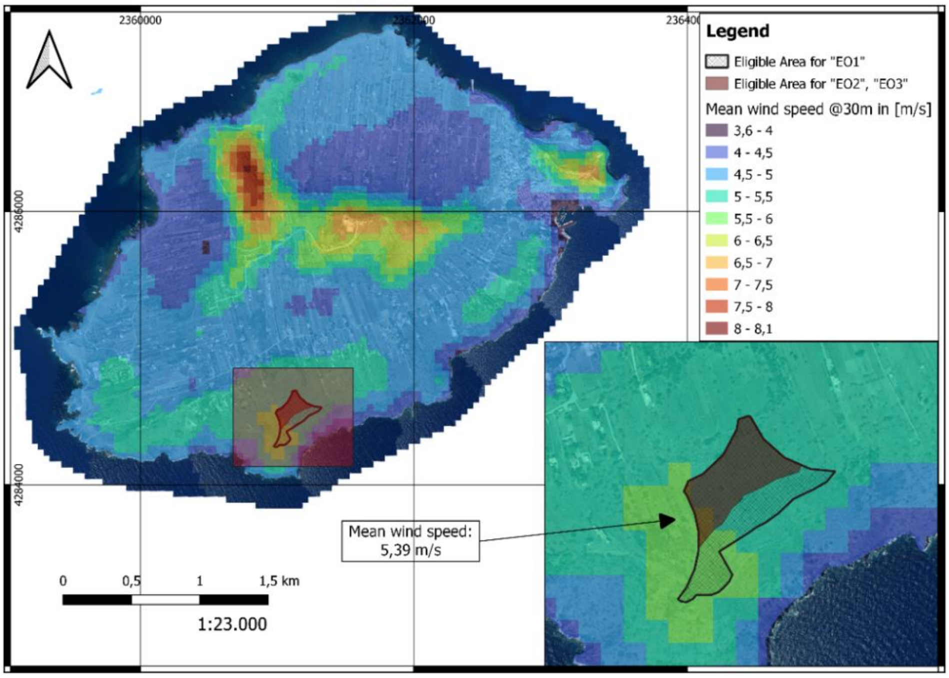


Figure 4.3: Ustica eligible area and mean wind speed

The layers, representing the normative constraints, utilized to define this area are reported in the appendix dedicated to the cartography. The results of the WAsP simulations, for the three WT considered, are reported in table 4.3:

WTs P_n	**Hub height**	**Mean wind speed**	**Wind farm**	**Net AEP**	**Wake losses**	**Capacity factor**	**Self-Sufficiency**
[kW]	**[m a.g.l.]**	**[m/s]**	**[N. WT]**	**[MWh/year]**	**[%]**	**[%]**	**[%]**
20	20	5,07	10	390	2,07	25,3	8,0
200	30	5,39	4	1.513	2,67	22,2	31,1
2000	80	5,63	1	5.631	0	32,1	115,6

Table 4.3: Wind technical potential results for Ustica island

Ustica has an annual electricity production from diesel of 4.870 MWh, so also small wind farms, in the power range of some hundreds of kW, can have a relevant impact. It can be noticed that only one 2 MW wind generator can produce more electricity than the island's needs but as discussed for Pantelleria it is not possible to install it due to the lack of adequate distance from residential areas.

For the exploitation of solar energy on the roofs, Ustica does not present any particular restrictions, so the methodology is applied for the entire territory. In figure 4.4 is shown the solar irradiance on the Ustica building roofs:

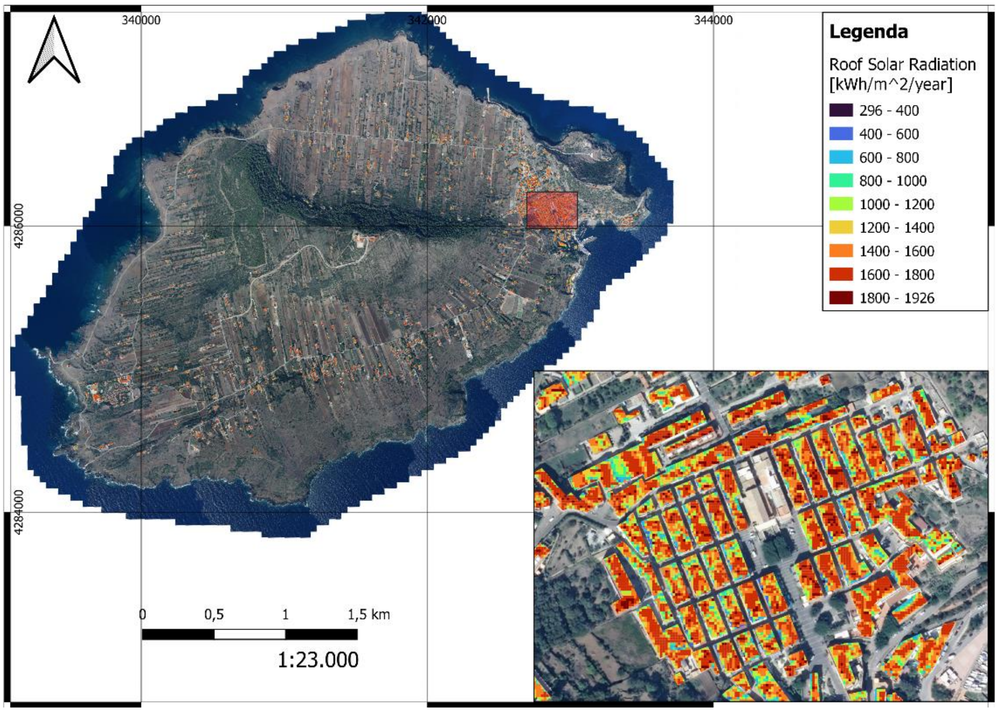


Figure 4.4: Ustica solar radiation on building roofs

The total suitable roof area is equal to 132.888 m^2 (~ 0,13 km^2) and the corresponding photovoltaic technical potential is equal to 8,21 GWh/year.

Suitable roofs area [m^2]	PV panels surface [m^2]	Electricity Production [GWh/year]	Potential PV power [MW]	Self-Sufficiency [%]
132.888	37.673	8,21	5,38	168,57

Table 4.4: Photovoltaic technical potential on Ustica roofs

It can be noticed that the PV panels electricity production is higher than the annual electricity demand of the island, so it is clear that the solar resource is abundant and can play a significant role for the energy transition of this island.

4.3 Pelagie islands

The Pelagie islands are two, Lampedusa and Linosa, and represent the southernmost archipelago of Italy. Lampedusa is the largest of the two with a surface of 20,2 km^2, instead Linosa is characterized by an extension of 5,4 km^2. The total inhabitants are 6.337 most of them live in the Lampedusa island, while about five hundred reside in Linosa. The municipality is one for both islands and it belongs to the province of Agrigento. Today, the electricity production covered from RES is low, about 6%, so the dependency on fossil fuel is critical [11].

Both the islands are characterized by sites of environmental and landscape importance such as SCI, SPA, IBA, natural reserve and a sea protected area. Moreover, the local territorial landscape plan prevents the construction of industrial plants larger than 20 kW. For wind energy exploitation the regional legislation identifies the unsuitable areas that in this case coincide with the whole islands' surface. Under the hypothesis of not considering the restriction regarding IBA, it is possible to find out an eligible area for the installation of a 20 kW wind generator in Lampedusa, while in Linosa it is not possible to define any eligible area.

The estimated area in Lampedusa for wind energy exploitation is about 19.806 m^2 (~ 2 ha). In figure 4.5, the Lampedusa eligible area and the mean wind speed are presented:

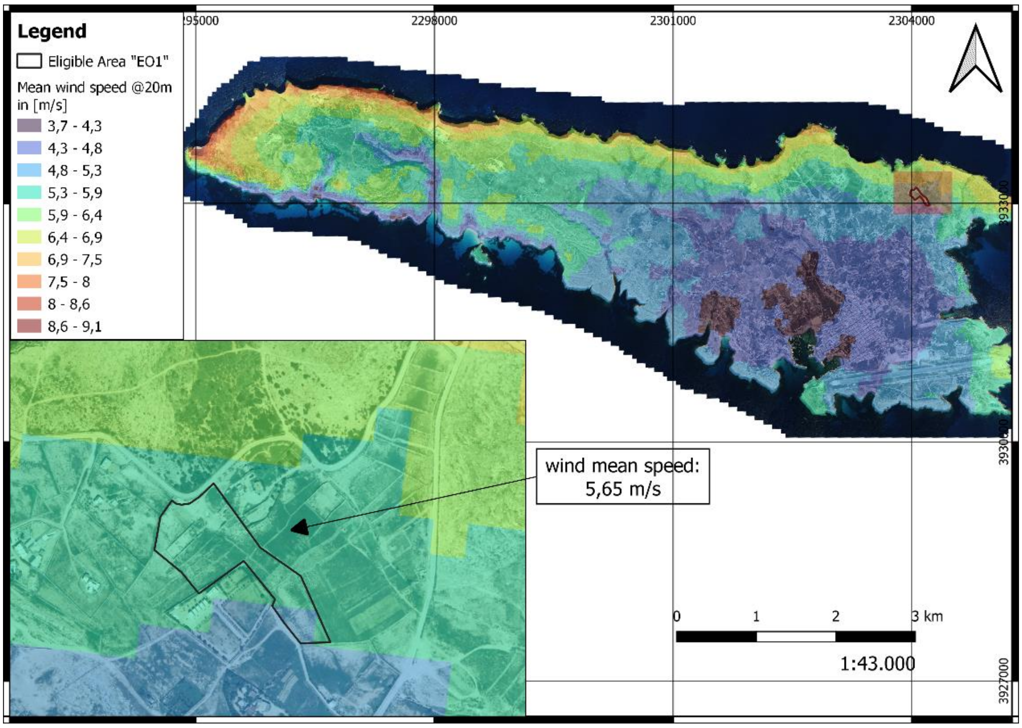


Figure 4.5: Lampedusa eligible area and mean wind speed

The layers, representing the normative constraints, utilized to define this area are reported in the appendix dedicated to the cartography. In table 4.4 are reported results of the WAsP simulations on the eligible area in Lampedusa for the three WT introduced.

WTs P_n	Hub height	Mean wind speed	Wind farm	Net AEP	Wake losses	Capacity factor	Self-Sufficiency
[kW]	[m a.g.l.]	[m/s]	[N. WT]	[MWh/year]	[%]	[%]	[%]
20	20	5,52	8	374	3,87	26,4	0,95
200	30	5,99	3	1.401	2,26	26,6	3,7
2000	80	7,19	1	7171	1,3	40,9	19,1

Table 4.5: : Wind technical potential results for Lampedusa island

The 200 kW and 2 MW wind generator can not be installed with the actual legislation framework, also under the relaxed restriction assumption. It can be noticed that the wind energy potential is relevant, but the restrictions largely limit its exploitation. In table 4.4, it is reported an overview of the wind technical potential exploitable on the Linosa territory, calculated for a single WT of each wind generator type. The minimum, average and maximum values are referred to the location where the WT could be located.

WTs P_n	Hub height	Mean wind speed			Power density			Net AEP		
[kW]	[m a.g.l.]	[m/s]			[W/m^2]			[MWh/year]		
-	-	Min	Aver.	Max	Min	Aver.	Max	Min	Aver.	Max
20	20	3,92	5,73	9,22	106	317	1227	24	48	83
200	30	4,82	6,15	9,29	180	372	1205	303	473	747
2000	80	6,53	7,19	9,35	386	504	1063	6.204	7.135	9.089

Table 4.6: Wind turbines potentiality in Linosa

For what concern the annual solar radiation per square meter of the Pelagie Islands, it is the highest in Italy and it is shown, for the roofs area, in figure 4.6 and 4.7:

Figure 4.6: Linosa solar radiation on building roofs

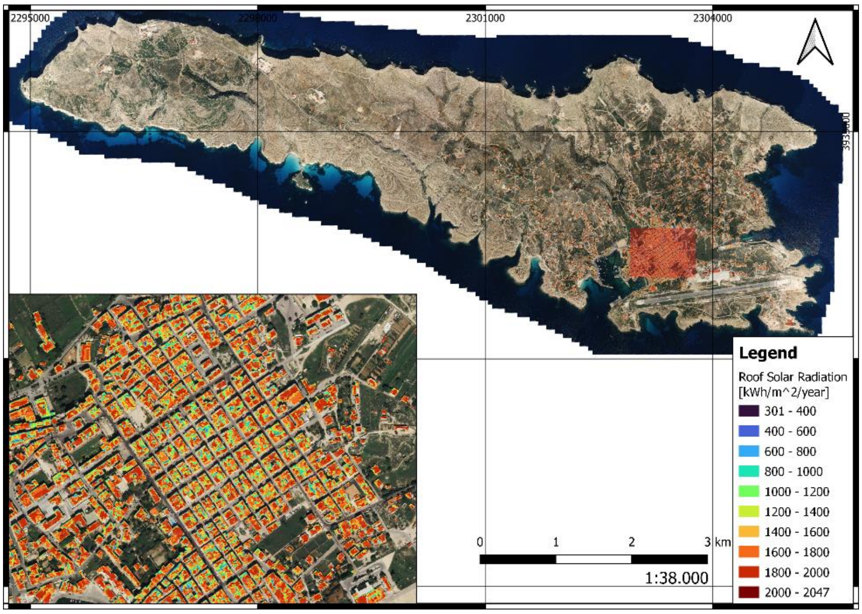


Figure 4.7: Lampedusa solar radiation on building roofs

The installation of PV panels on the buildings roofs is not particularly limited. However, the territorial landscape plan provides that the PV panels must be installed so that they are not visible from the main roads and squares. Moreover, they must be installed with an inclination that does not permit exceeding the height of the parapets. For this reason, the total electricity production, evaluated as explained in section 3.4, is decreased by a further 10% to consider the losses due to the not optimal inclination [49]. Despite this reduction, the photovoltaic technical potential of Lampedusa and Linosa is exceptionally high due to the geographic position.

In table 4.5 the final results are summarized:

Island	Suitable roofs area	PV panels surface	Electricity Production	Potential PV power	Self-Sufficiency
-	[m^2]	[m^2]	[GWh/year]	[MW]	[%]
Lampedusa	530.367	150.359	32,11	21,5	84,7
Linosa	60.710	17.211	3,67	2,5	130,9

Table 4.7: Photovoltaic technical potential on Pelagie Islands roofs

It can be noticed that for Lampedusa the photovoltaic technical potential on roofs represents a large slice of the local electricity demand, while for Linosa the self-sufficiency parameter is even greater than 100%.

4.4 Egadi islands

The Egadi islands are three, Favignana, Marettimo and Levanzo. The largest one is Favignana which is characterized by a surface extension of 19,3 km^2, while the other two are large 12,4 km^2 and 5,8 km^2 respectively. The municipality is one for all the islands, named Favignana, and it belongs to the province of Trapani. Despite their proximity to Sicily, the Egadi islands are not interconnected to the national electricity grid and to meet their energy needs they use diesel-powered generators as the other Sicilian minor islands. On the three islands a total photovoltaic power of 404 kW is installed, it is able to cover only 3% of the archipelago's entire electricity needs [11].

The renewable sources are abundant, for example the annual mean wind speed in Favignana is higher than 6 m/s on average with peaks of 10 m/s in specific areas, and the annual solar radiation reaches values of 1950 kWh/m^2 on the unshaded surfaces. However, the wind energy exploitation is widely limited on all the Sicilian minor islands including the Egadi archipelago. Relaxing the restriction relative to the IBA, it is possible to make use of a small area on the Favignana island. The eligible area has an extension of 35.090 m^2 (~ 3,5 ha) and it is shown in figure 4.8 overlayed to the mean wind speed map:

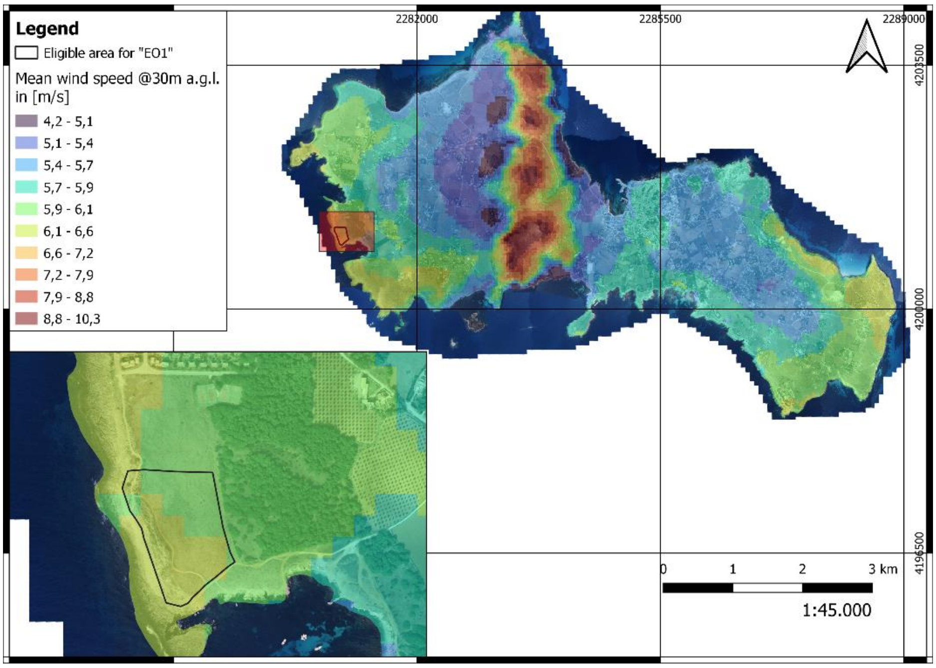


Figure 4.8: Favignana eligible area and mean wind speed

As in the case of the Pantelleria eligible area, this area is within 150 m from the line cost, but it is possible to install WTs if they are identified as "public works or declared to be of pre-eminent public interest". The layers, representing the normative constraints, utilized to define this area are reported in the appendix dedicated to the cartography.

Under the above mentioned assumptions, it is possible to install the 20 kW and 200 kW wind generator in this area but not the 2 MW for the distance from the residential area. By means of the WAsP software the potential wind farms are simulated, for the three WT considered, and the results are reported in table 4.6:

WTs P_n	Hub height	Mean wind speed	Wind farm	Net AEP	Wake losses	Capacity factor	Self-Sufficiency
[kW]	**[m a.g.l.]**	**[m/s]**	**[N. WT]**	**[MWh/year]**	**[%]**	**[%]**	**[%]**
20	20	5,8	8	382	4,04	31,5	2,5
200	30	6,14	4	1.887	3,03	27,8	12,2
2000	80	7,15	1	7.027	0	40,1	45,4

Table 4.8: Favignana wind technical potential results

Even if the suitable area is small and it can be installed wind farms of some hundreds of kW the annual energy production is relevant with respect to the annual electricity demand of the Favignana island.

In the case of Marettimo and Levanzo it is not possible to install any WT anywhere considering the actual normative context, also relaxing some constraints. Therefore, the wind energy technical potential is zero, but it is reported an overview of the potentiality of the three wind turbine considered in this study for both the islands.

WTs P_n	Hub height	Mean wind speed			Power density			Net AEP		
[kW]	**[m a.g.l.]**	**[m/s]**			**[W/m^2]**			**[MWh/year]**		
-	-	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
20	20	0,1	4,2	10,9	0	175	2.357	0,82	50,1	101,7
200	30	2	6,4	13,1	14	472	3.073	36,5	482	812
2000	80	5,2	7,4	12,7	199	597	2.500	4.168	7.044	9.726

Table 4.9: Wind turbines potentiality in Marettimo

WTs P_n	Hub height	Mean wind speed			Power density			Net AEP		
[kW]	**[m a.g.l.]**	**[m/s]**			**[W/m^2]**			**[MWh/year]**		
-	-	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
20	20	3,2	5,8	9	58	354	1.129	14,7	48,4	81,2
200	30	4	6,2	9,2	102	410	1.181	203	477	737
2000	80	5,9	7,2	9,6	282	555	1.193	5.391	7.012	8.948

Table 4.10: Wind turbines potentiality in Levanzo

The minimum, average and maximum values are referred to the location where the WT could be located. It is clear that the wind energy potential is high, the annual mean wind speed can reach 9 m/s or more at each of the altitudes considered and the estimated annual energy production confirms that wind farms could contribute to cover an interesting percentage of the annual electricity demand of the islands.

From the constraints point of view, the photovoltaic source is easier to exploit, by means of PV panels installed on the building roofs, than the wind source. In fact, there are not particular limitations for the Egadi archipelago, so all the building roofs that satisfy the technical constraints introduced in the previous chapter can be considered for the technical potential estimation.

In table 4.9, the main output parameters from the PV technical potential evaluation are presented for the three islands that compose the archipelago.

Island	**Suitable roofs area**	**PV panels surface**	**Electricity Production**	**Potential PV power**	**Self-Sufficiency**
-	**[m^2]**	**[m^2]**	**[GWh/year]**	**[MW]**	**[%]**
Favignana	303.734	86.108	18,97	12,3	122,6
Marettimo	26.057	7.387	1,52	1,06	74,3
Levanzo	18.038	5.113	1,12	0,73	186,8

Table 4.11: Photovoltaic technical potential on Egadi Islands roofs

As expected Favignana has the highest photovoltaic technical potential between the Egadi islands, since it is the largest and the most populated and it is characterized by a greater roof area. Therefore, it is important to focus the attention on the self-sufficiency parameter which point out the percentage of electricity, currently produced from fossil fuels, which can be replaced by the energy produced by PV panels on roofs. Both Favignana and Levanzo report a self-sufficiency higher than 100%, while it is about 75% for Marettimo. From these results it is evident that the technical potential is relevant and should be exploited more to aim for energy independence. Obviously, the electricity production from PV panels on roofs is not the solution alone, because the distributed production has some other issues to face but it can greatly contribute to the energy transition of these places.

4.5 Eolie islands

The Eolie archipelago is composed of seven islands of volcanic origins. The largest island is Lipari which is characterized by a surface of 37,6 km^2, while Lipari is the second for extension with 26,2 km^2. Six out of seven islands: Lipari, Vulcano, Stromboli, Filicudi, Alicudi and Panarea are included in a single municipality, named Lipari, which have a total population of 12.266 people. Instead, Salina is divided into three municipalities: Santa Marina Salina, Malfa and Leni, where overall 2.522 people reside. The four municipalities belong to the province of Messina.

As for the other islands, the territory of the Eolie archipelago is characterized by wide areas subject to environmental and landscape constraints. All the islands fall within the IBA restriction, where it is not possible to install any type of wind turbine, moreover each island is characterized by areas of particular environmental value, such as SCI, SPA and natural reserve, as presented in the cartography appendix. Neglecting the IBA restriction, the few non-protected areas correspond to urban centres and the nearby locations, where it is not possible to install wind turbines because of the proximity to residential houses. It is possible to individuate some small pieces of land not constrained and sufficiently distant from urban areas, which are just above the valleys of the volcanoes. However, assessing a slope analysis the result is that the slope does not technically permit the installation of wind turbines because is greater than 20°, furthermore, there are no roads easily practicable by work vehicles. Therefore, those areas are not technically, economically and environmentally compatible for WTs installation.

For these reasons, the on-shore wind technical potential is zero for the entire Eolie archipelago. To understand how much the wind theoretical potential of the Eolie islands is, in table 4.12 is presented an overview of the main wind parameters that characterize each island, calculated for a height of 30 m using WAsP. In addition, it is reported the average annual energy production of the 200 kW wind turbine:

Island	**Mean wind speed**		**Power density**		**Net AEP**	
-	**[m/s]**		**[W/m^2]**		**[MWh/year]**	
	Average	**Max**	**Average**	**Max**	**Average**	**Max**
Alicudi	4,73	8,99	451	2161	294,4	527,3
Filicudi	4,11	8,50	285	1975	245,5	507,3
Salina	3,87	8,50	274	2104	222,8	517,9
Lipari	3,96	7,46	210	1282	239,4	503,3
Vulcano	4,34	8,13	242	1335	272,7	547,2
Panarea	4,37	9,08	323	2189	270,5	538,7
Stromboli	4,41	10,01	317	2547	272,2	571,8

Table 4.12: Wind theoretical potential parameters @30m a.g.l. of the Eolie islands

The average values are lower with respect to the islands previously analysed mainly due to the geographical position and territorial conformation. The maximum values are relevant because of the volcanic origin of the islands that are characterized by elevation peaks in the order of hundreds of meters. Overall, the theoretical potential is significant and the annual energy production simulated for a 200 kW wind turbine could have an impact on the annual electricity demand.

Four out of seven Eolie islands are characterized by a surface lower than 13 km^2, and the other three are not much larger. These territories present a particular ecosystem and a valuable landscape heritage which must be protected and respected. Solar energy is abundant in these places and the environmental impact of its exploitation, in the case of roof installation, is much lower than the wind energy technology. Applying the proposed methodology, the photovoltaic technical potential on roofs has been estimated and the results, for each Eolie island, are reported in table 4.13:

Island	Suitable roofs area	PV panels surface	Electricity Production	Potential PV power	Self-Sufficiency
-	[m^2]	[m^2]	[GWh/year]	[MW]	[%]
Alicudi	23.874	6.768	1,45	0,97	363,5
Filicudi	65.394	18.539	4,01	2,65	286,7
Salina	269.907	76.518	16,16	10,93	176,4
Lipari	735.264	208.447	44,65	29,8	128,3
Vulcano	198.647	56.316	12,09	8,05	166,1
Panarea	59.242	16.795	3,56	2,4	113,5
Stromboli	98.224	27.846	5,96	3,98	153,9

Table 4.13: Photovoltaic technical potential on Eolie islands' roofs

The territorial landscape plan of the Eolie islands does not provide particular restriction for solar energy exploitation on building roofs, so it is possible to use all the suitable roofs surface for the buildings category individuated by the methodology. For this reason, the photovoltaic technical potential is relatively high, and observing the self-sufficiency parameter, it can be noticed that the potential electricity production of PV panels is higher than the electricity demand of each island. Actually, it is not feasible to cover all the building roofs with PV panels, but the solar energy can be harvest also from ground-mounted configurations and there is the possibility of using other technologies to exploit different renewable energy sources

In conclusion, it is not possible to install wind turbines in the Eolie islands territory with the current legislation context. Nevertheless, the photovoltaic technical potential is enough to heavily contribute to the energy transition of these minor islands.

4.6 Summary

In this paragraph it is presented a summary of the calculated on-shore wind and photovoltaic technical potential, for the fourteen Sicilian minor islands, in terms of annual energy production and total power installable. The wind power installable represents the total size of the wind farm composed by the 200 kW wind generators, which are taken as reference for the estimation of the wind technical potential as it is considered the most suitable size for the minor islands analysed. The photovoltaic technical potential is referred only to PV panels installed on the building roofs. As mentioned before, the Sicilian minor islands territory is characterized by wide areas subject to environmental and landscape constraints. Even if the IBA restriction has not been considered, these areas cover most of the islands limiting the potential exploitation of RES, in particular, the wind energy technologies which have a great impact on the landscape. For this reason, the on-shore wind technical potential is zero for most of the minor islands.

In table 4.14, the obtained results for all the fourteen Sicilian minor islands are presented:

Island	Potential Wind AEP	Installable Wind Power	Potential PV AEP	Installable PV Power	Self-Sufficiency
-	[GWh/y]	[MW]	[GWh/y]	[MW]	[%]
Pantelleria	3,04	1,4	12,53	7,87	39,9
Ustica	1,51	0,8	8,21	5,38	199,6
Lampedusa	1,40	0,6	32,11	21,5	88,9
Linosa	-	-	3,67	2,5	130,9
Favignana	1,89	0,8	18,97	12,3	134,8
Marettimo	-	-	1,52	1,06	74,3
Levanzo	-	-	1,12	0,73	186,8
Alicudi	-	-	1,45	0,97	363,5
Filicudi	-	-	4,01	2,65	286,7
Salina	-	-	16,16	10,93	176,4
Lipari	-	-	44,65	29,8	128,3
Vulcano	-	-	12,09	8,05	166,1
Panarea	-	-	3,56	2,4	113,5
Stromboli	-	-	5,96	3,98	153,9

Table 4.14: Wind and photovoltaic technical potential of the Sicilian minor islands

The self-sufficiency parameter is defined as the sum of wind and photovoltaic technical potential divided by the electricity production from fossil fuels reported in table 2.2, therefore it represents the amount of electricity production potentially replaced by RES. Observing the self-sufficiency parameter, it is clear that the estimated technical potential is from 1 to 3 times the diesel electricity production, with the exception of Pantelleria, Lampedusa and Marettimo. This study does not consider the ground-mounted photovoltaic potential that can significantly increase the solar energy conversion into electricity.

In figure 4.9 the wind and photovoltaic technical potential is compared with the actual electricity production from fossil fuels of each island:

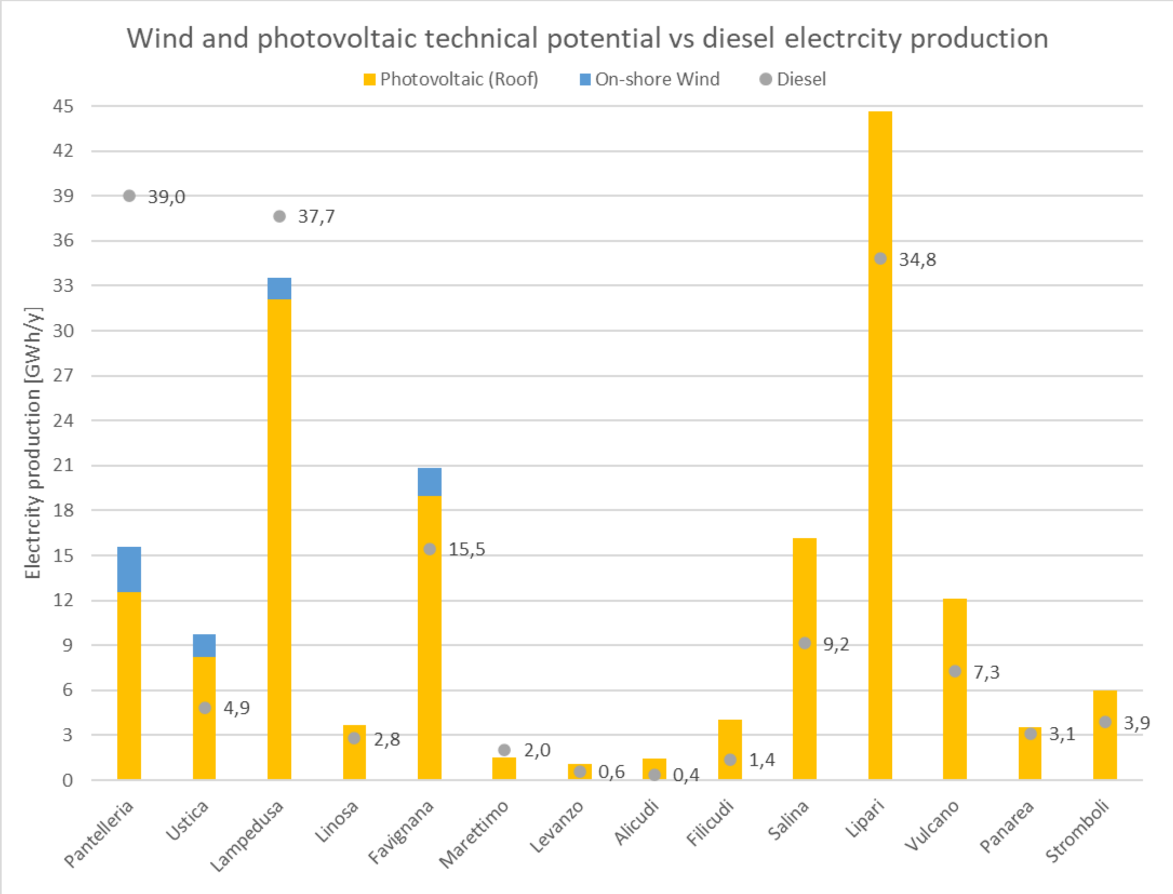


Figure 4.9: Wind and PV technical potential vs diesel electricity production

The obtained results disclosed that the on-shore wind and roof photovoltaic technical potential could cover the diesel generator electricity production on eleven out of fourteen analysed islands. The three islands with a not sufficient technical electricity production from the RES considered are Pantelleria, Lampedusa and Marettimo. In the case of Pantelleria, this is due to the restrictions introduce by the territorial landscape plan, which limit most of the roof surface of the island. Lampedusa is also characterized by restrictions that limit the technical potential, furthermore it is characterized by a high electricity demand with respect to other islands comparable for extension and population as Lipari and Favignana. Lastly, Marettimo has a potential self-sufficiency slightly lower than 100% because of the low density of population and available buildings.

It is clear that there is a great unexplored photovoltaic potential which could contribute to the production of electricity in a relevant way. Wind energy exploitation is possible only in four out of the fourteen Sicilian minor islands following the restrictions considered in this study. However, the wind energy potential is not negligible and the wind farms proposed are small with a relatively low environmental and landscape impact, so they can contribute considerably to the energy transition of the islands.

Currently, the RES power installed, reported in table 2.1, generates few percent of the total electricity production of the islands, moreover it is almost negligible with respect to the estimated technical potential and it is not subtracted to the overall energy potential. There are some projects which aim to increase RES production in the minor islands in the coming years and many funds have been allocated by the RRP to finance many others. An example is the project in Lipari founded by the NESOI consortium, which aims to conclude the unfinished work of the photovoltaic system located in Monte S. Angelo, the largest (1,12 MW) among the Italian minor islands.

5 Conclusion

The scope of this master's thesis is to introduce an original methodology for wind and photovoltaic energy technical potential estimation, with reference to the Italian minor islands' context. The originality of the methodology consists in considering aspects beyond the techno-economic ones, which are usually overlooked; to do this, the methodology is based on a spatial energy planning approach, which considers the current legislation, mainly about environment and landscape safeguard, on a national, regional and local scale to determine the suitable areas for RES exploitation. The proposed methodology is implemented in the geographic information system software, QGIS, that is used to identify the eligible areas, by means of normative and technical considerations, and to graphically visualize input and output data. Furthermore, a georeferenced dataset to exclude areas considering normative constraints aspects was created. Two different processes have been designed for estimating wind and photovoltaic technical potential. The on-shore wind potential assessment is based on the WAsP software which is used to site the wind turbines and for the energy yield calculation of the wind farms. Instead, the photovoltaic potential assessment utilizes the "Solar Energy on Building Envelopes" model, incorporated in the QGIS plug-in, named UMEP, which adopts high resolution digital surface models and observed solar radiation data as inputs to derive irradiance information of extensive areas on a pixel wise scale. Then, the photovoltaic technical potential on the roof surfaces is estimated introducing corrective area coefficients and PV panels technical specifications.

The primary contribution of this thesis is the scalable methodology, which represent a new approach that can be applied to the Italian minor islands' framework and, in some extent, to the European one. In this study the method is applied to the fourteen non-interconnected Sicilian minor islands and the presented results are in line with the current knowledge about wind and photovoltaic resources availability in the case study islands. The particularity of this study is that the results are not limited to the resource assessment of the wind mean speed or average solar radiation values, but it is provided a punctual estimation of the technical potential intended as the usable amount of energy generated by on-shore wind turbines and photovoltaic panels installed on building roofs in the available area, whilst accounting for technical specifications. Therefore, this study indicates the potential electricity produced by the existing technology that could be a starting point for future RES development plan.

The focus on the minor islands is not accidental, but it is determined by the necessity of new energy solutions as the current technologies used are characterized by high economic, environmental and social costs no longer sustainable. The Recovery and Resilience Plan has laid the foundations for accelerating the energy transition path of the minor islands, guaranteeing funds like never before. Photovoltaic and on-shore wind technologies are commercially ready and convenient to be employed and many projects are underway to make the most of the RES available locally.

The results obtained by this thesis contribute to corroborate the availability of the huge RES energy potential, which could replace the actual electricity production based on diesel generator. The energy transition is crucial for these communities and there are plans that ascertain its technical feasibility in the coming years. The are also barriers of different nature to overcome, as the technical problems in the dispatching service, or in the instant-by-instant balance between the demand and the supply of electricity. However, the main obstacle is the regulatory framework which often does not represent the current context and extremely limits the exploitation of RES. Therefore, it would be necessary to simplify and accelerate the rules governing the authorization processes of the plants necessary for the autonomy and sustainability of the islands, both in terms of landscape protection and economic and environmental development of the territories. This master's thesis is intended to be a contribution that aims to encourage the definition of the next interventions in the field of energy production from RES, as policy-makers heavily relies on the assessment of the implementable potential for the successful development of the energy transition.

5.1 Improvements and recommendation for future research

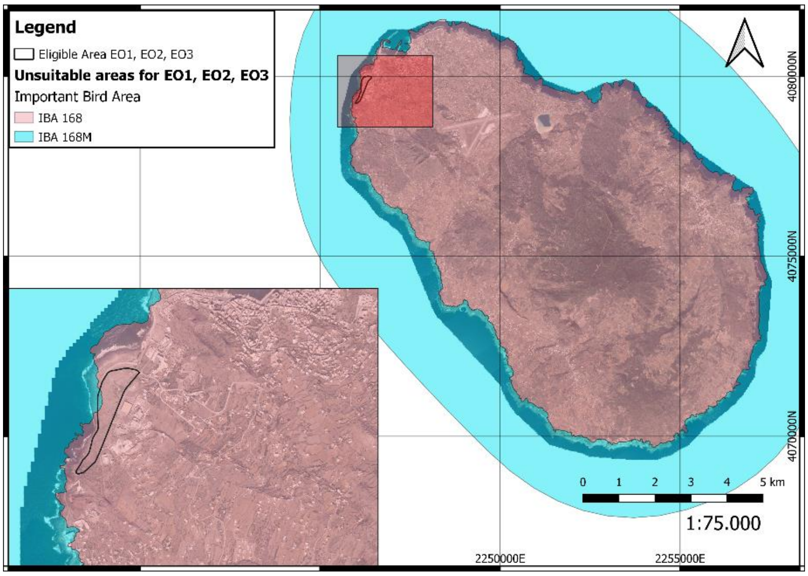
In this paragraph some improvements for future research work are outlined, together with some recommendations. The Italian minor islands are the target of the proposed methodology, so a further development would be to extend the analysis to the minor islands not covered by this study. The assessment process requires an initial analysis of the national, regional and municipal legislation that, as regards the renewable energy sector, is constantly evolving. Therefore, it is suggested to refer to the latest regulations in force before starting the process. All the data utilized are public and most of them can be downloaded directly from institutional geoportals, while some other have to be formally requested for study purpose. The data reliability is high, as well as the overall performance of the software employed; however, some improvements can be made.

The solar irradiance results, provided by the SEBE model, can be enhanced increasing the resolution of the DSM, from 2 meter to 1 meter, taking into account that this will increase the computational time. Moreover, additional DSMs including 3D vegetation structures can also be incorporated to generate more accurate shadow patterns [42]. For what concerns the wind technical potential simulation provided by WAsP can be improved utilizing local wind measurements to generate the actual observed wind climate and then the predicted wind climate, instead of referencing to the generalized wind climate of the Wind Global Atlas.

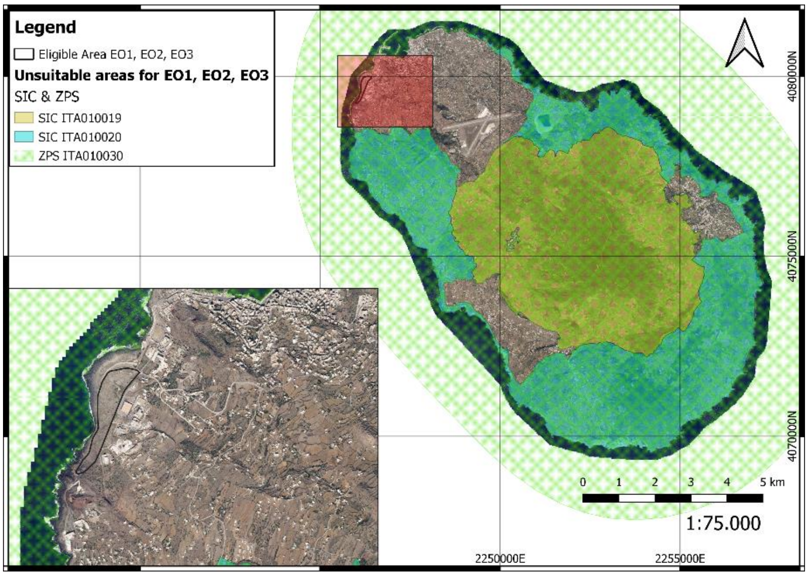
This work could evolve into a larger study adding the estimation of the solar thermal energy technical potential by means of the same approach utilized for the photovoltaic technical potential assessment. Furthermore, it could be also possible to perform the technical potential estimation of the photovoltaic ground-mounted configuration. For this purpose, it is possible to make use of the identification of suitable areas method introduced in the wind technical potential assessment, with a proper normative analysis; then, the solar irradiance and the technical potential can be estimated as presented in the photovoltaic potential assessment. Therefore, future work should give a more complete overview of the configurations and technologies for the solar energy exploitation.

Appendix: Cartography

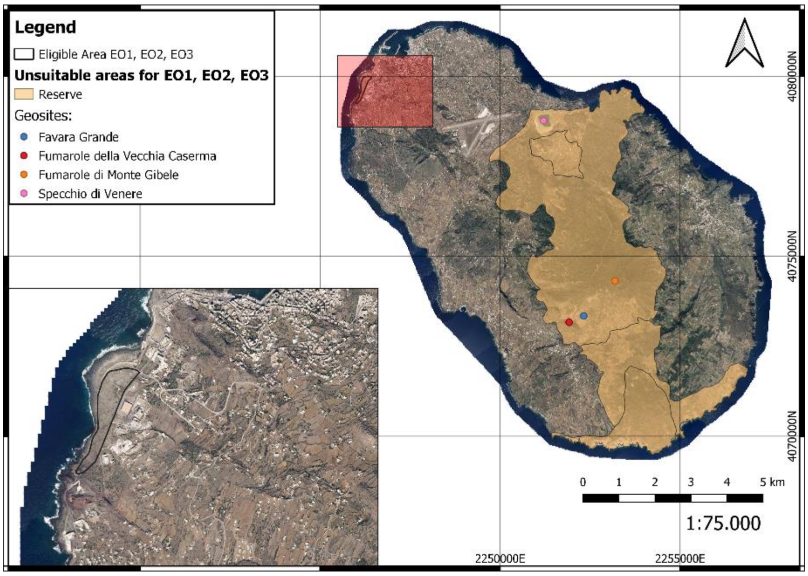
Pantelleria



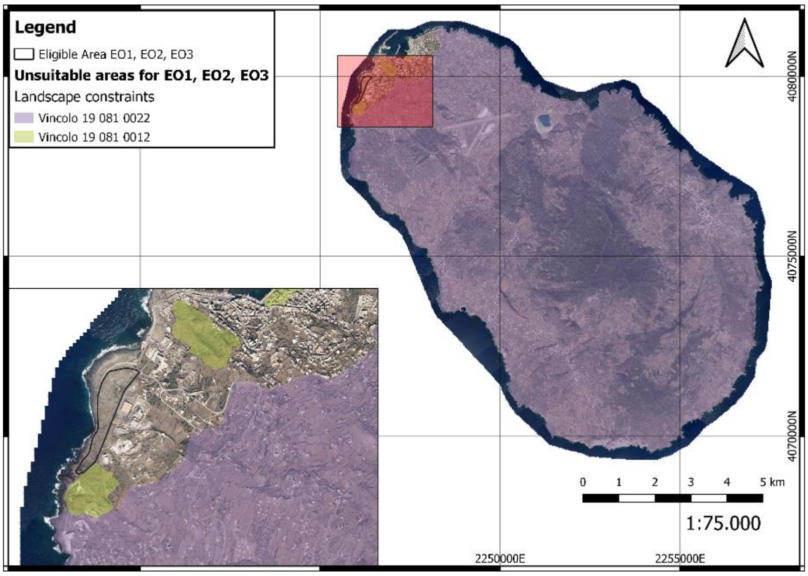
Map 1: Important Bird Area | Pantelleria



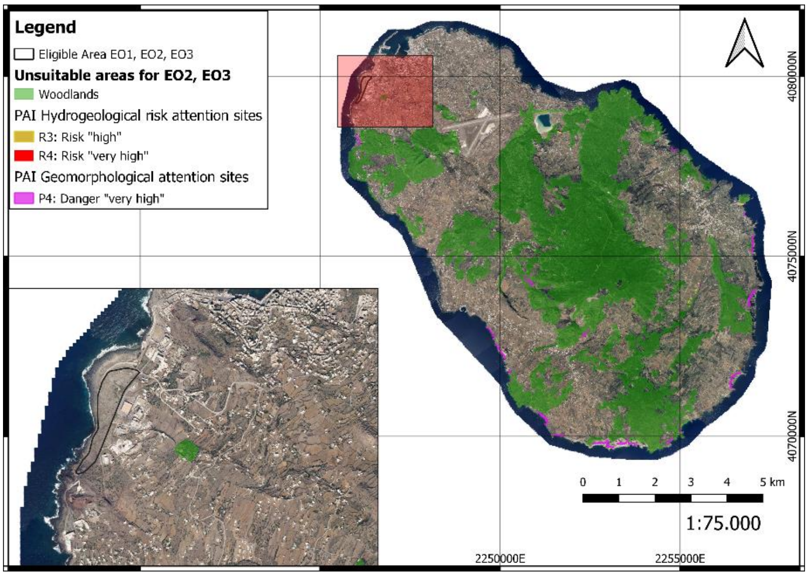
Map 2: SIC & ZPS zones | Pantelleria



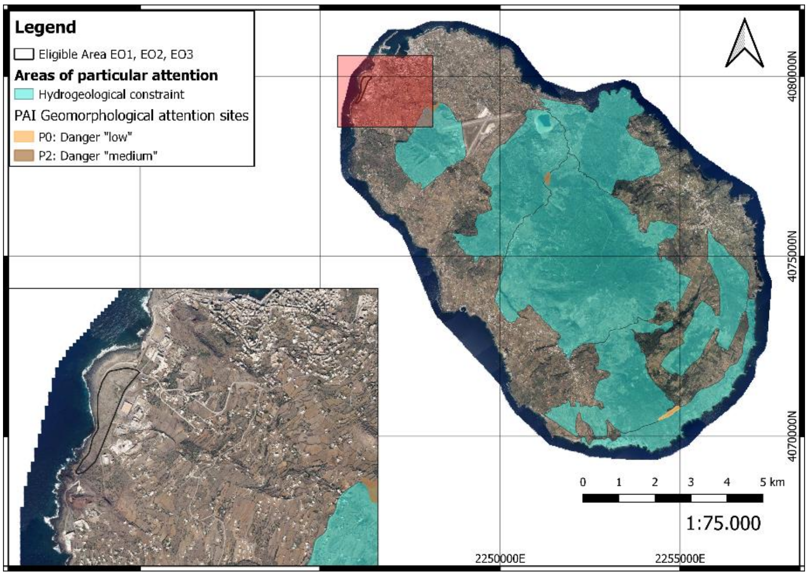
Map 3: Reserve & Geosites | Pantelleria



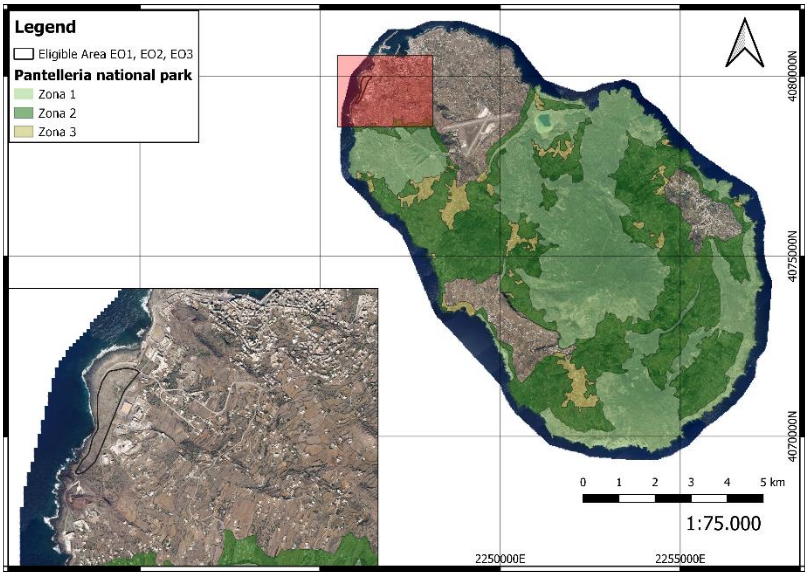
Map 4: Landscape constraints | Pantelleria



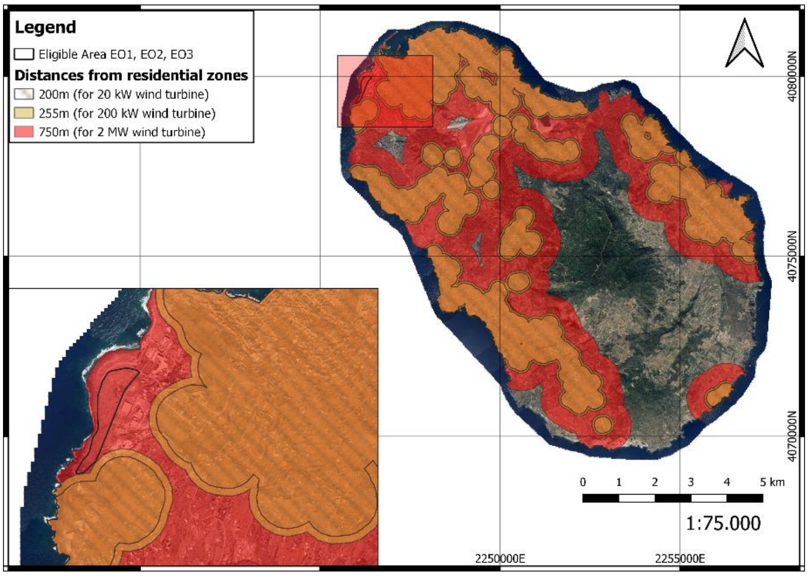
Map 5: Unsuitable areas for EO2, EO3 | Pantelleria



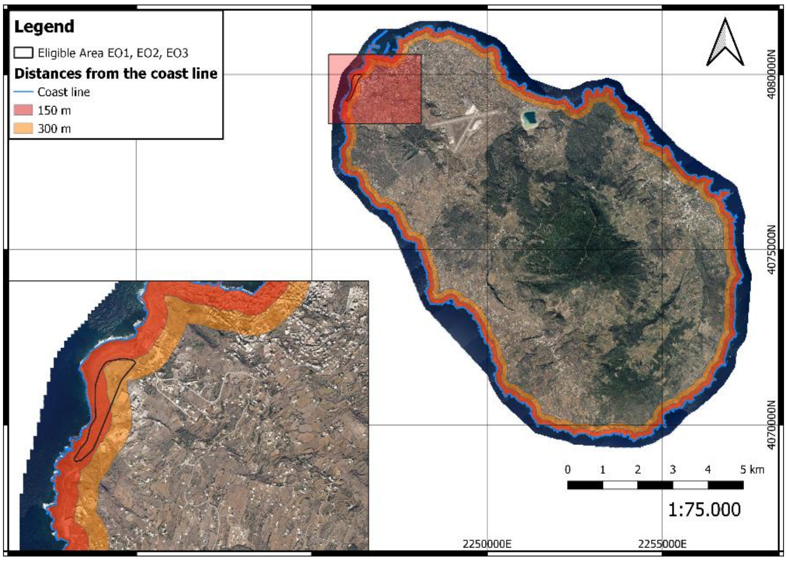
Map 6: Areas of particular attention | Pantelleria



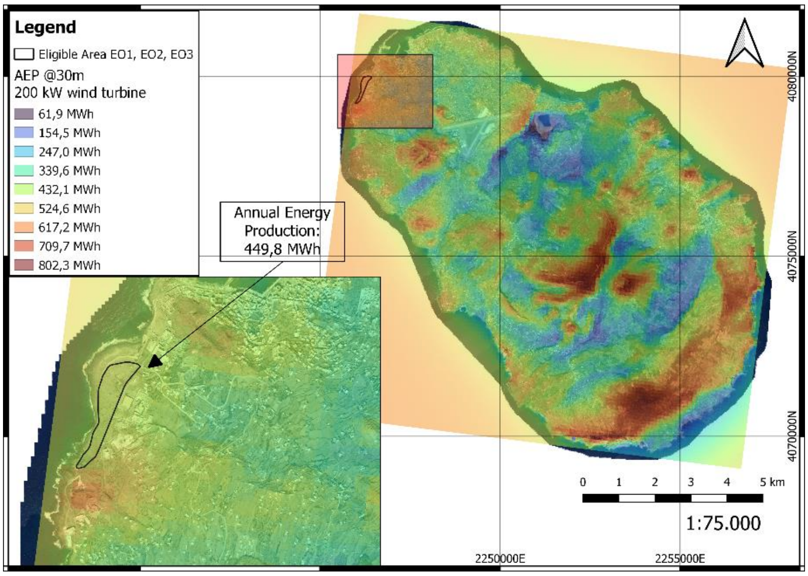
Map 7: National Park | Pantelleria



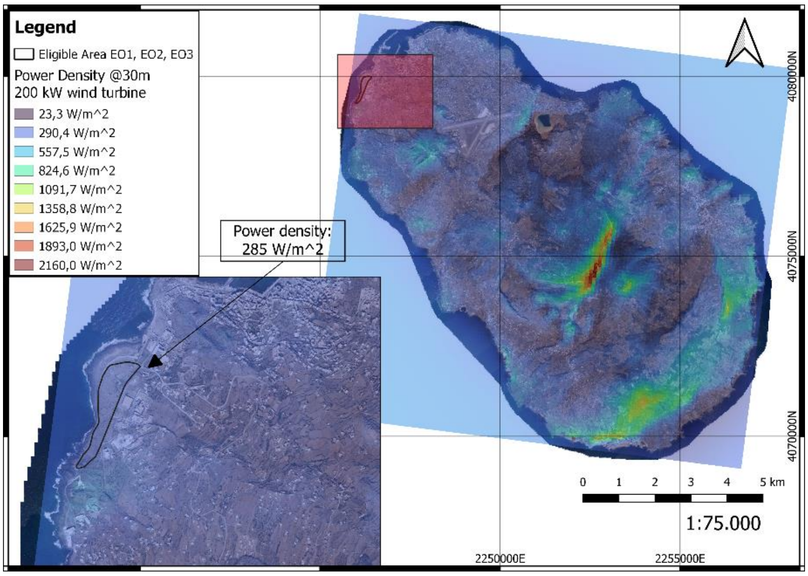
Map 8: Distances from residential zones | Pantelleria



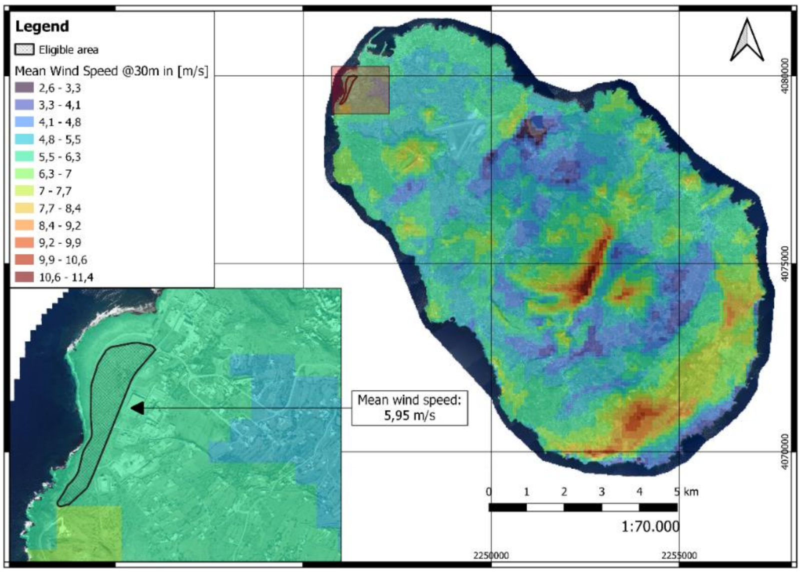
Map 9: Distances from coastline | Pantelleria



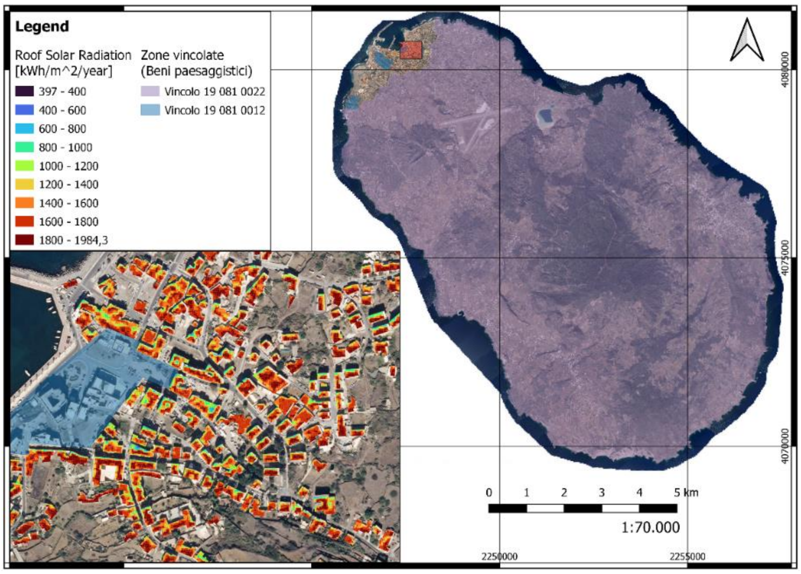
Map 10: Annual energy production 200 kW wind turbine @30m a.g.l. | Pantelleria



Map 11: Power density @30m a.g.l. | Pantelleria

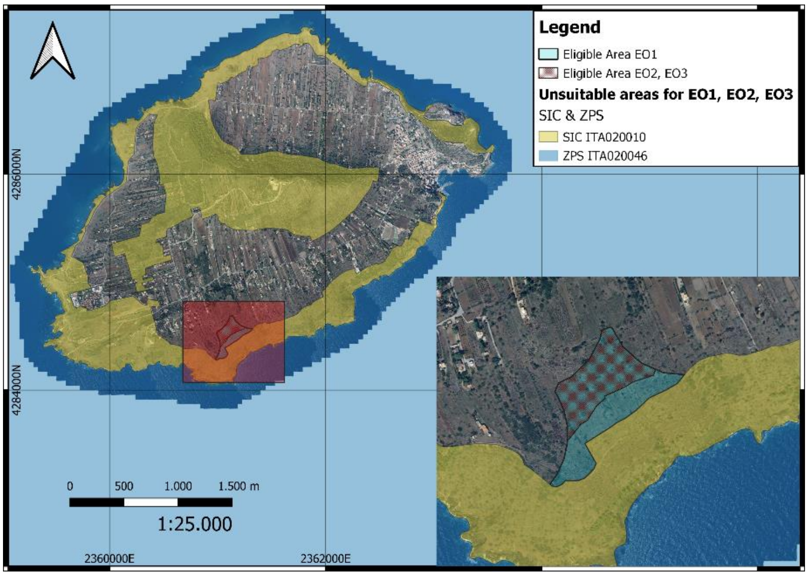


Map 12: Mean wind speed @30m a.g.l. | Pantelleria

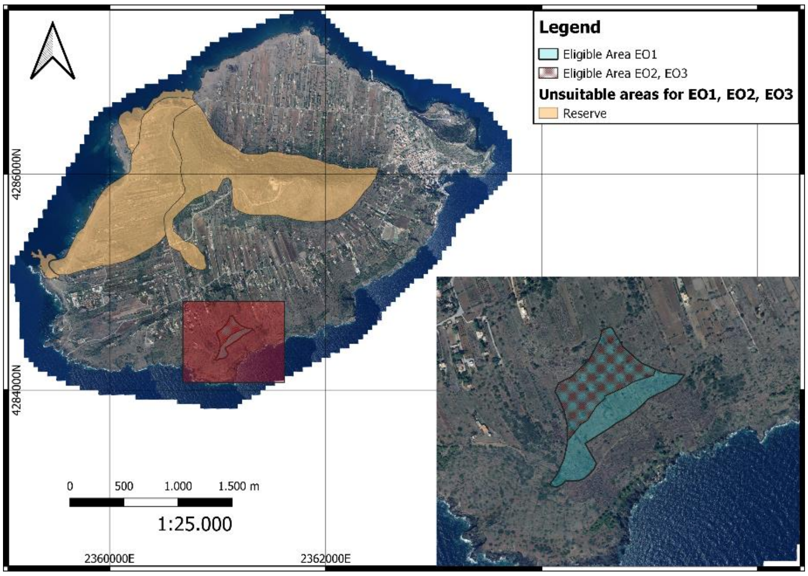


Map 13: Solar radiation on urban centre roofs and restrictions | Pantelleria

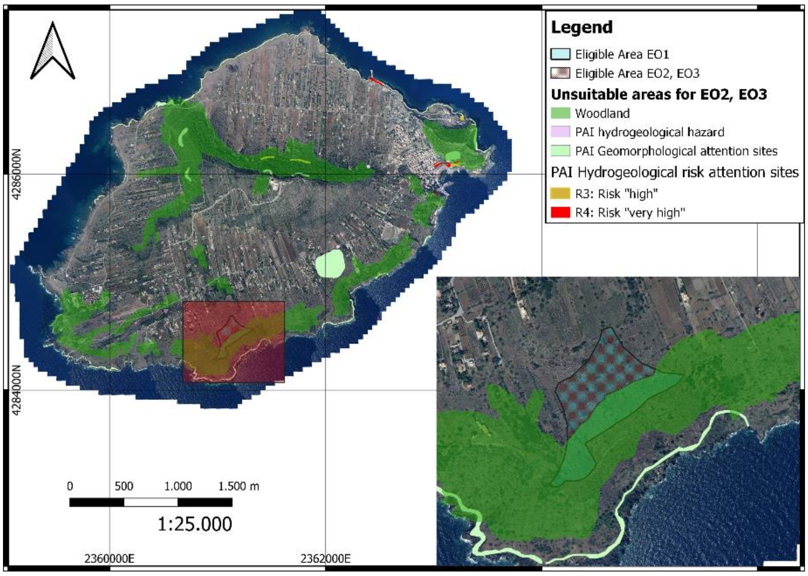
Ustica



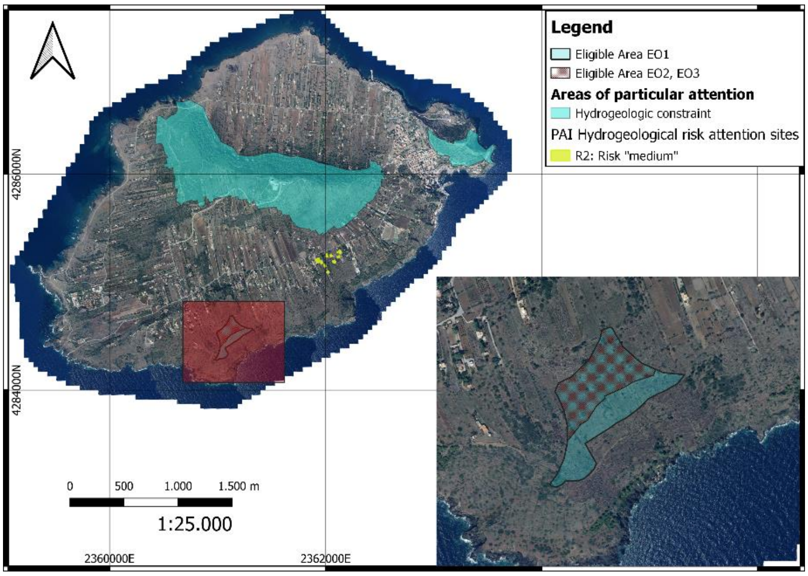
Map 14: SIC & ZPS zones | Ustica



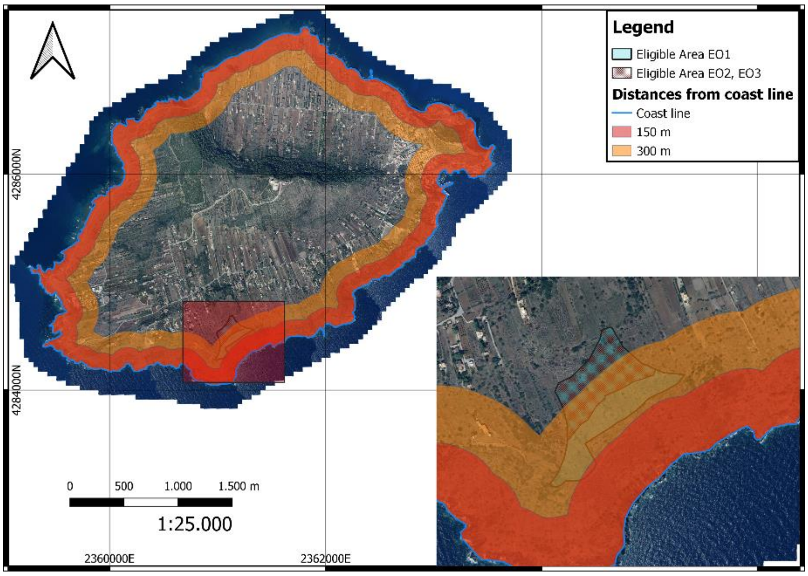
Map 15: Reserve | Ustica



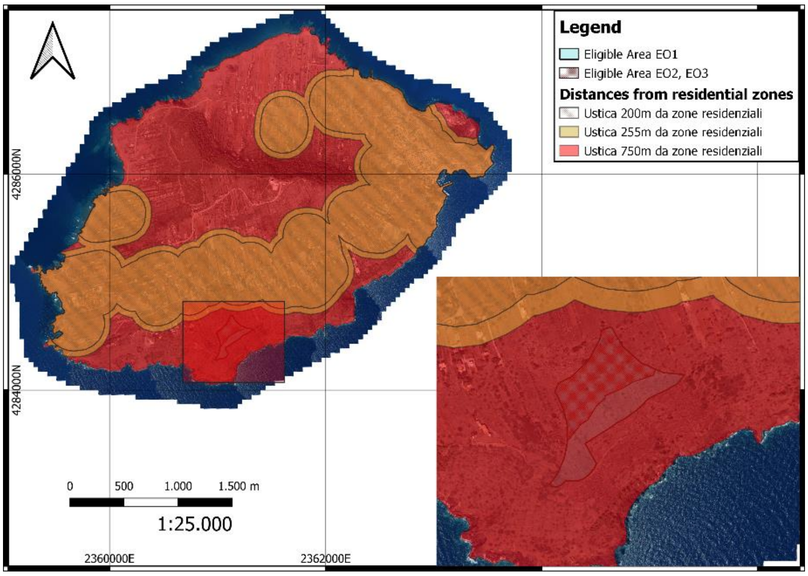
Map 16: Unsuitable areas for EO2, EO3 | Ustica



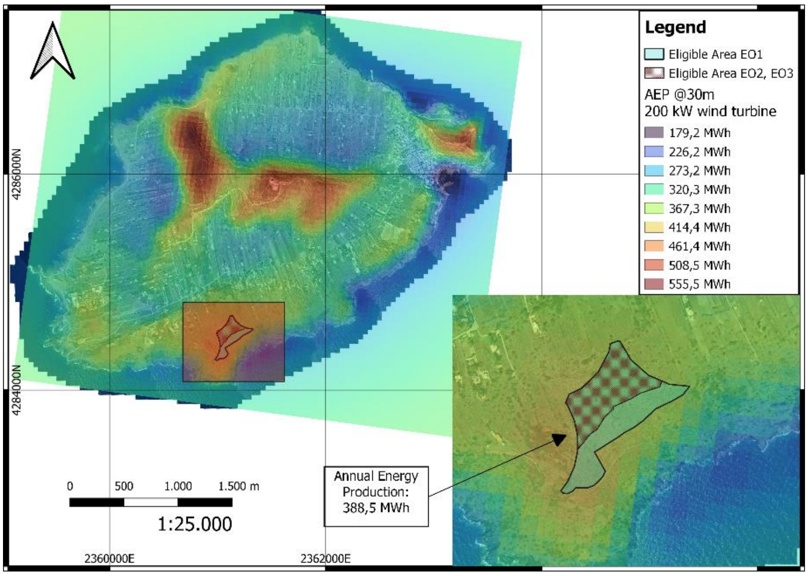
Map 17: Areas of particular attention | Ustica



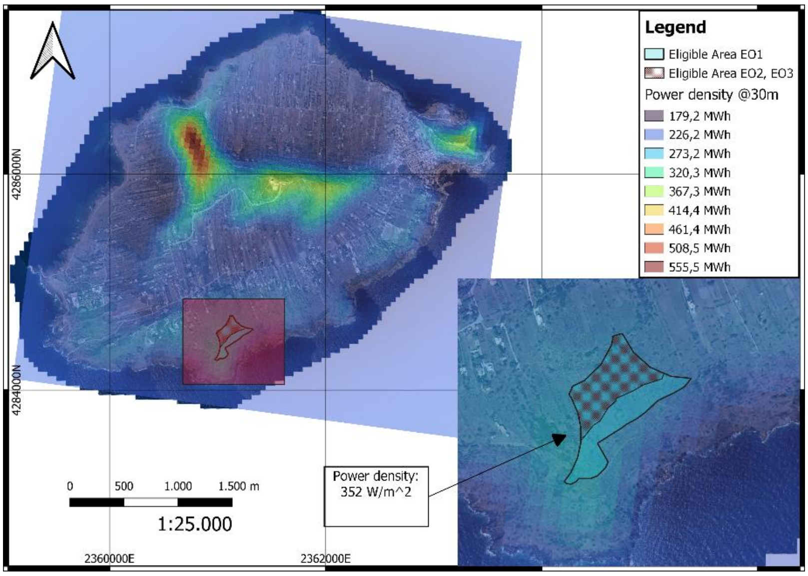
Map 18: Distances from coastline | Ustica



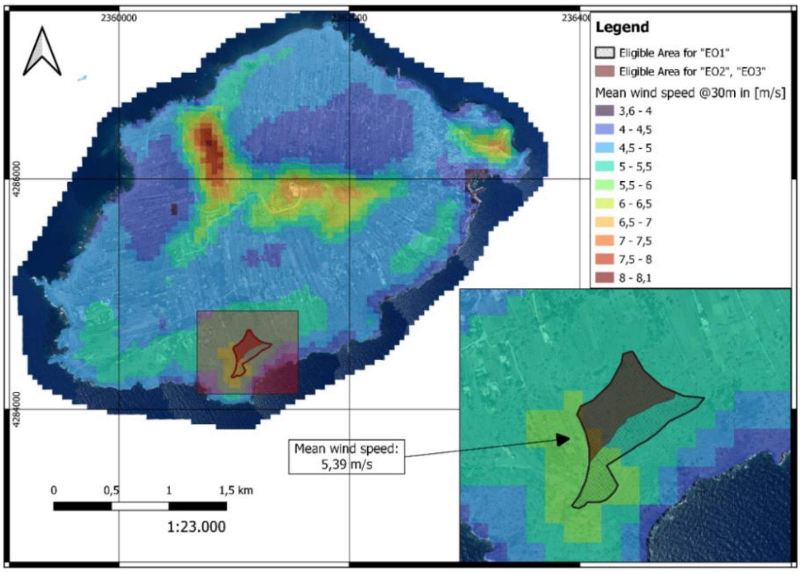
Map 19: Distances from residential zones | Ustica



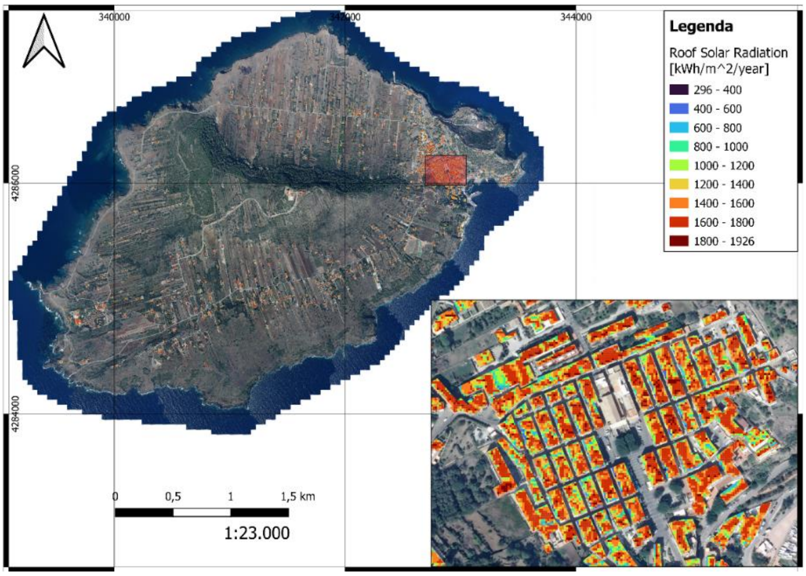
Map 20: Annual energy production 200 kW wind turbine @30m a.g.l. | Ustica



Map 21: Power density @30m a.g.l. | Ustica



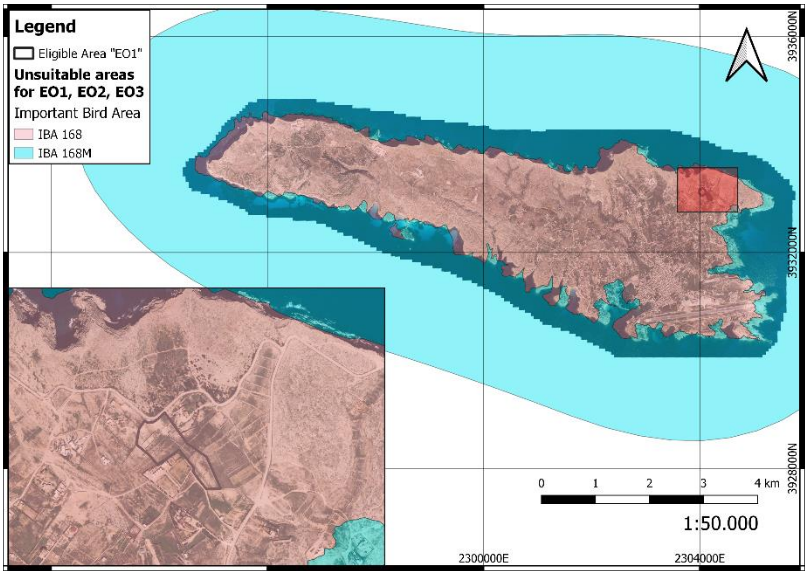
Map 22: Mean wind speed @30m a.g.l. | Ustica



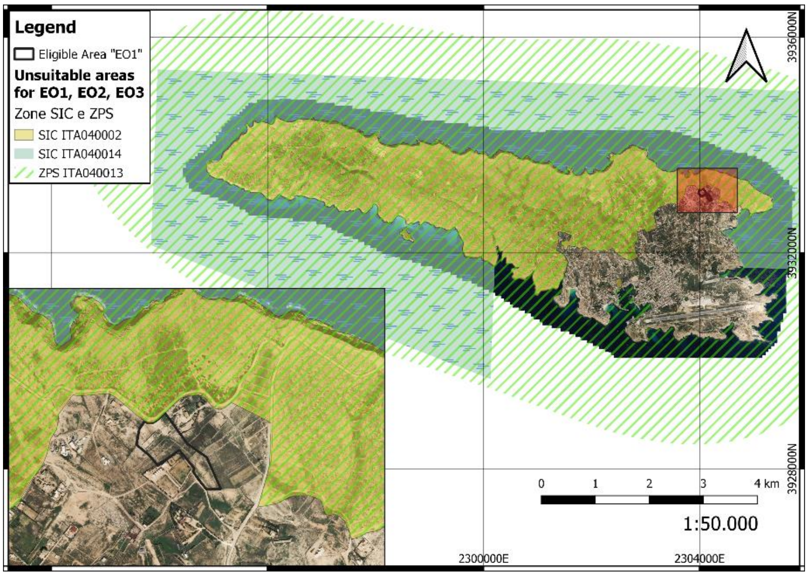
Map 23: Solar radiation on suitable roofs | Ustica

Pelagie islands

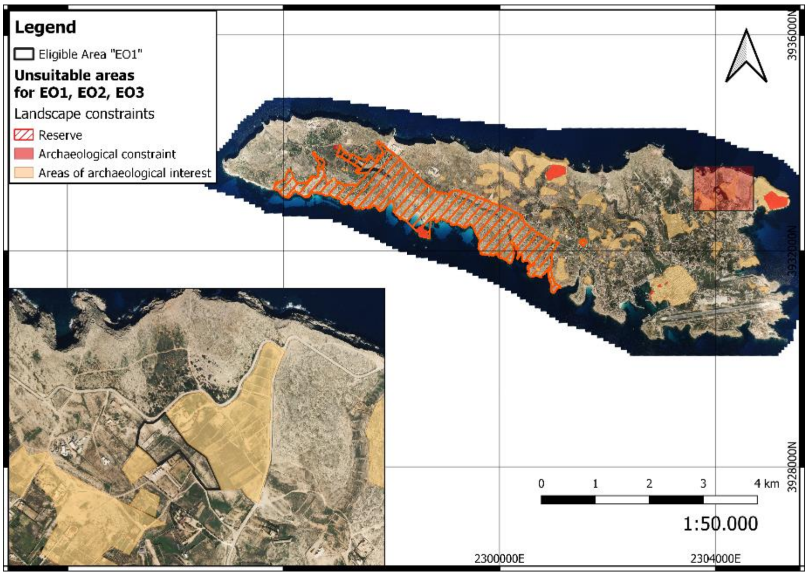
Lampedusa



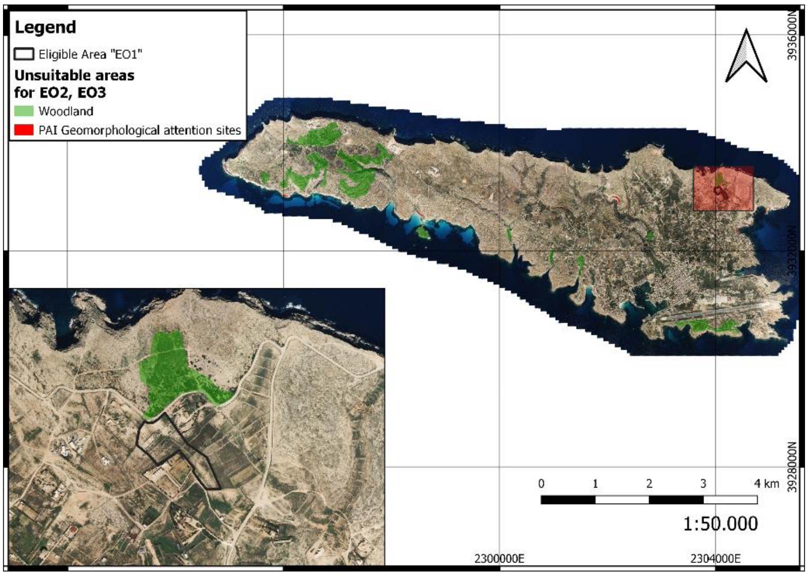
Map 24: Important Bird Area | Lampedusa



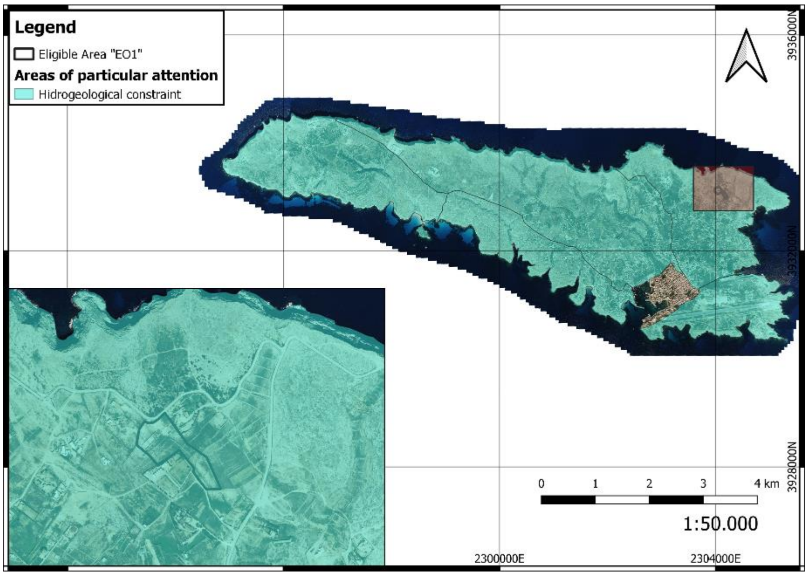
Map 25: SIC & ZPS zones | Lampedusa



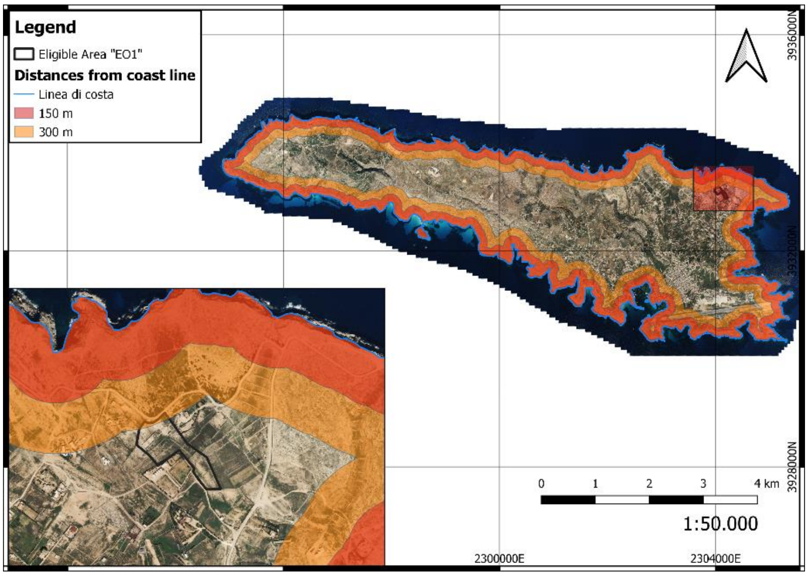
Map 26: Landscape constraints | Lampedusa



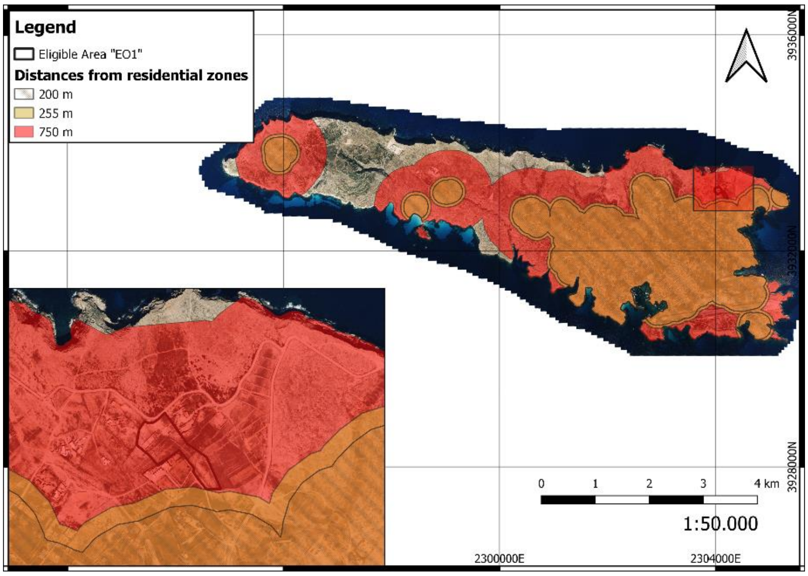
Map 27: Unsuitable areas for EO2, EO3 | Lampedusa



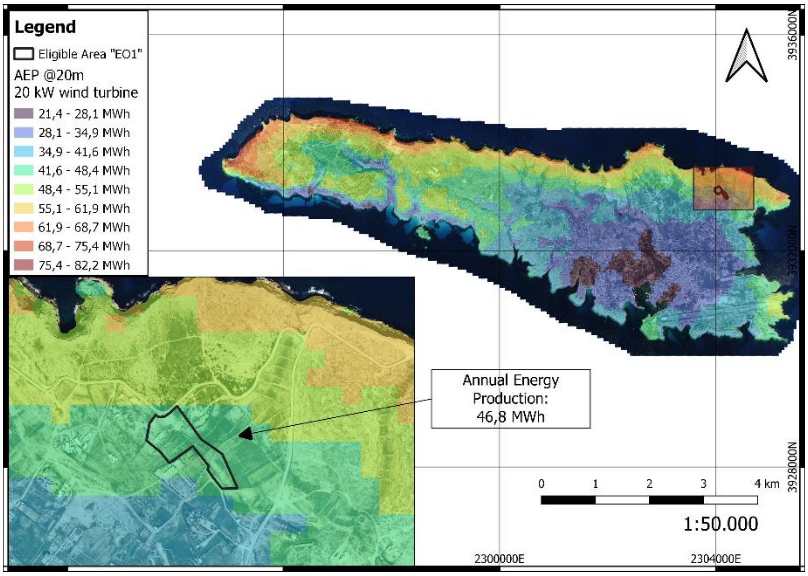
Map 28: Areas of particular attention | Lampedusa



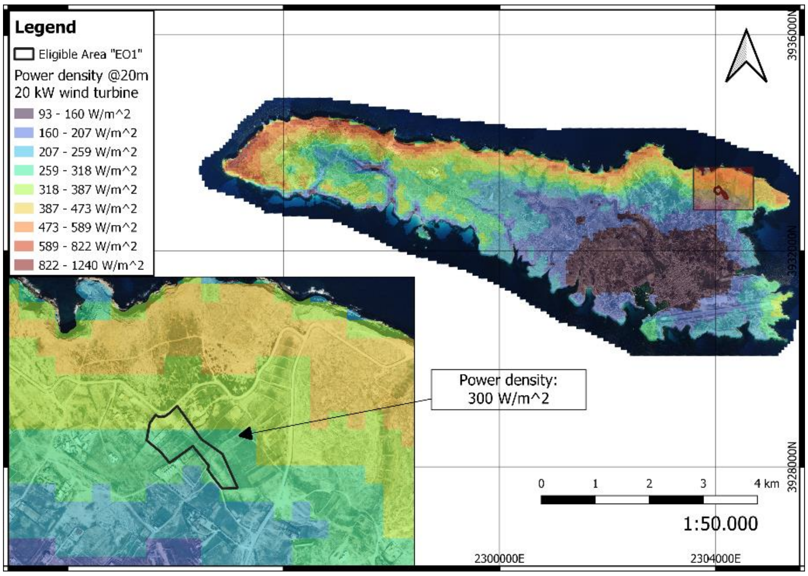
Map 29: Distances from coastline



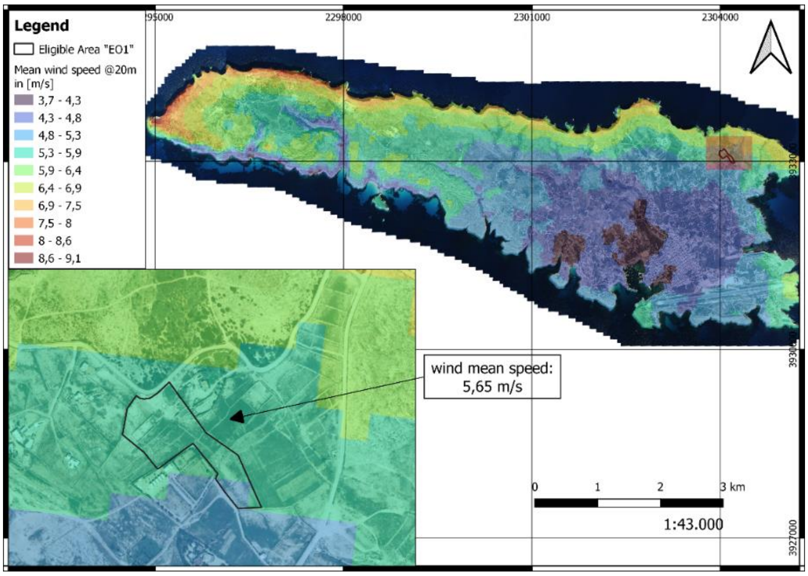
Map 30: Distances from residential zones



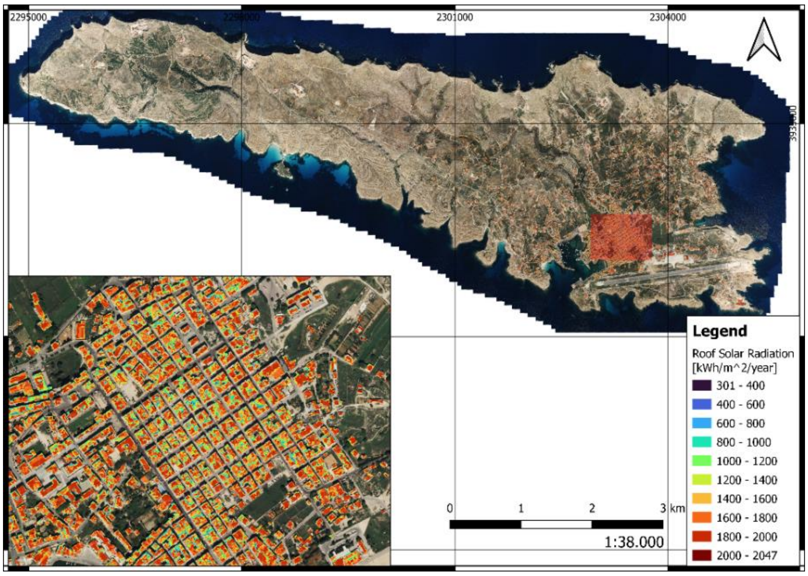
Map 31: Annual energy production 20 kW wind turbine @20m a.g.l. | Lampedusa



Map 32: Power density @20m a.g.l. | Lampedusa

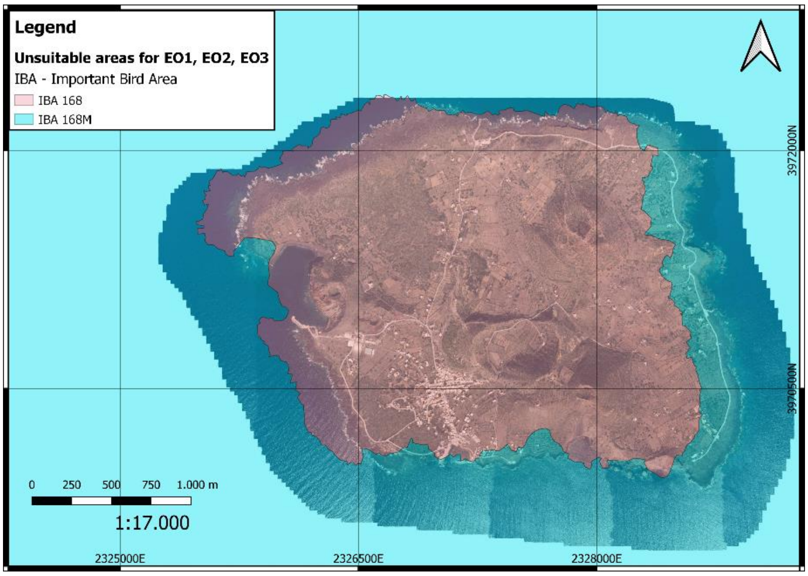


Map 33: Mean wind speed @20m a.g.l. | Lampedusa

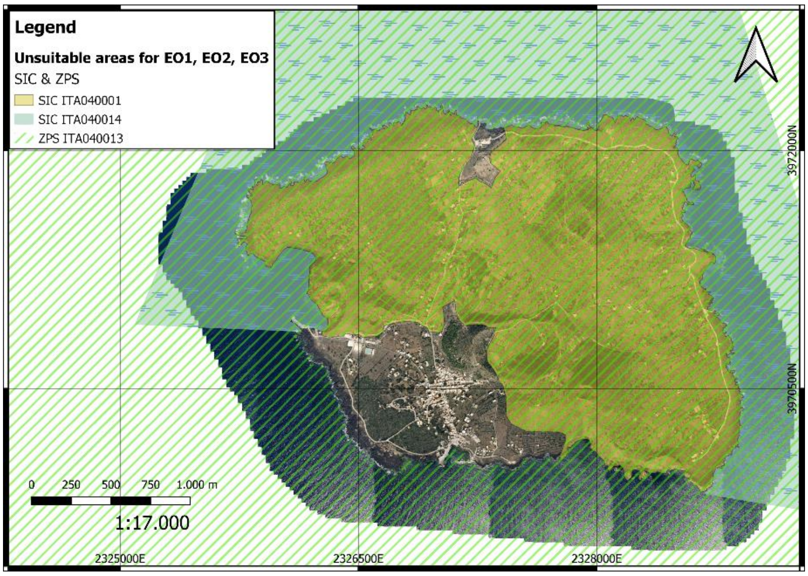


Map 34: Solar radiation on building roofs | Lampedusa

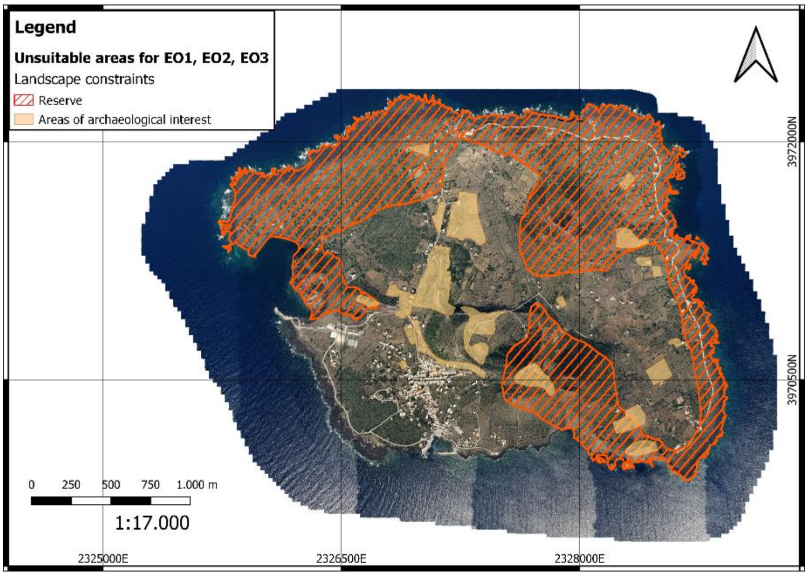
Linosa



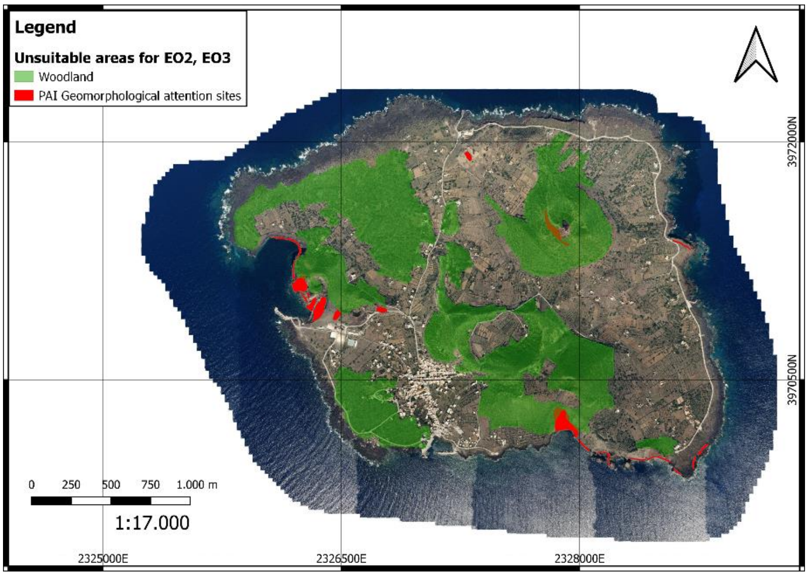
Map 35: Important Bird Area | Linosa



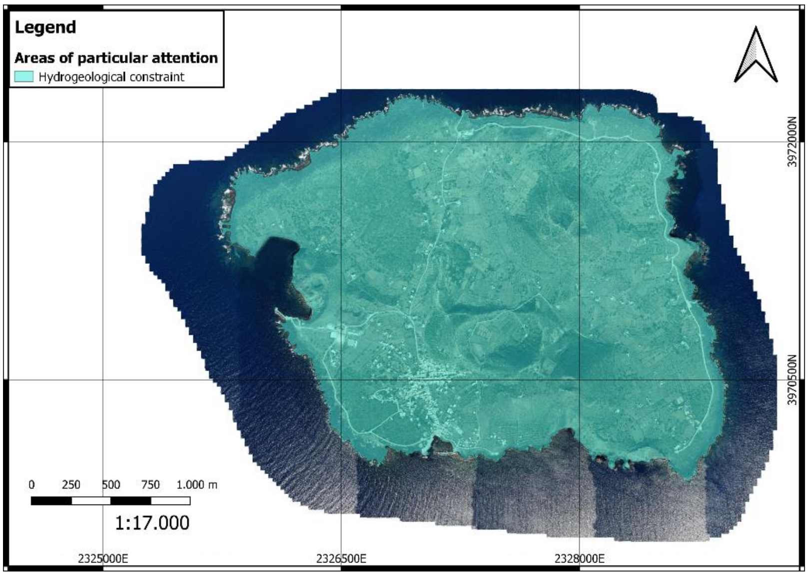
Map 36: SIC & ZPS zones | Linosa



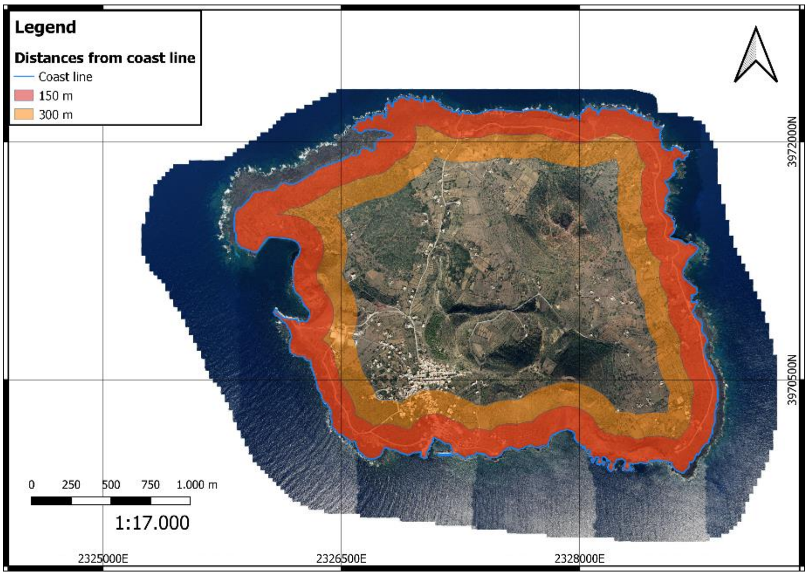
Map 37: Landscape constraints | Linosa



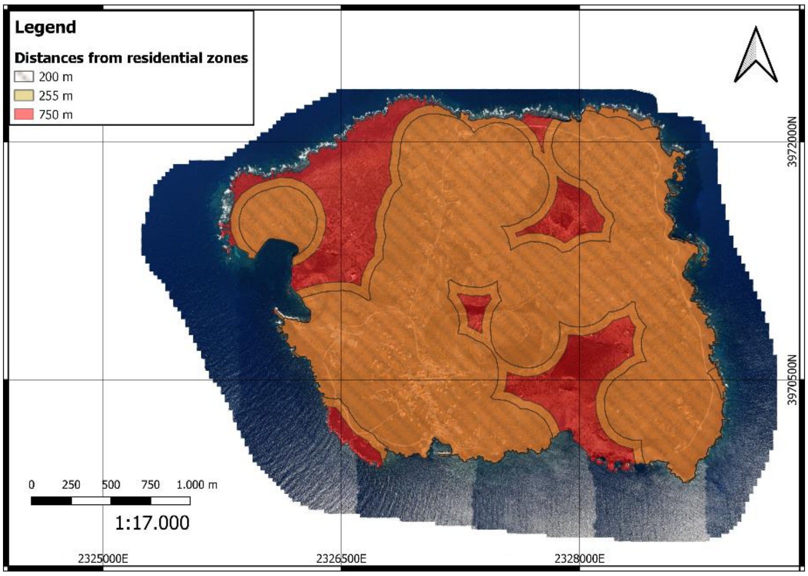
Map 38: Unsuitable areas for EO2, EO3 | Linosa



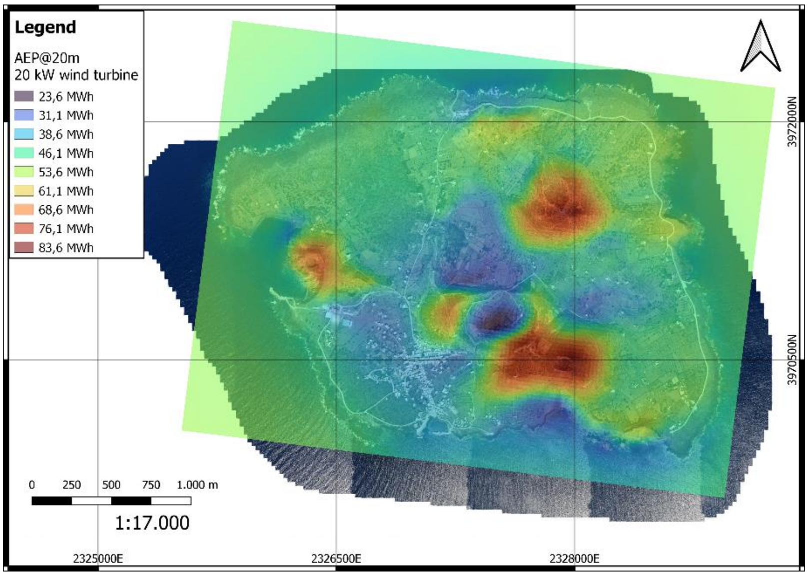
Map 39: Areas of particular attention | Linosa



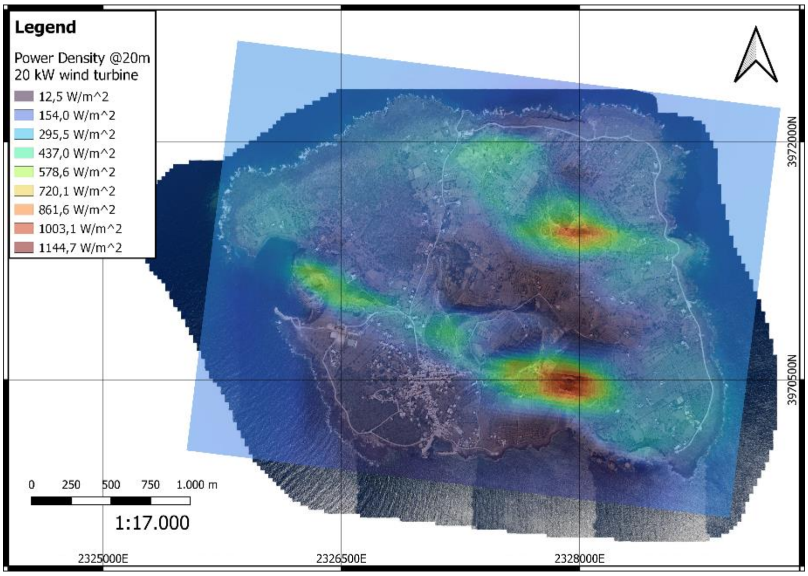
Map 40: Distances from coastline | Linosa



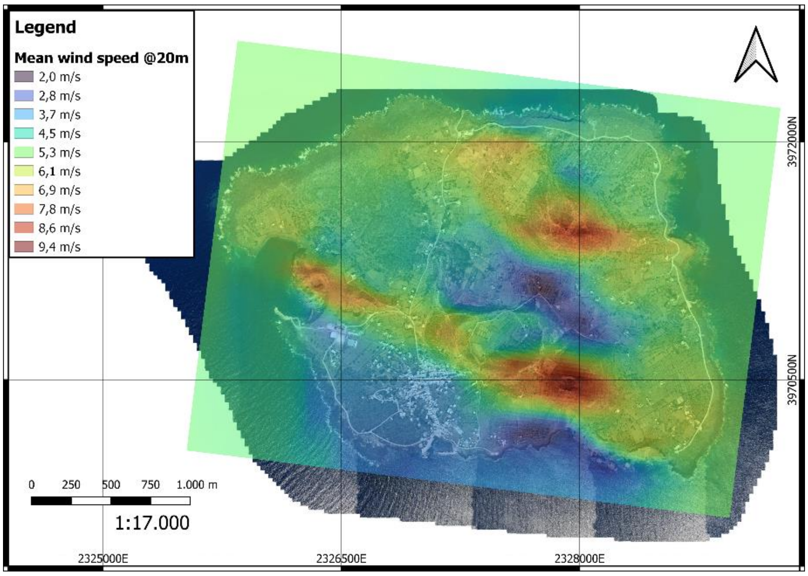
Map 41: Distances from residential zones | Linosa



Map 42: Annual energy production 20 kW wind turbine @20m a.g.l. | Linosa



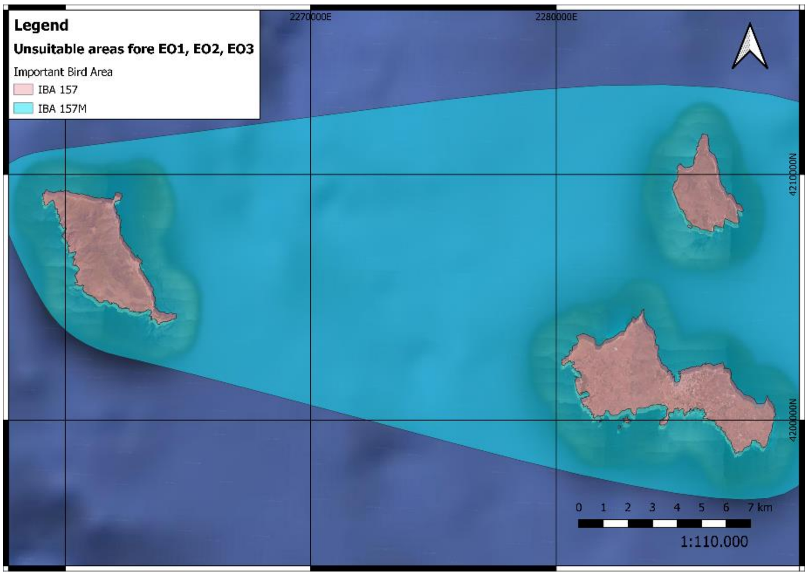
Map 43: Power density @20 m | Linosa



Map 44: Mean wind speed @20m | Linosa

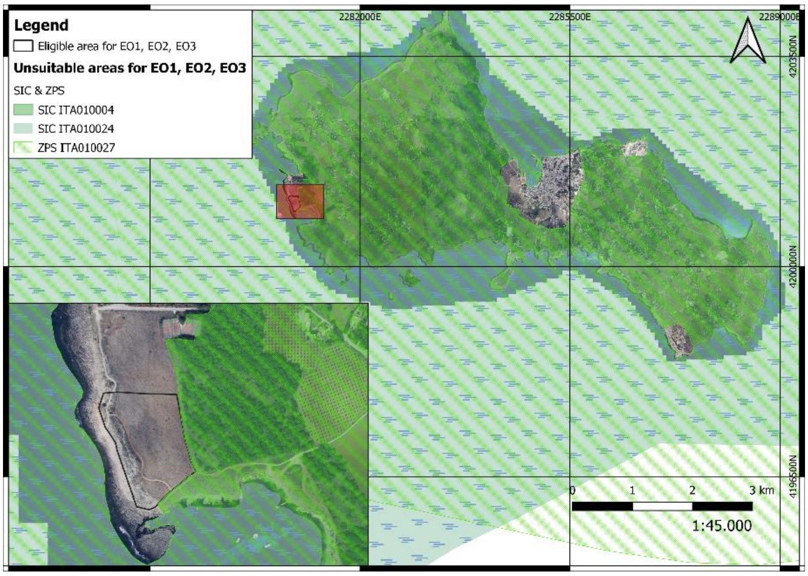
Map 45: Solar radiation on building roofs | Linosa

Egadi islands

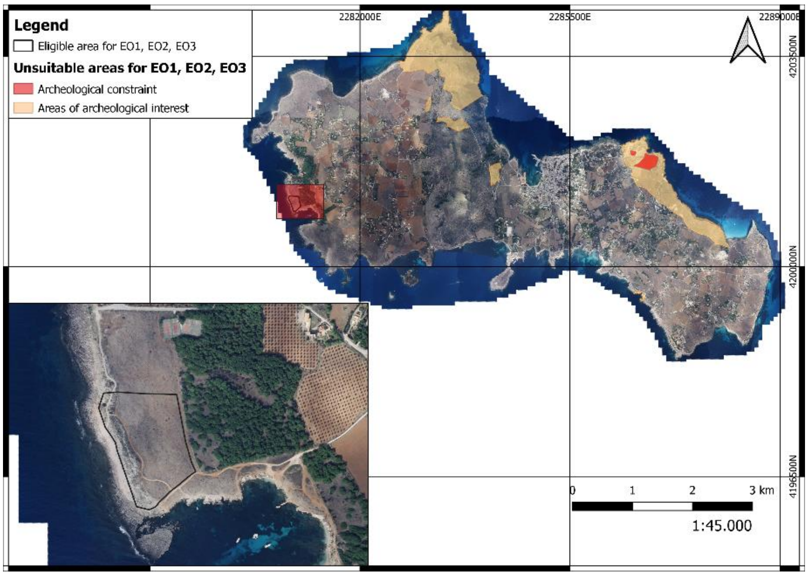


Map 46: Important Bird Area | Egadi islands

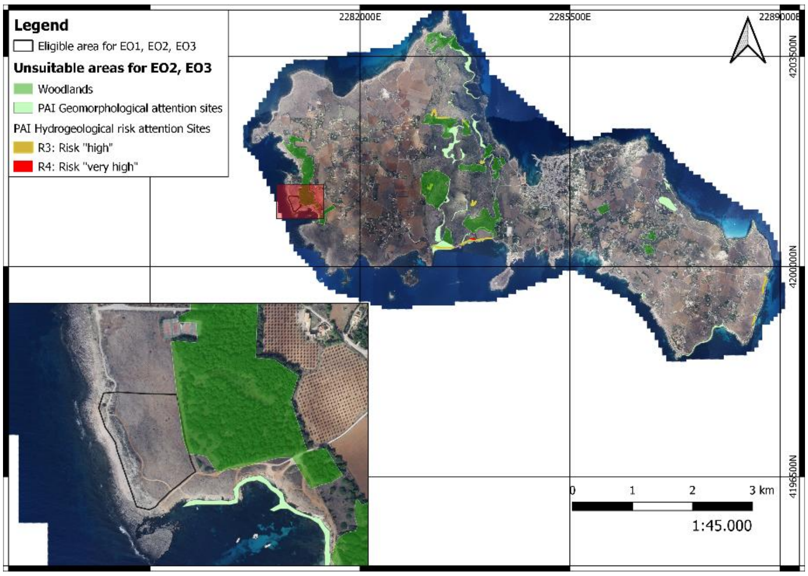
Favignana



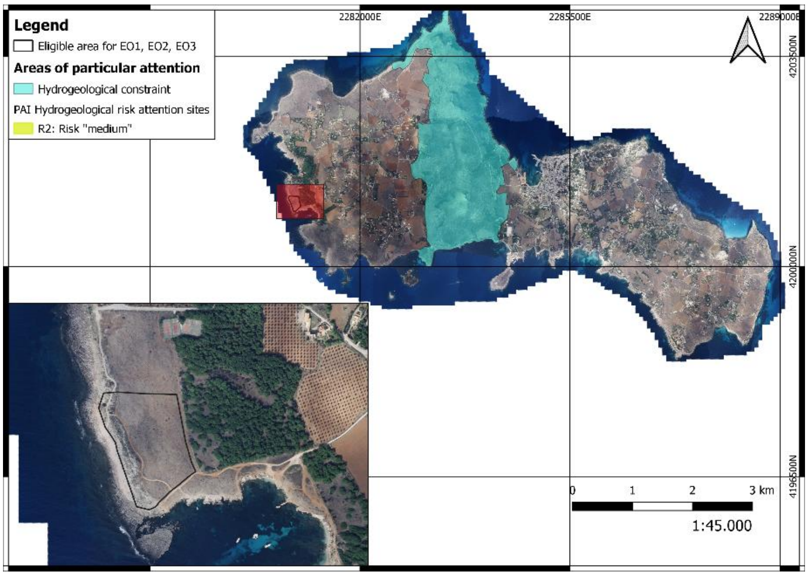
Map 47: SIC & ZPS zones | Favignana



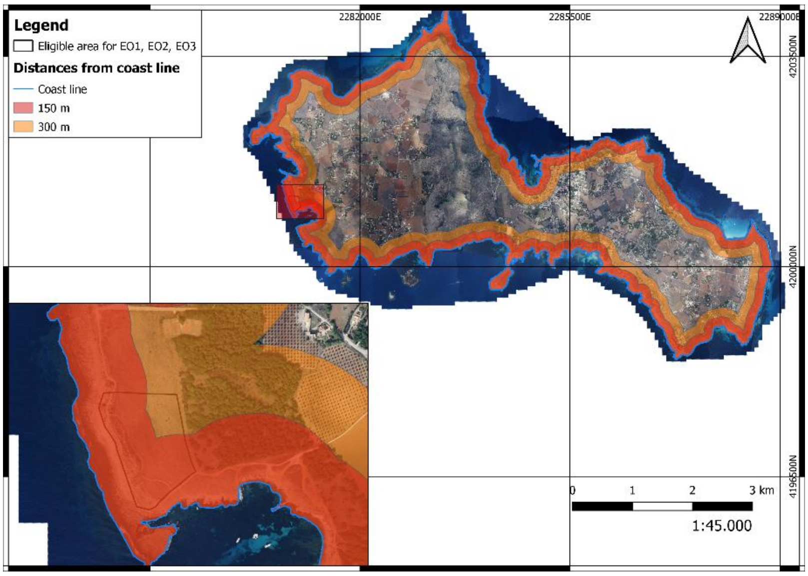
Map 48: Landscape constraints | Favignana



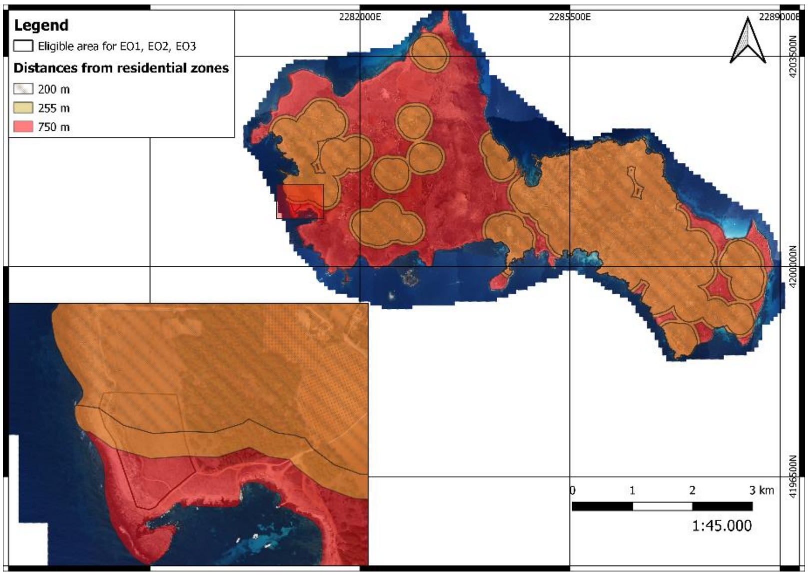
Map 49: Unsuitable areas for EO2, EO3 | Favignana



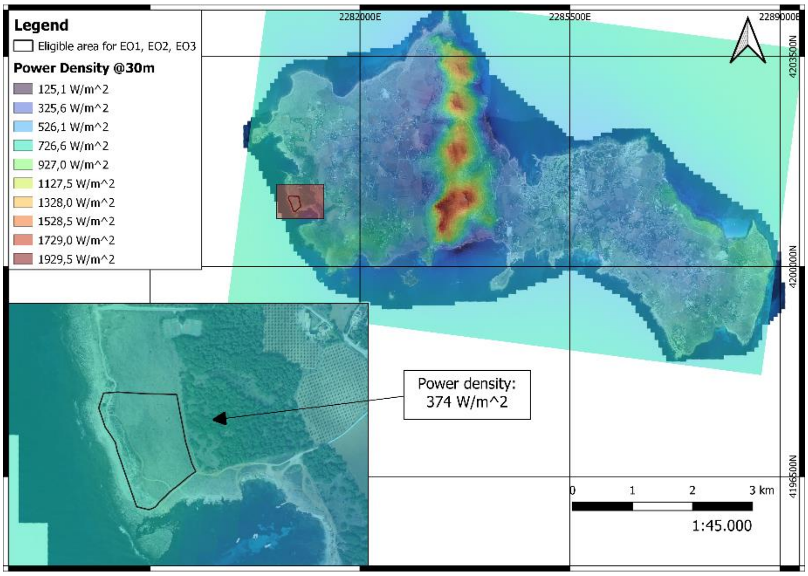
Map 50: Areas of particular attention | Favignana



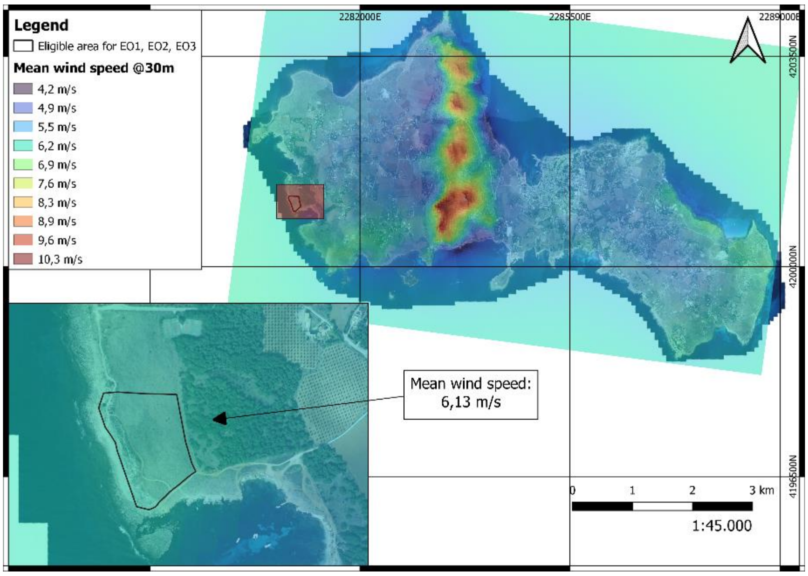
Map 51: Distances from coastline | Favignana



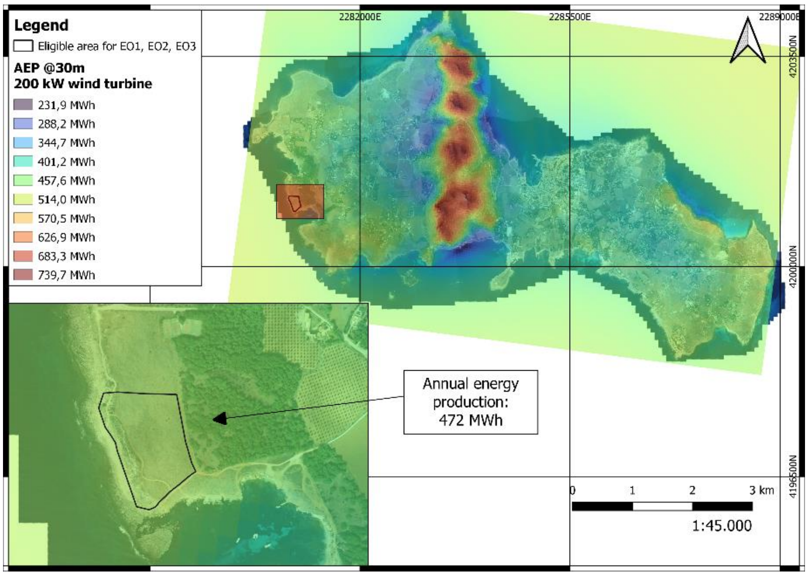
Map 52: Distances from residential zones | Favignana



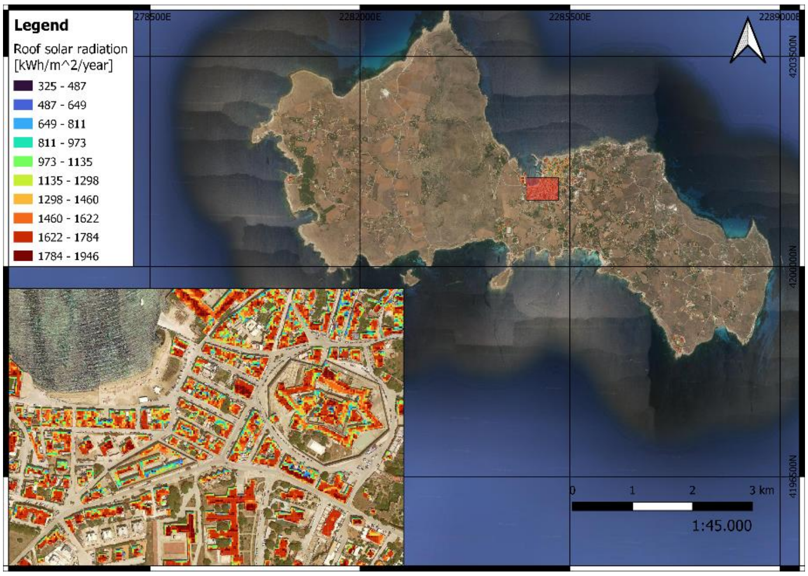
Map 53: Power density @30 a.g.l. | Favignana



Map 54: Mean wind speed @30m a.g.l. | Favignana

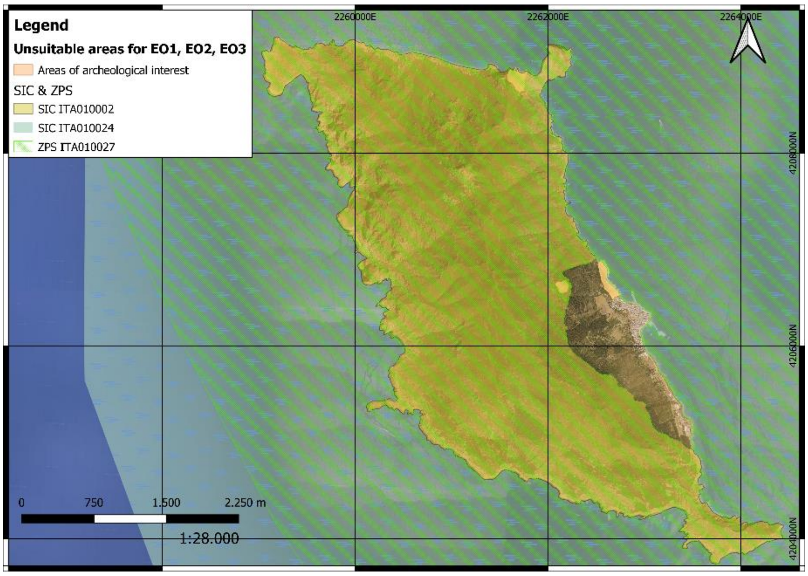


Map 55: Annual energy production 200 kW wind turbine @30m a.g.l. | Favignana

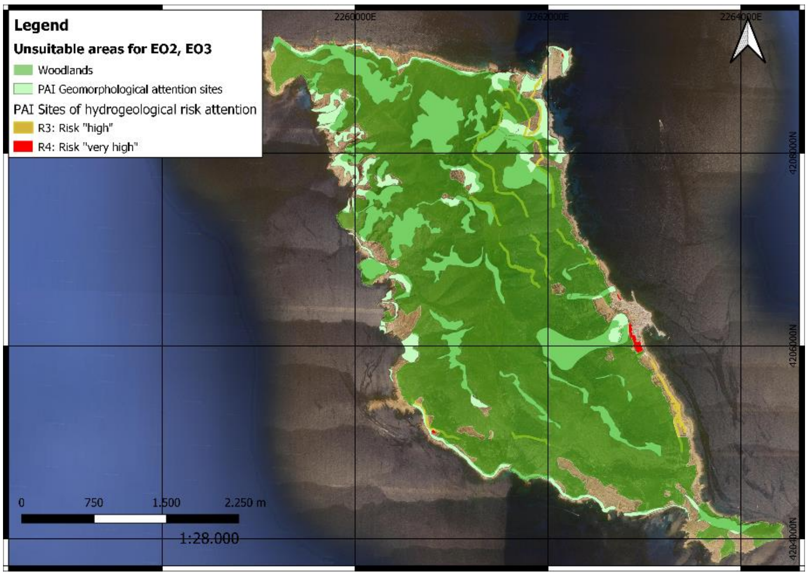


Map 56: Solar radiation on building roofs | Favignana

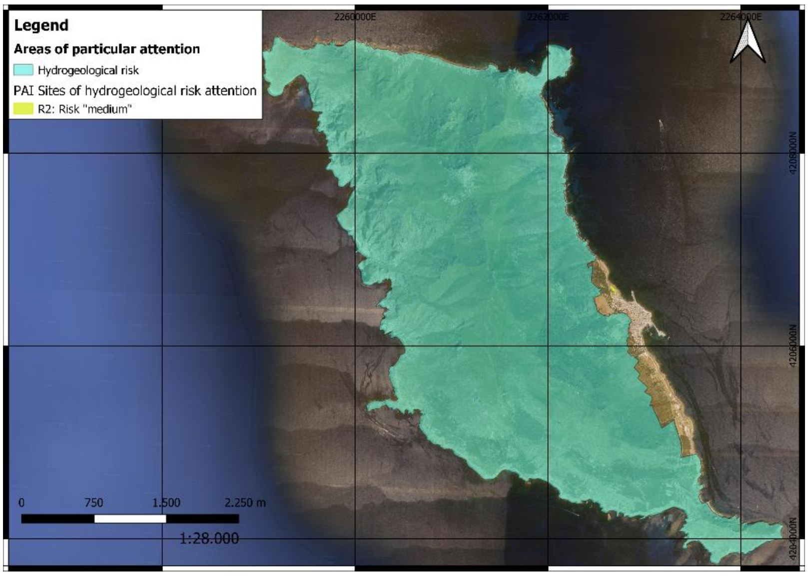
Marettimo



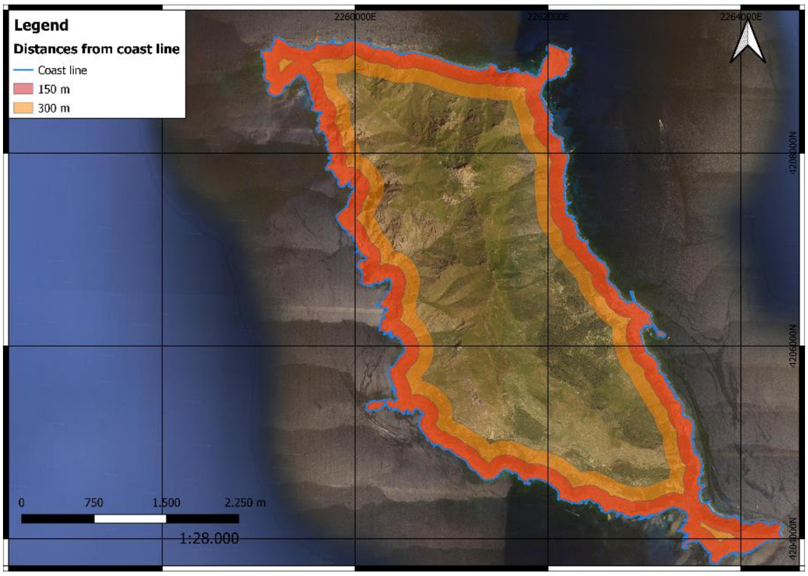
Map 57: Unsuitable areas for EO1, EO2, EO3 | Marettimo



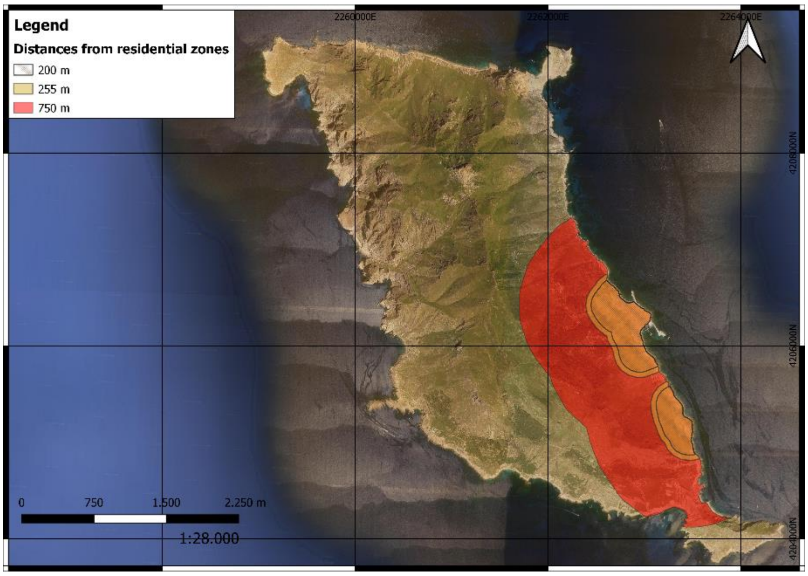
Map 58: Unsuitable areas for EO2, EO3 | Marettimo



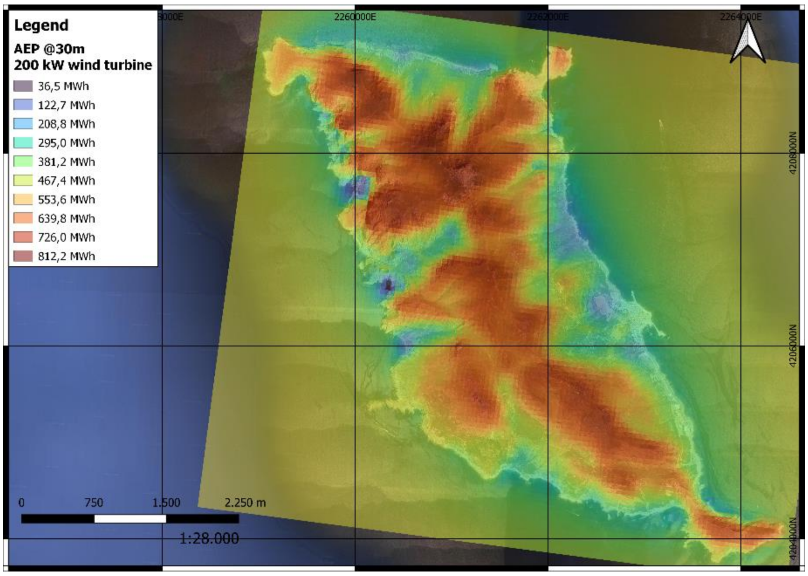
Map 59: Areas of particular attention | Marettimo



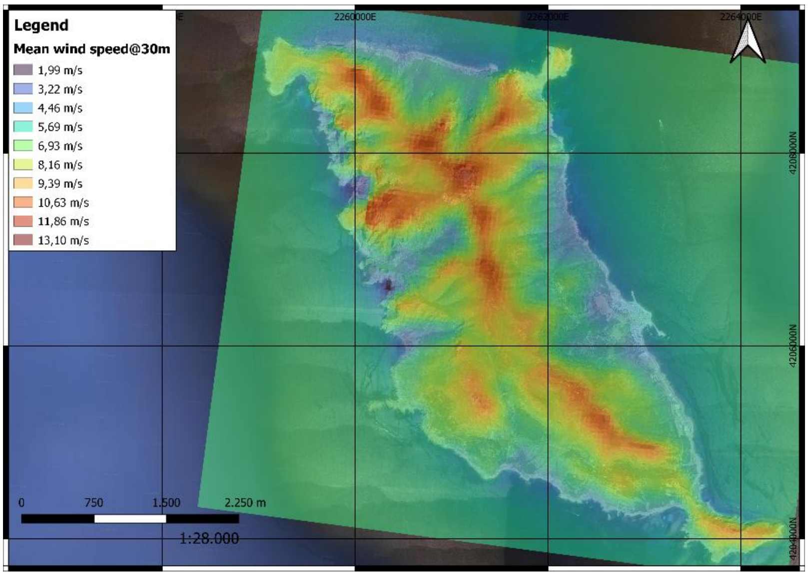
Map 60: Distances from coastline | Marettimo



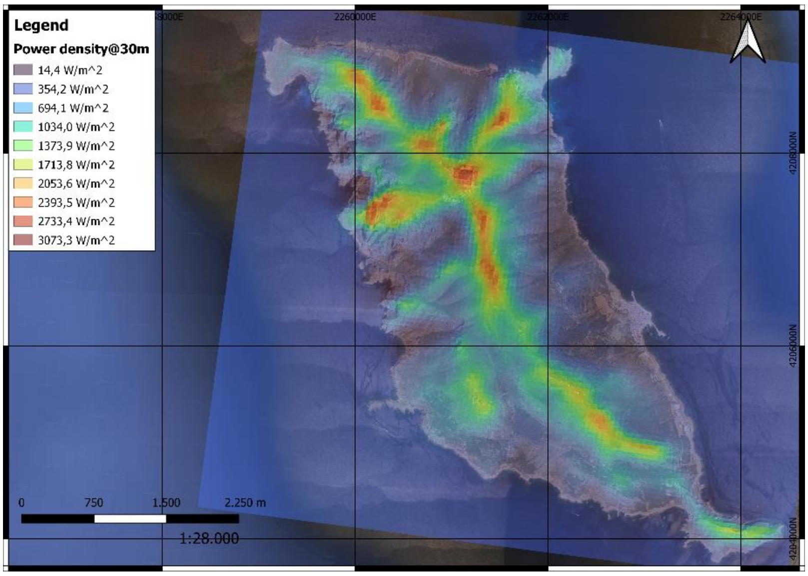
Map 61: Distance from residential zones | Marettimo



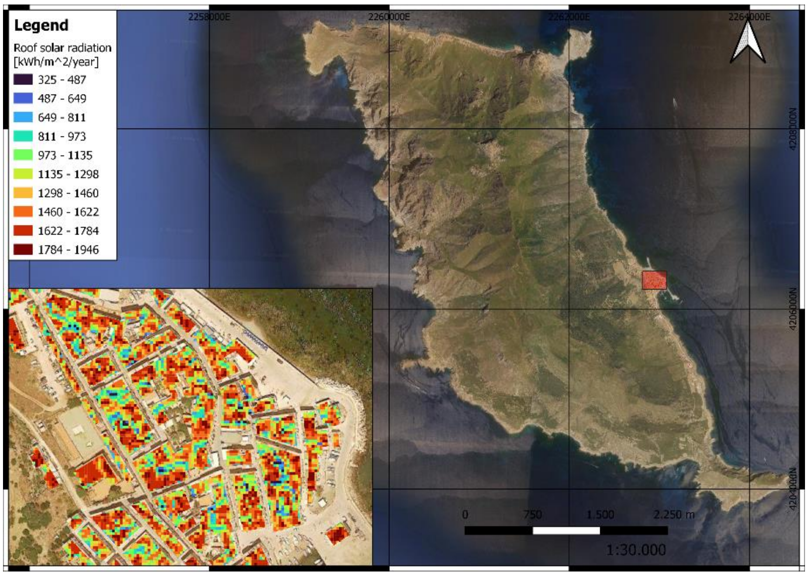
Map 62: Annual energy production 200 kW wind turbine @30m a.g.l. | Marettimo



Map 63: Mean wind speed @30m a.g.l. | Marettimo

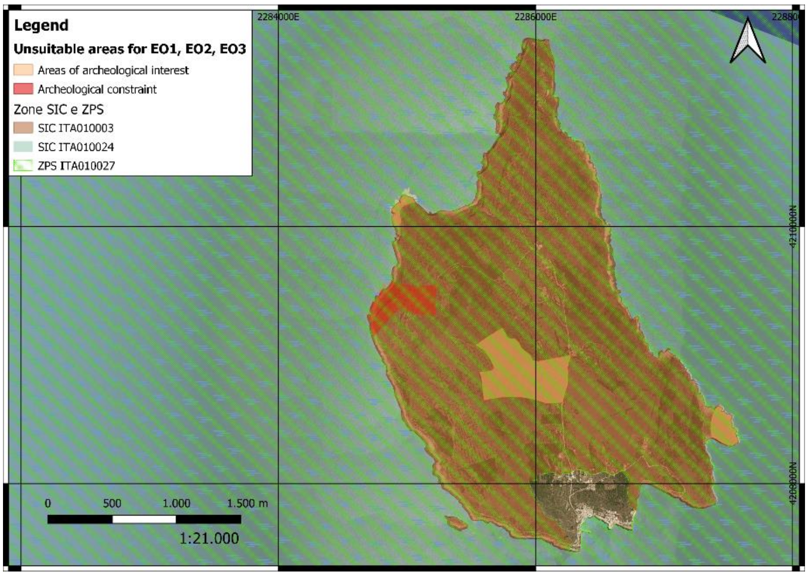


Map 64: Power density @30m a.g.l | Marettimo

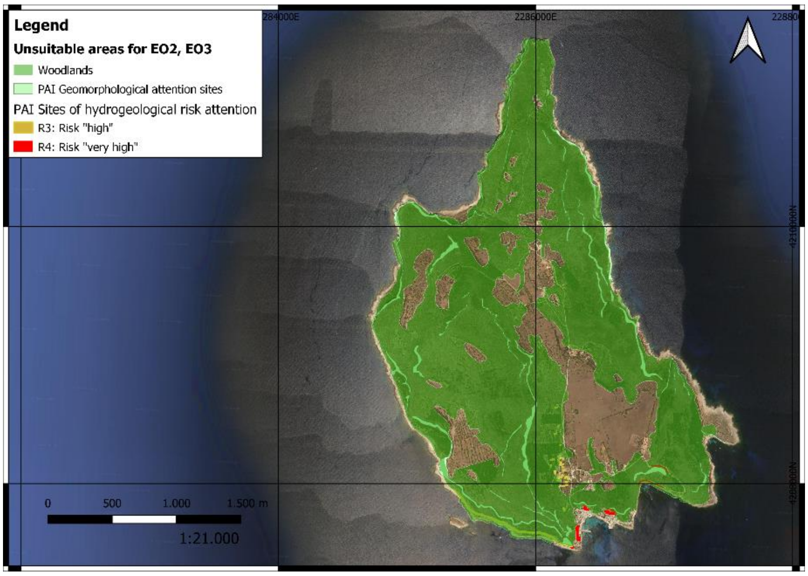


Map 65: Solar radiation on building roofs | Marettimo

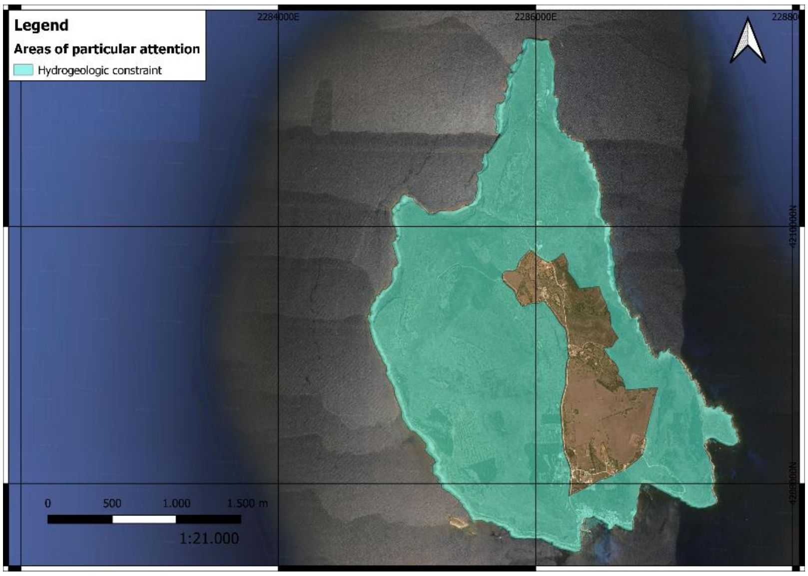
Levanzo



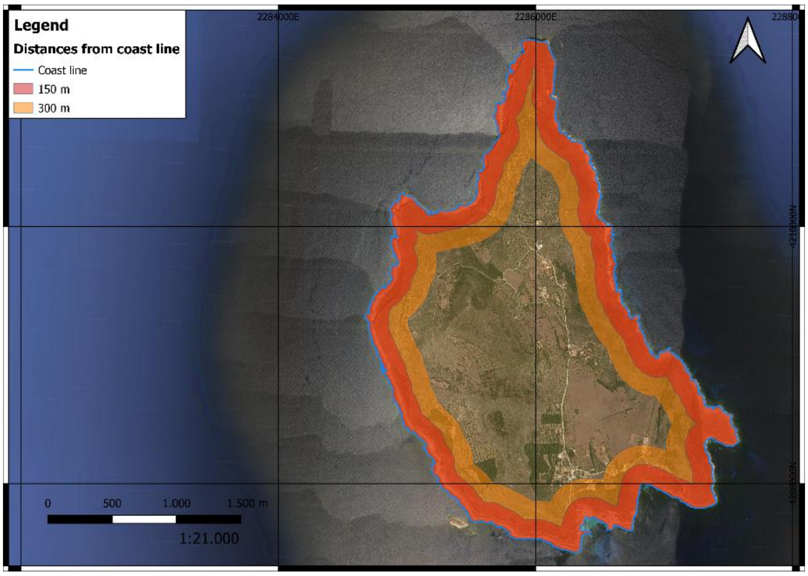
Map 66: Unsuitable areas for EO1, EO2, EO3 | Levanzo



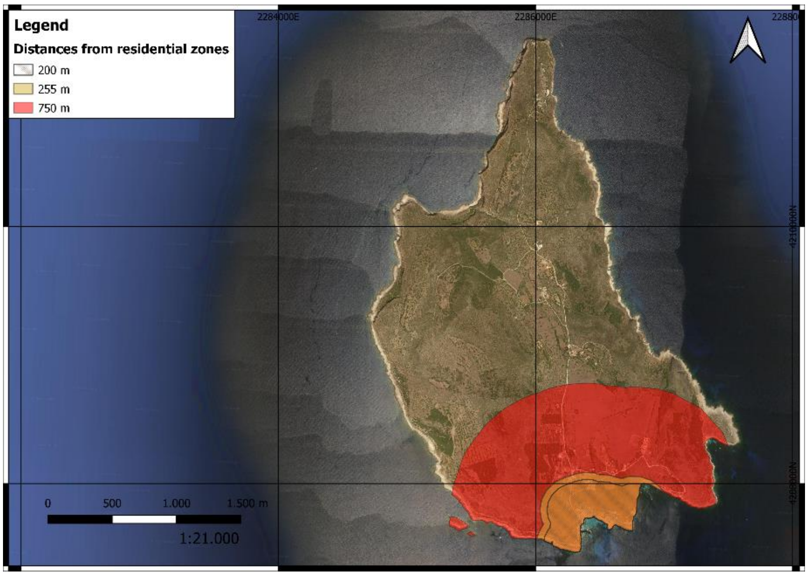
Map 67: Unsuitable areas for EO2, EO3 | Levanzo



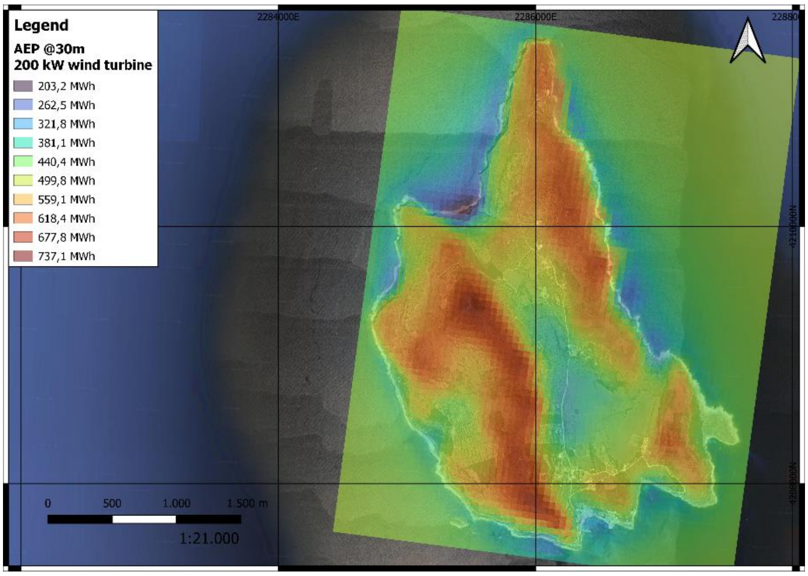
Map 68: Areas of particular attention | Levanzo



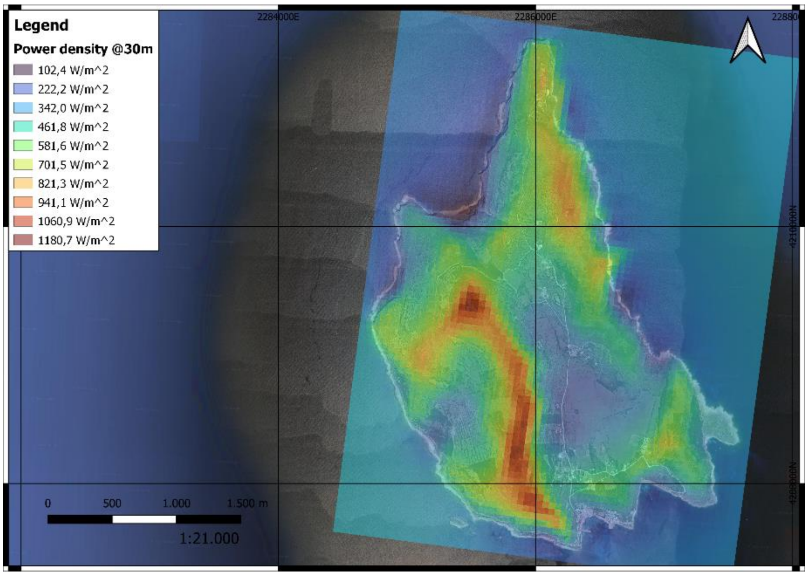
Map 69: Distances from coastline | Levanzo



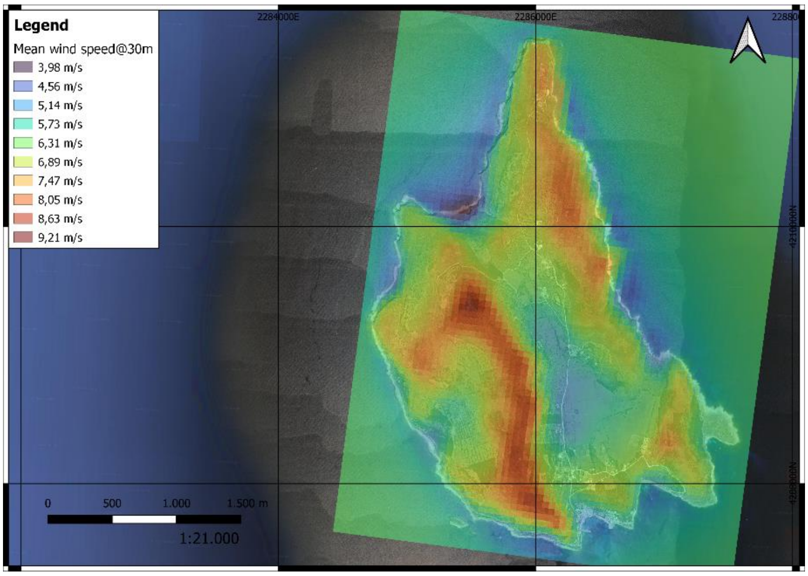
Map 70: Distances from residential zones | Levanzo



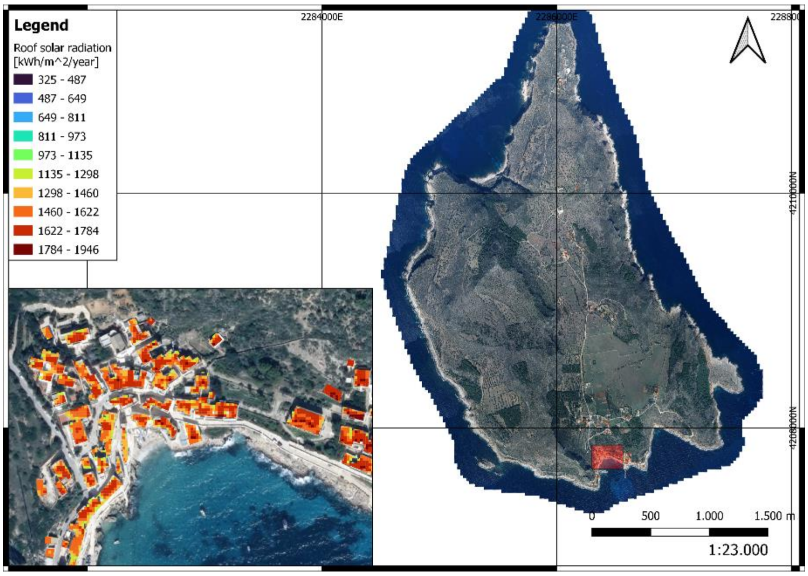
Map 71: Annual energy production 200 kW wind turbine @30m a.g.l. | Levanzo



Map 72: Power density @30m a.g.l. | Levanzo

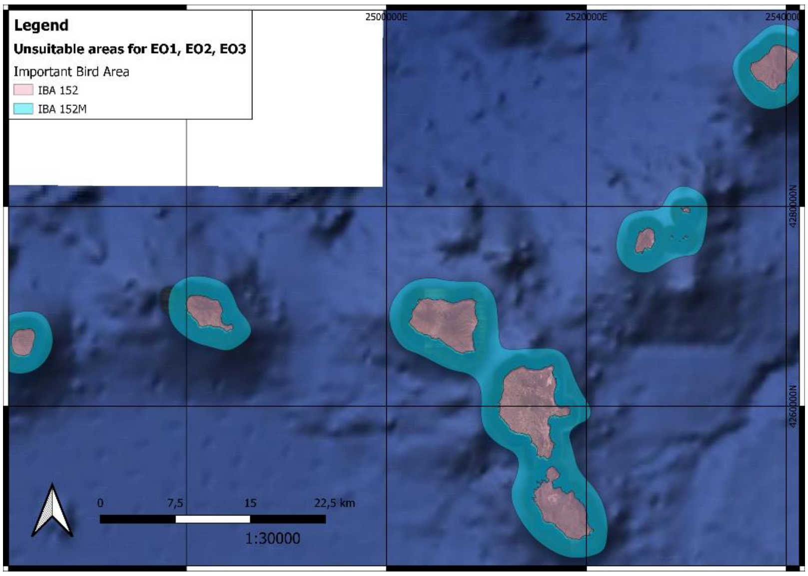


Map 73: Mean wind speed @30m a.g.l. | Levanzo

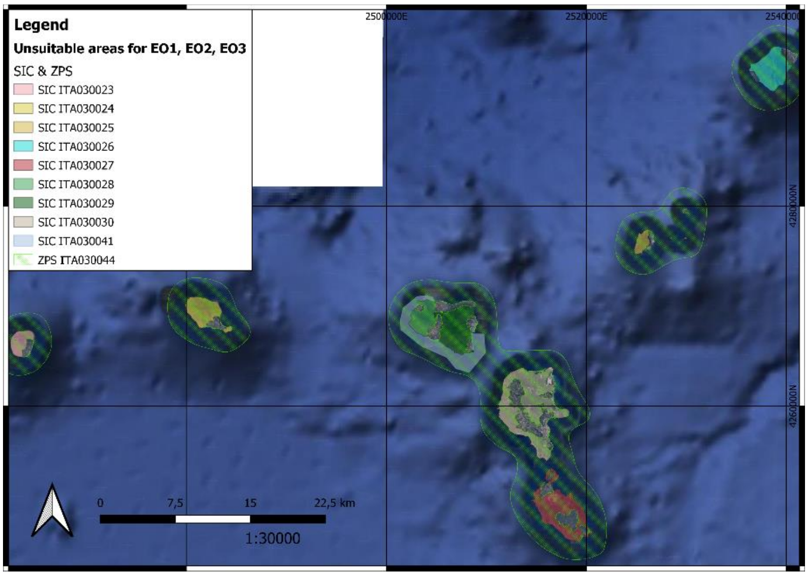


Map 74: Solar radiation on building roofs | Levanzo

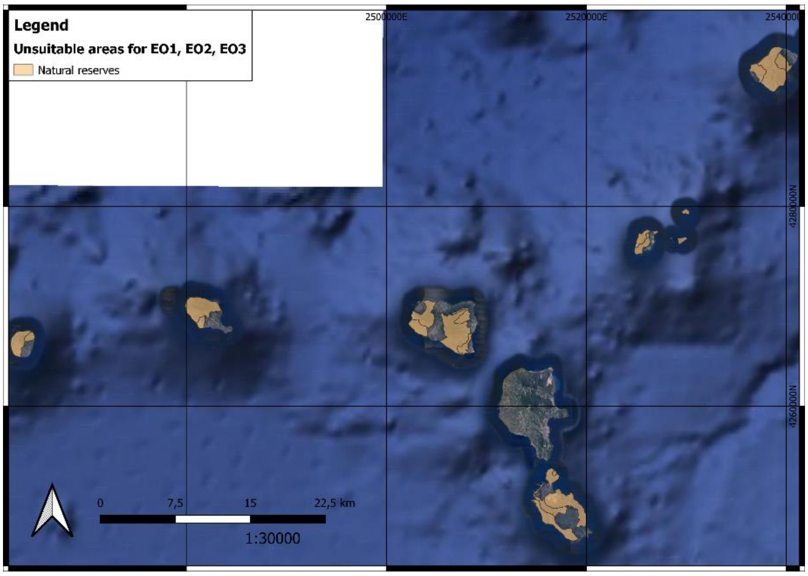
Eolie islands



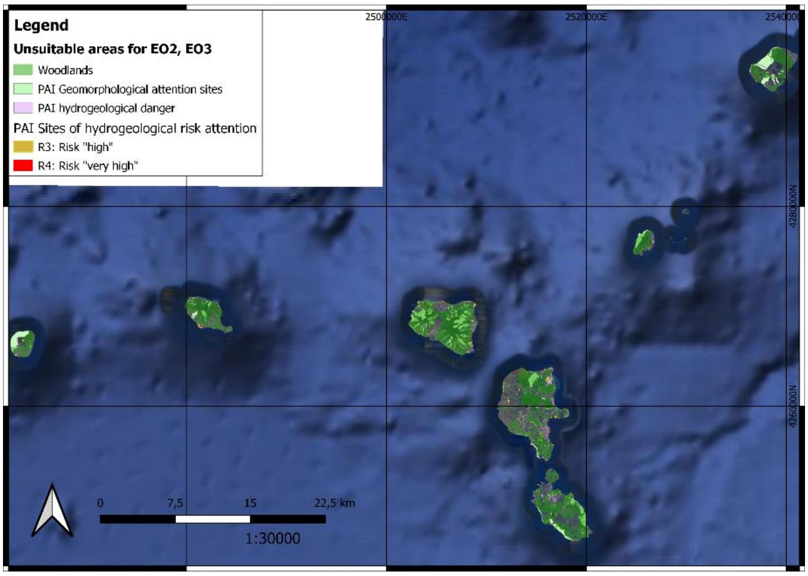
Map 75: Important Bird Area | Eolie islands



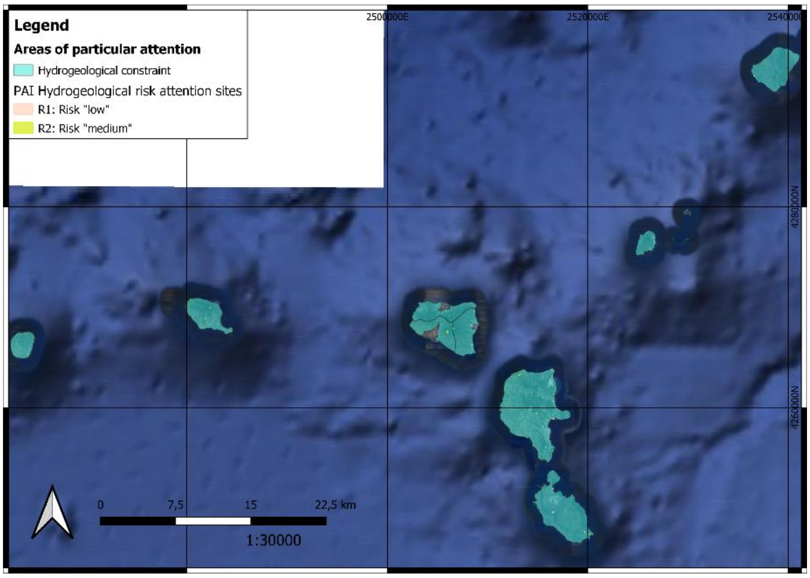
Map 76: SIC & ZPS zones | Eolie islands



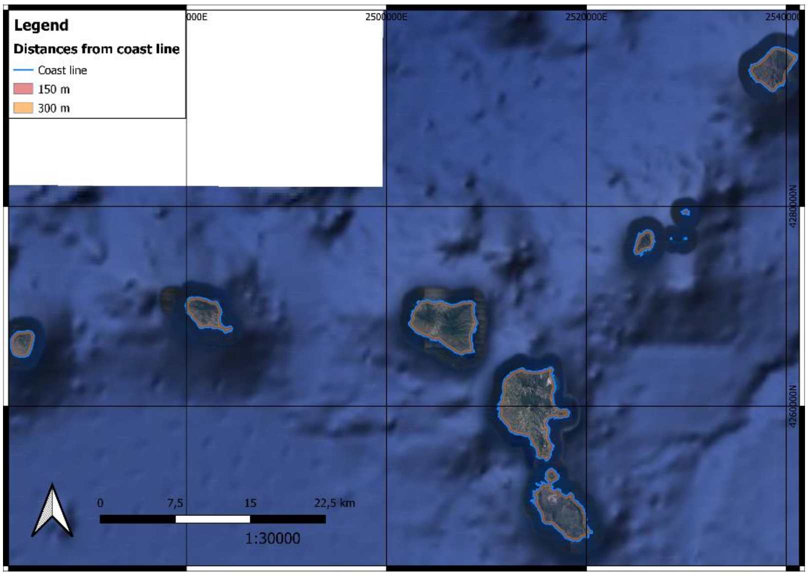
Map 77: Natural reserves | Eolie islands



Map 78: Unsuitable areas for EO2, EO3 | Eolie islands

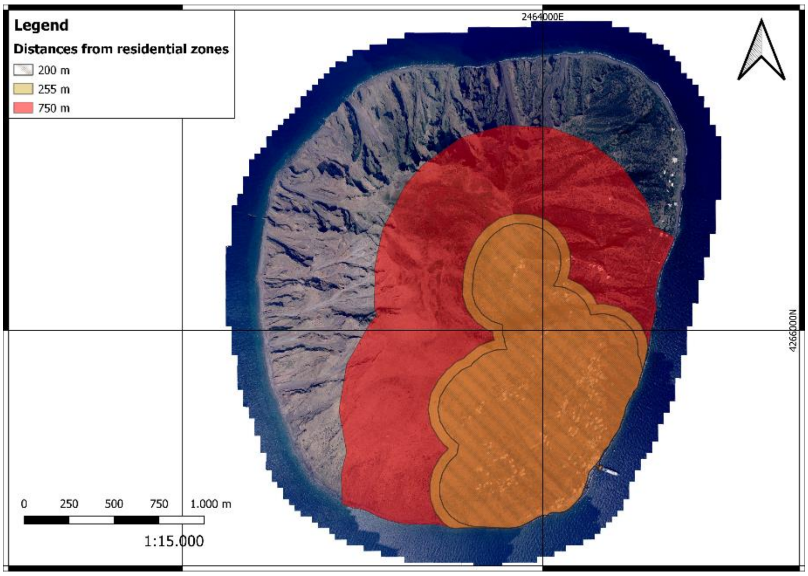


Map 79: Areas of particular attention | Eolie islands

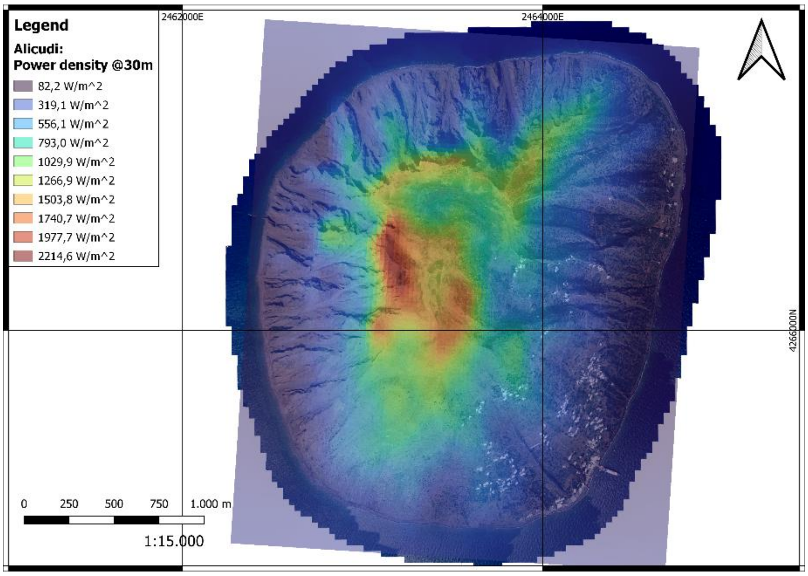


Map 80: Distances from coastline | Eolie islands

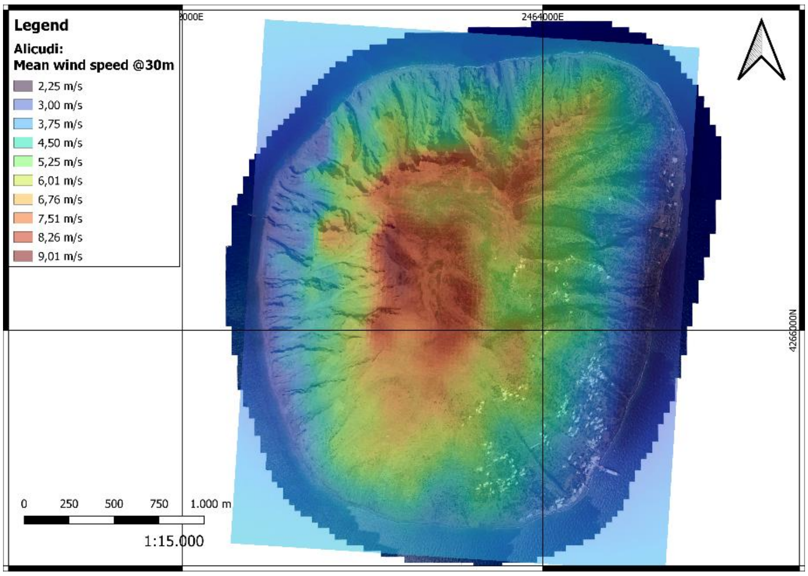
Alicudi



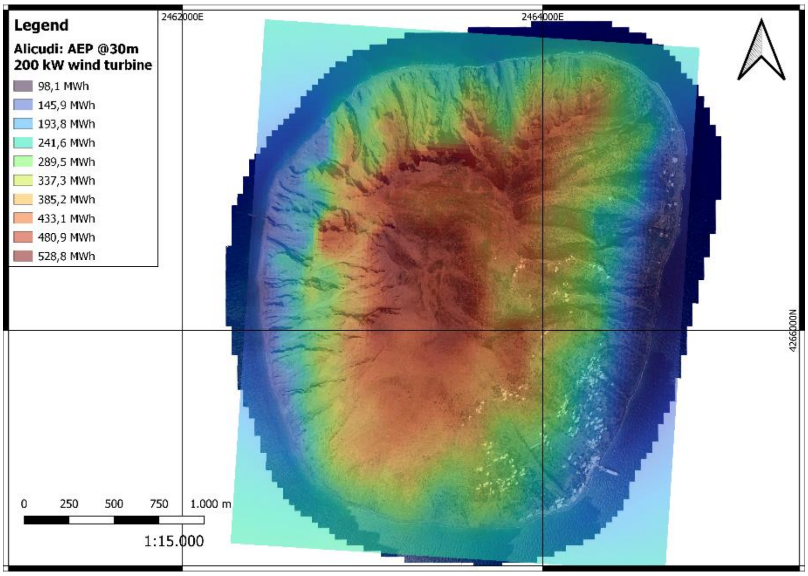
Map 81: Distances from residential zones | Alicudi



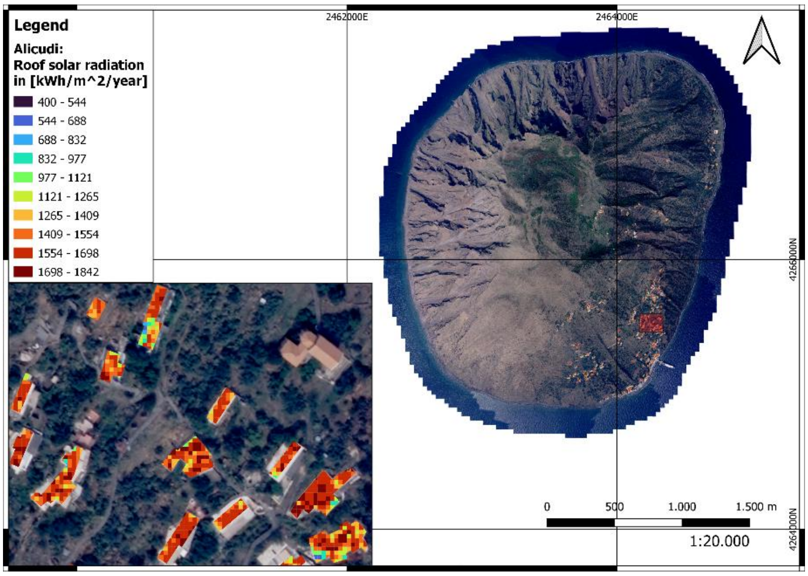
Map 82: Power density @ 30m a.g.l. | Alicudi



Map 83: Mean wind speed @30m a.g.l. | Alicudi

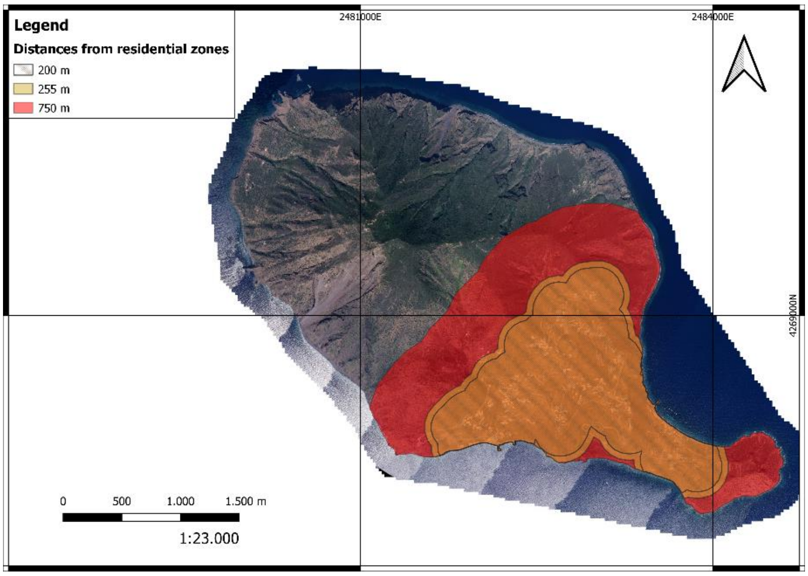


Map 84: Annual energy production 200 kW wind turbine @30m a.g.l. | Alicudi

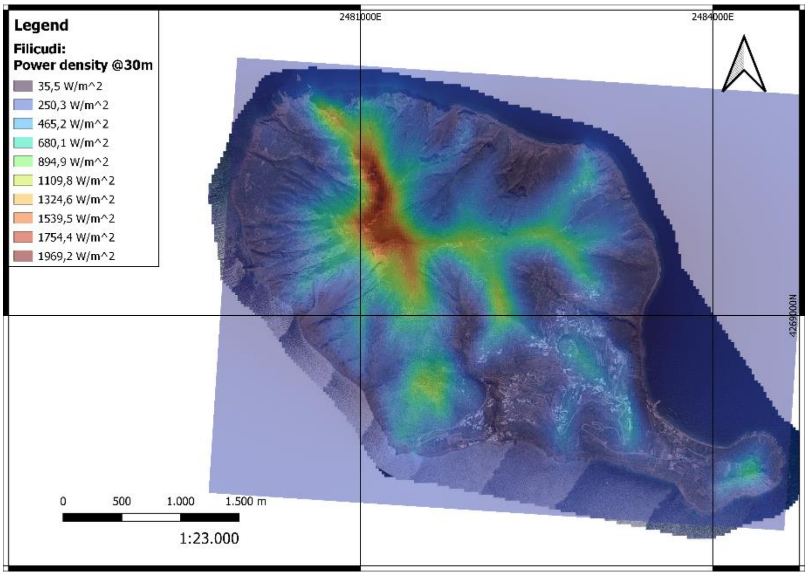


Map 85: Solar radiation on building roofs | Alicudi

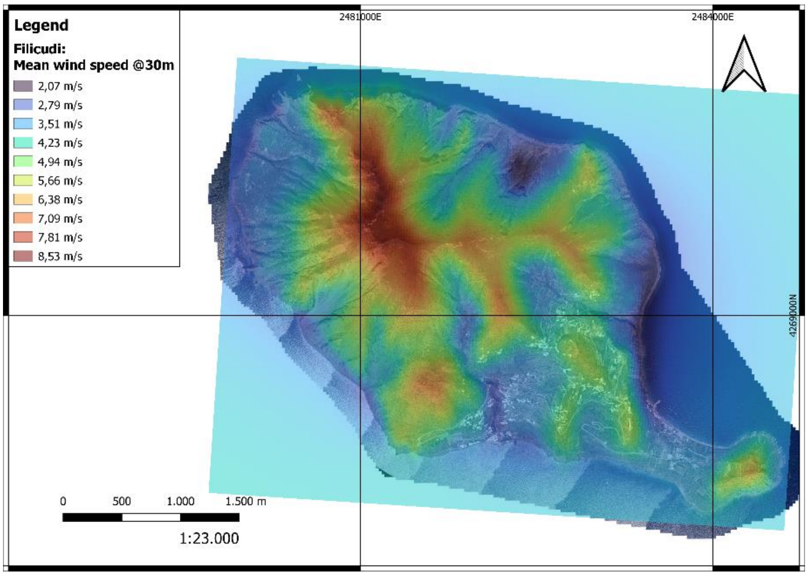
Filicudi



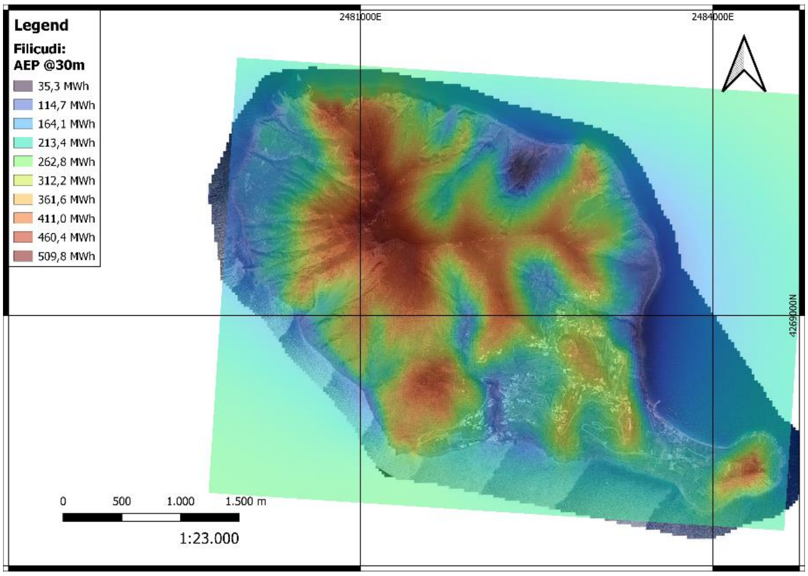
Map 86: Distances from residential zones | Filicudi



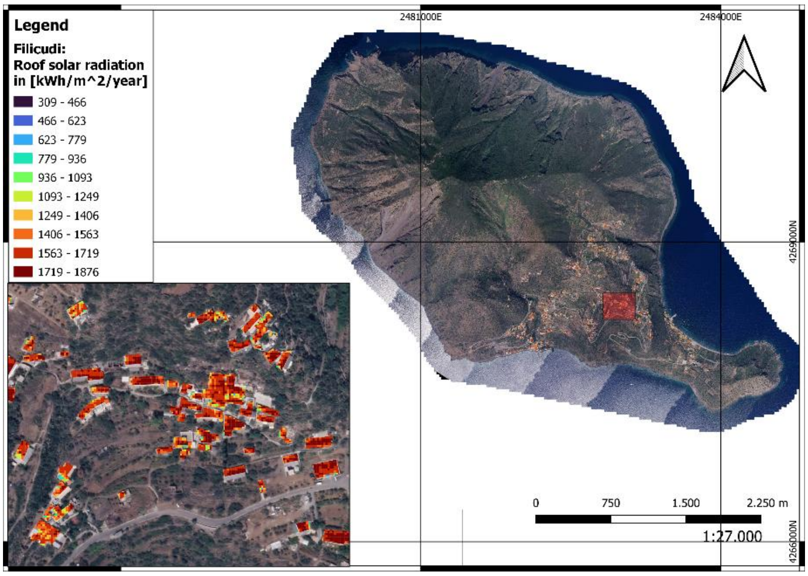
Map 87: Power density @30m a.g.l. | Filicudi



Map 88: Mean wind speed @ 30m a.g.l. | Filicudi

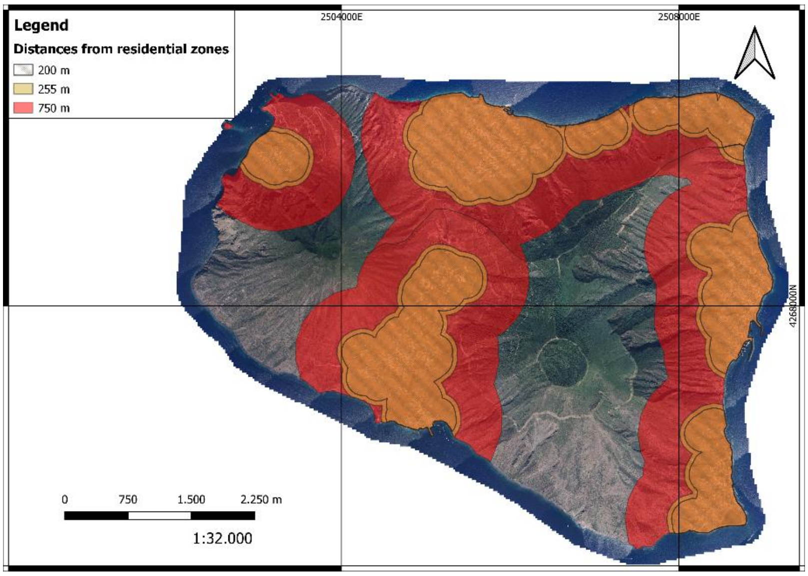


Map 89: Annual energy production 200 kW wind turbine @30m a.g.l. | Filicudi

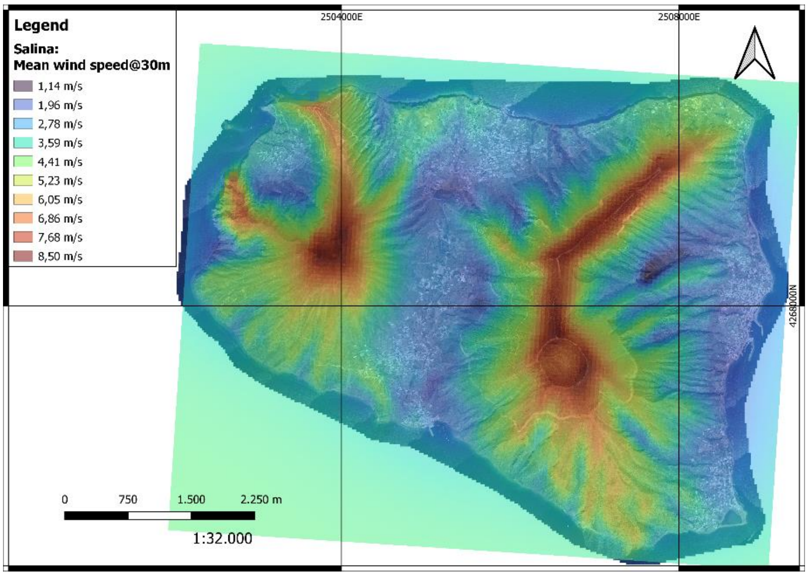


Map 90: Solar radiation on building roofs | Filicudi

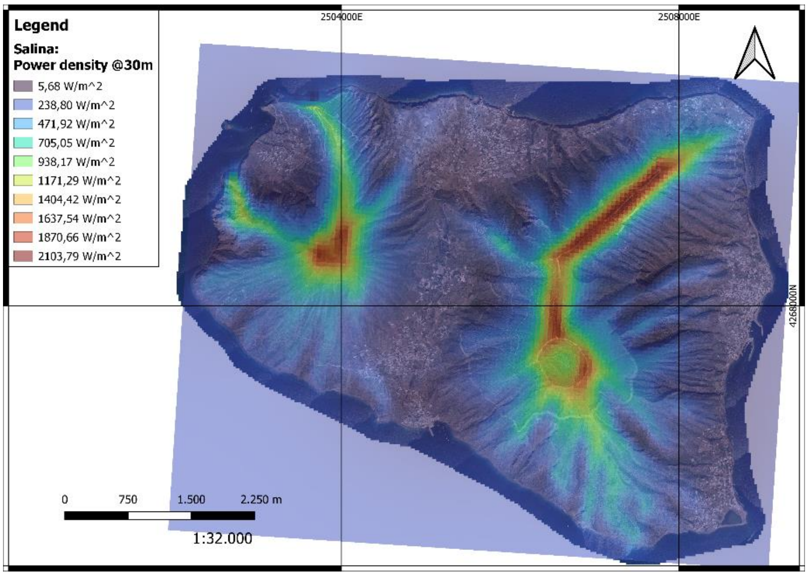
Salina



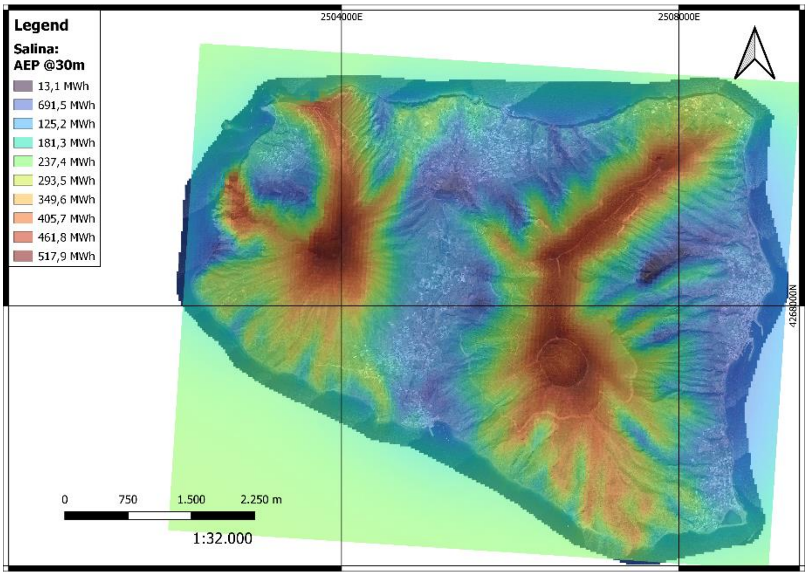
Map 91: Distances from residential zones | Salina



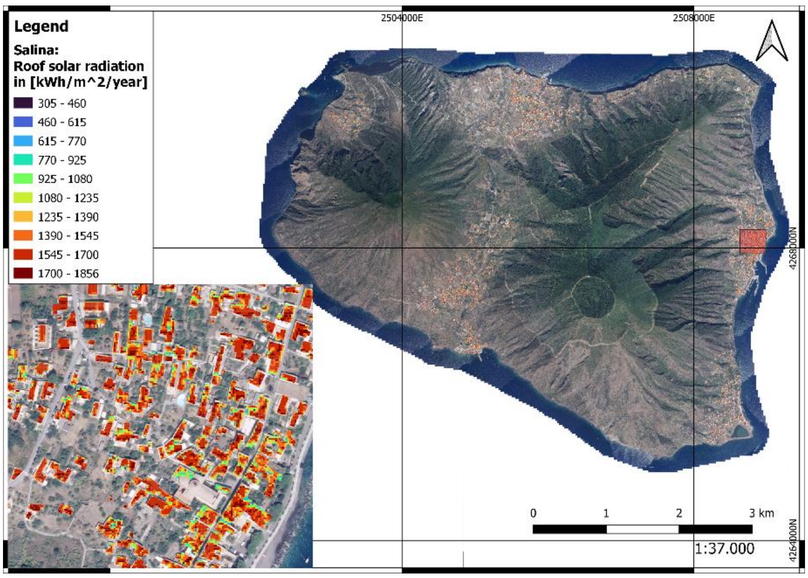
Map 92: Wind mean speed @30m a.g.l. | Salina



Map 93: Power density @30m a.g.l. | Salina

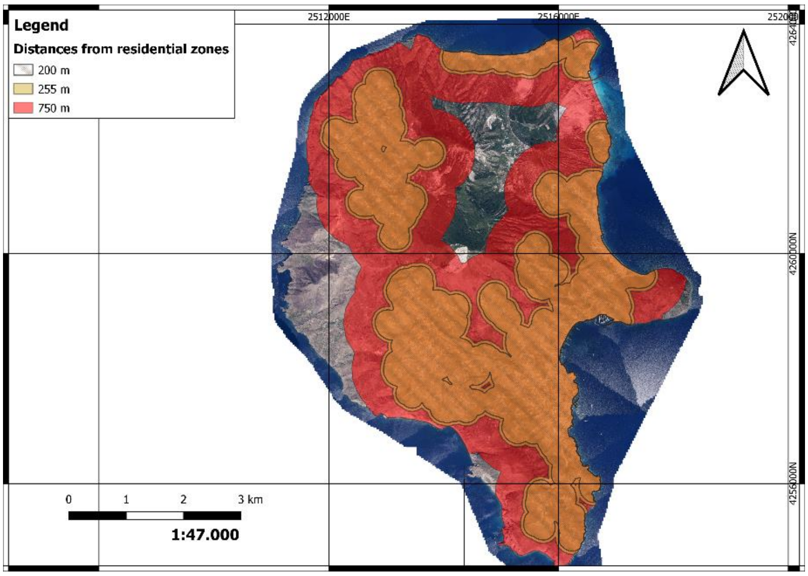


Map 94: Annual energy production 200 kW wind turbine @20m a.g.l. | Salina

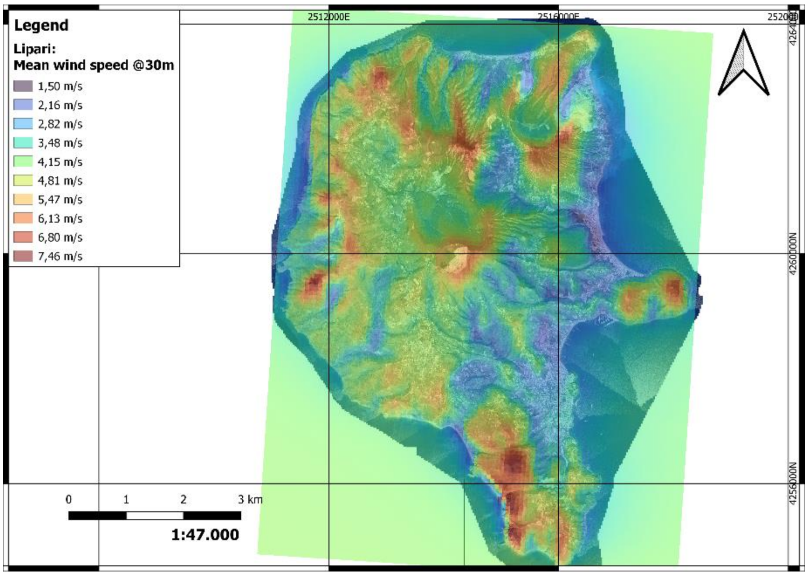


Map 95: Solar radiation on building roofs | Salina

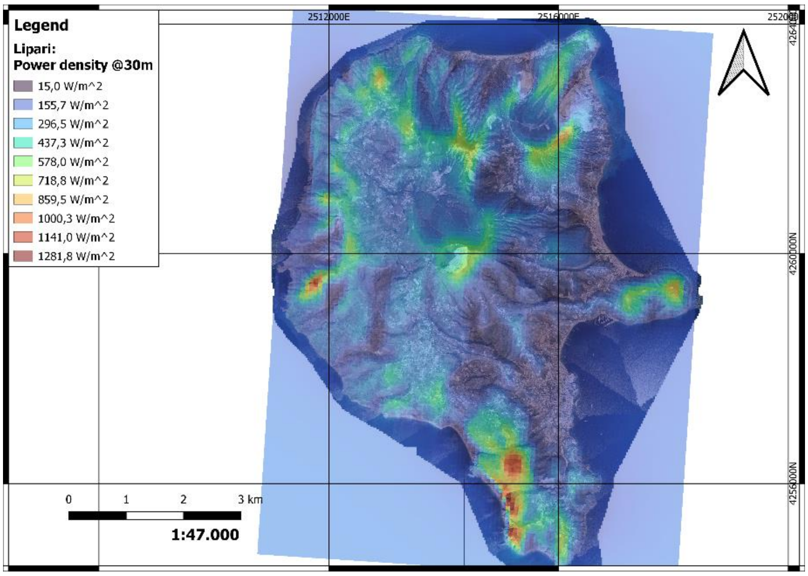
Lipari



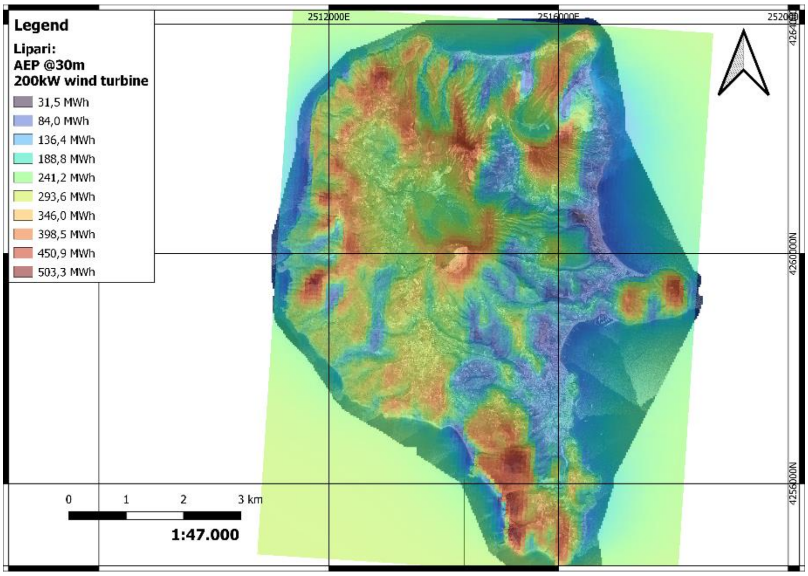
Map 96: Distances from residential zones | Lipari



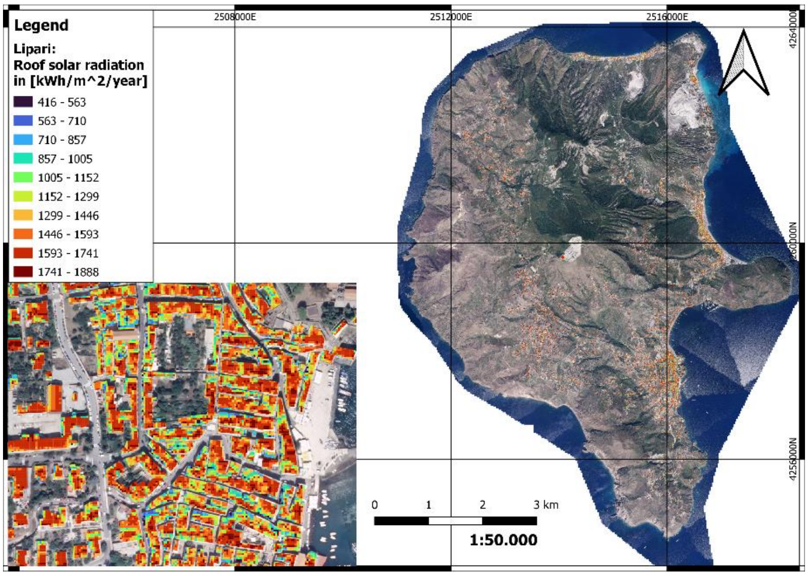
Map 97: Mean wind speed @30m a.g.l. | Lipari



Map 98: Power deinsity @30m a.g.l. | Lipari

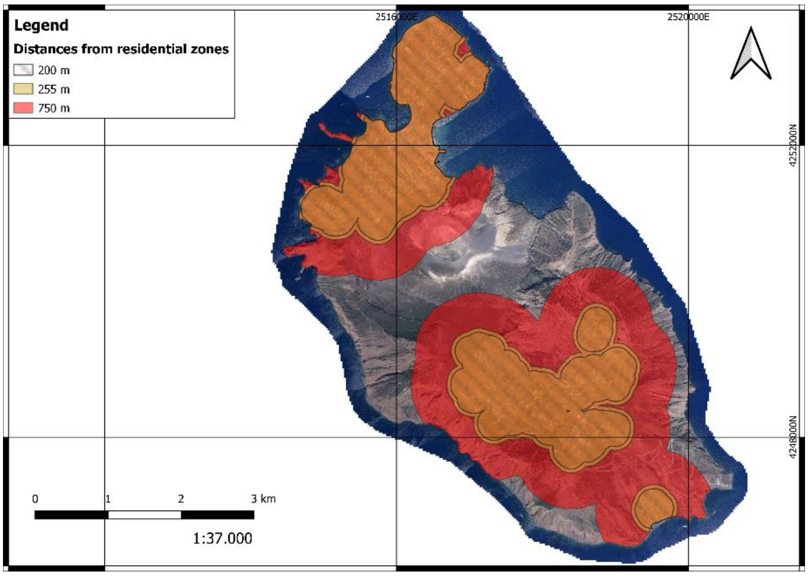


Map 99: Annual energy production 200 kW wind turbine @30m a.g.l. | Lipari

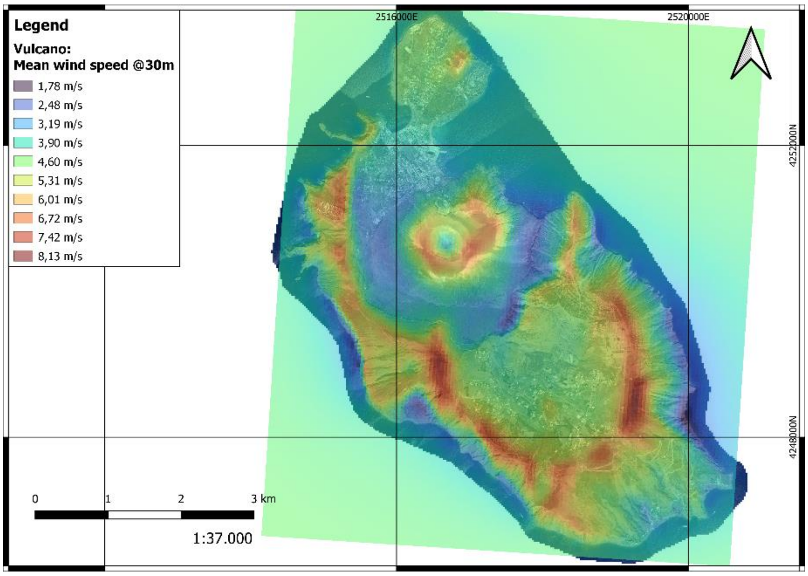


Map 100: Solar radiation on building roofs | Lipari

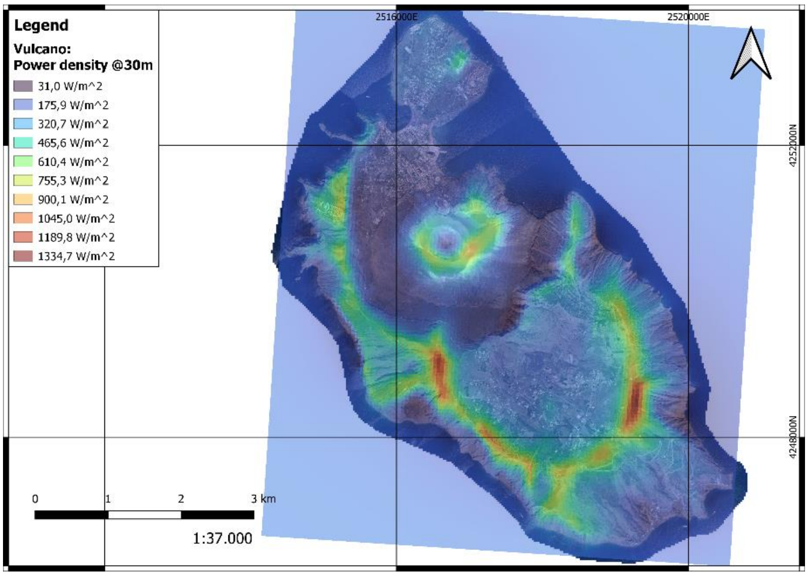
Vulcano



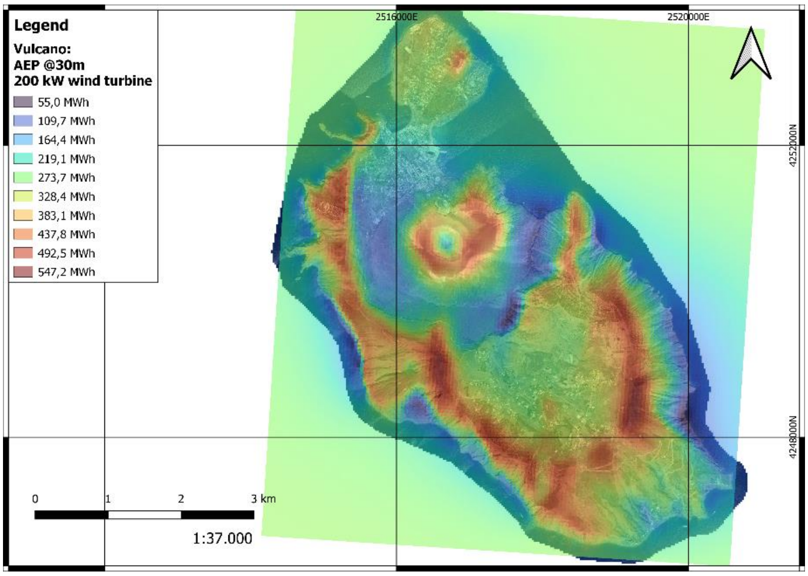
Map 101: Distances from residential zones | Vulcano



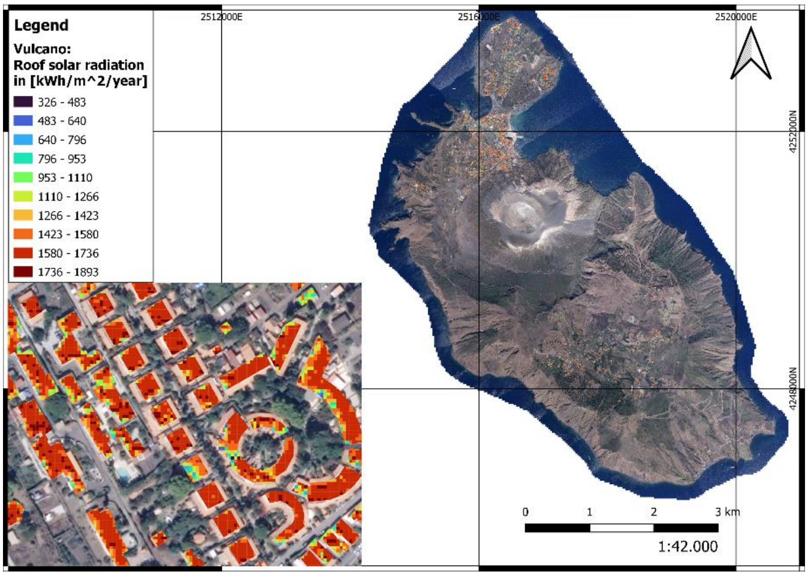
Map 102: Mean wind speed @30m a.g.l. | Vulcano



Map 103: Power density @30m a.g.l. | Vulcano

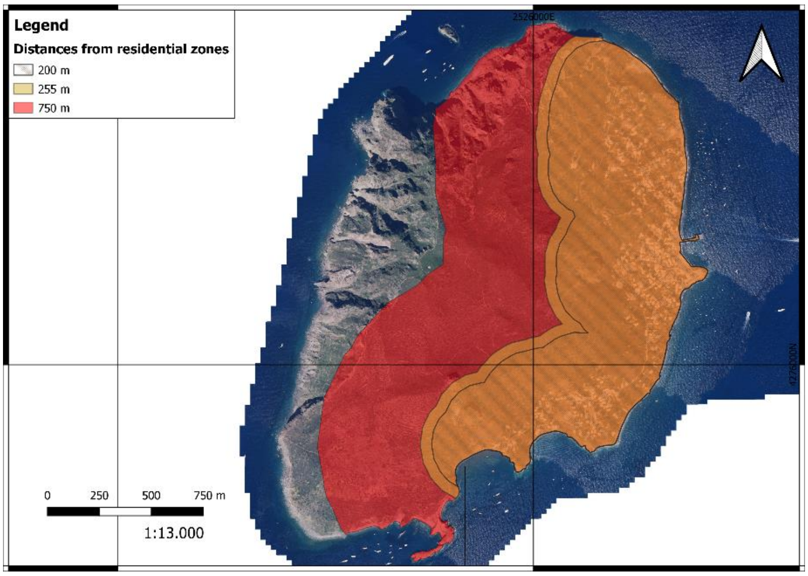


Map 104: Annual energy production 200 kW wind turbine @30m a.g.l. | Vulcano

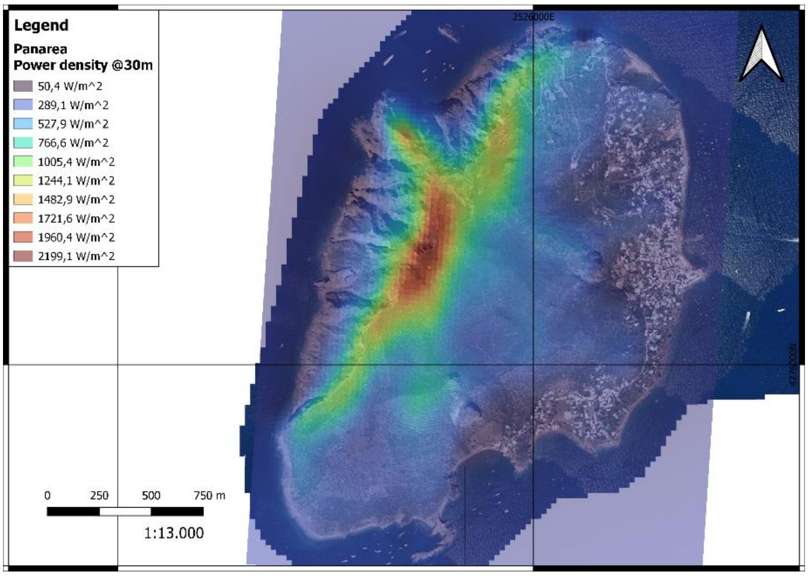


Map 105: Solar radiation on building roofs | Vulcano

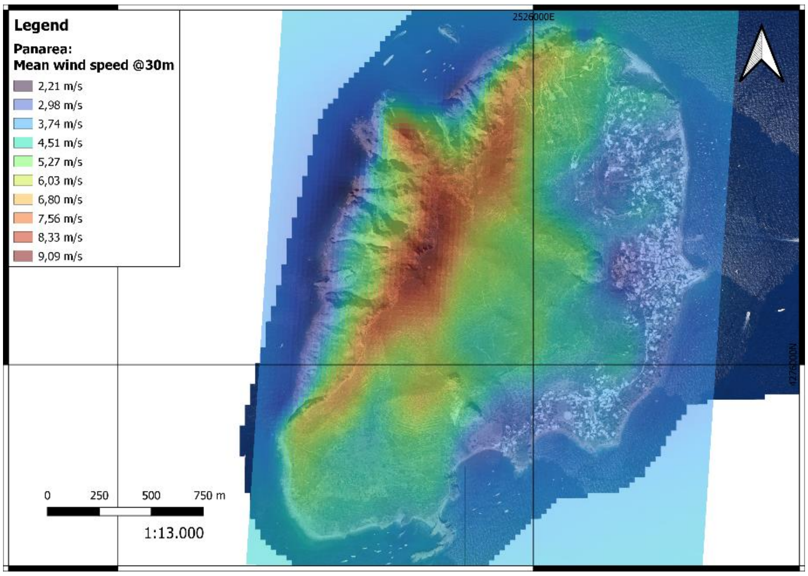
Panarea



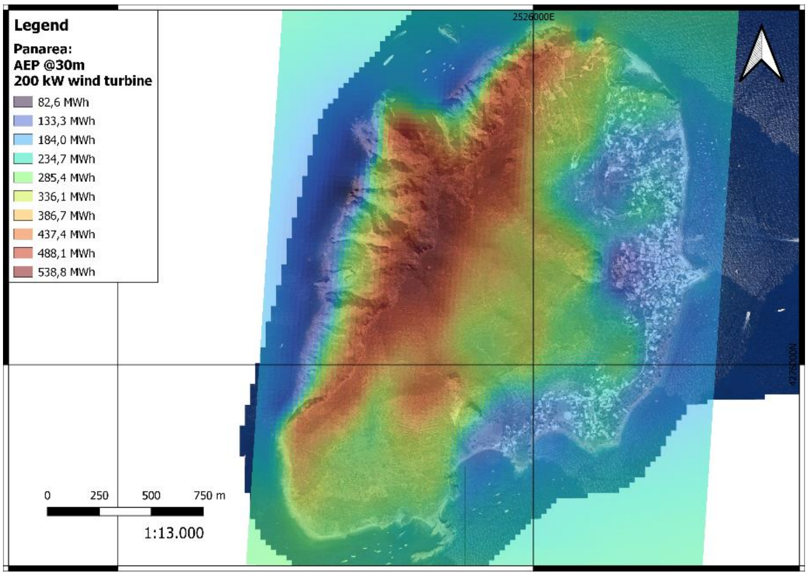
Map 106: Distances from residential zones | Panarea



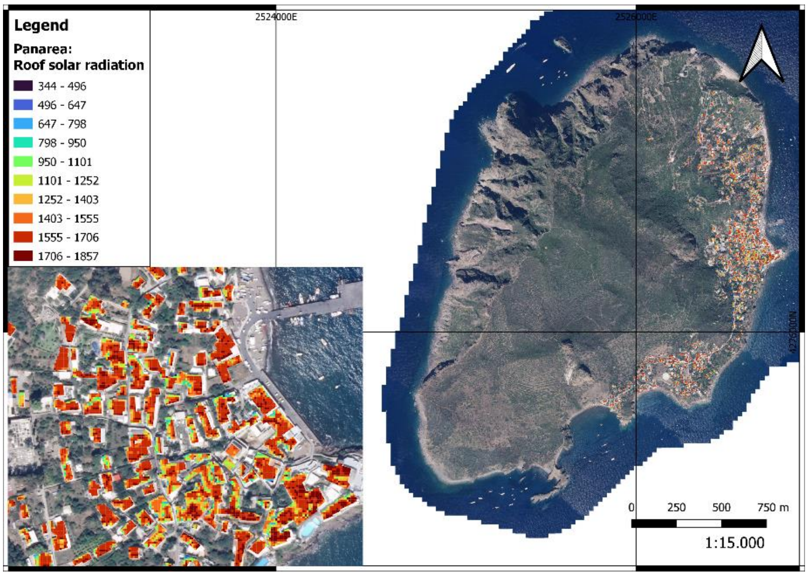
Map 107: Power density @30m a.g.l. | Panarea



Map 108: Mean wind speed @30m a.g.l. | Panarea

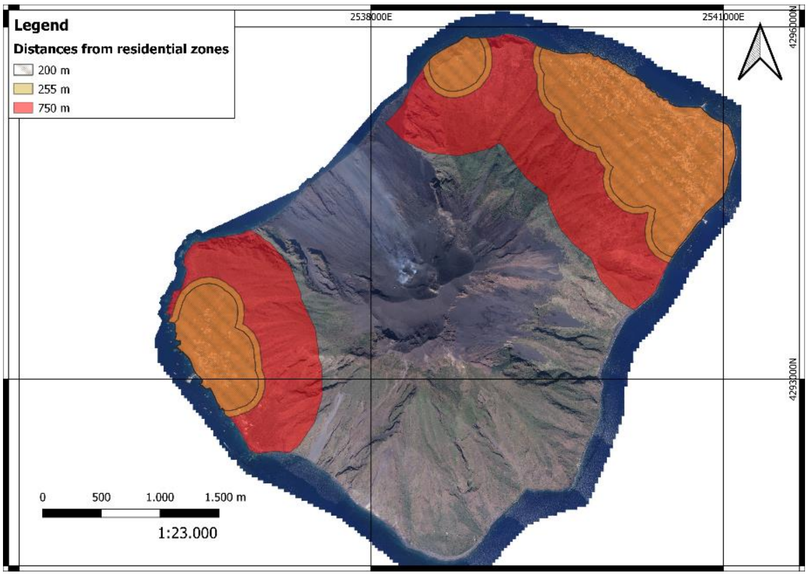


Map 109: Annual energy production 200 kW wind turbine @30m a.g.l. | Panarea

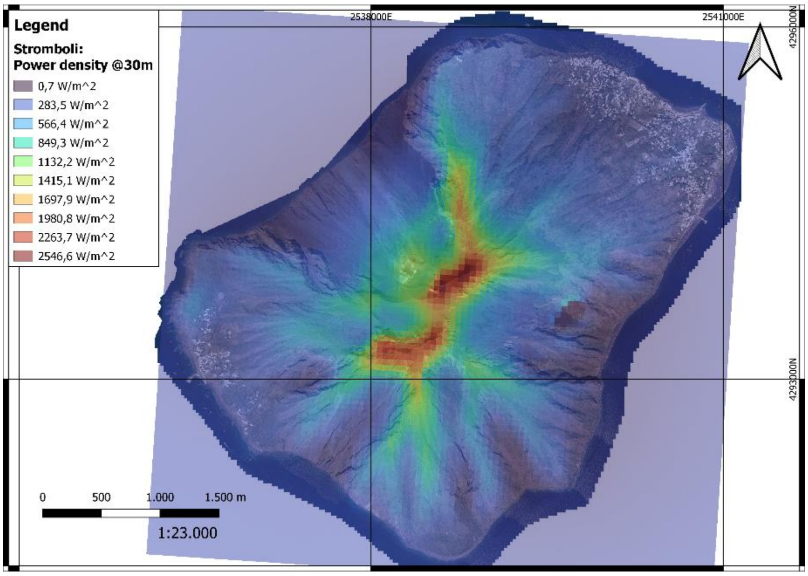


Map 110: Solar radiation on suitable roofs | Panarea

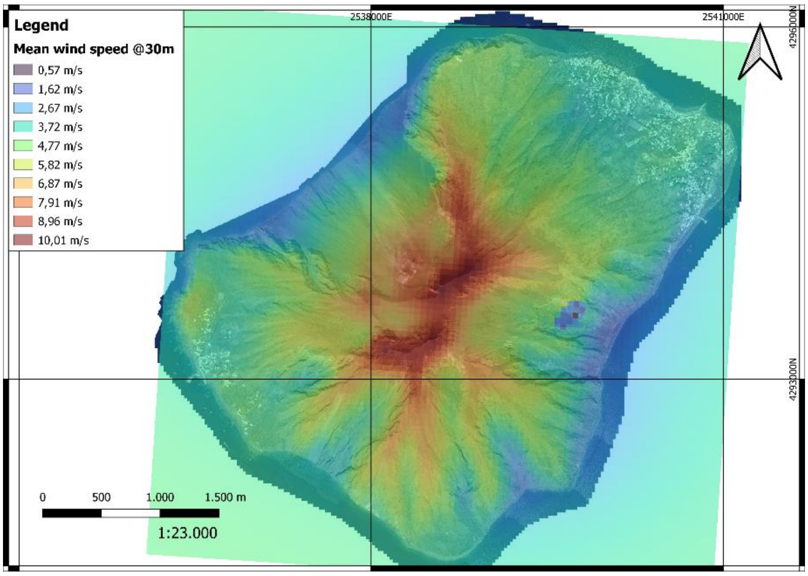
Stromboli



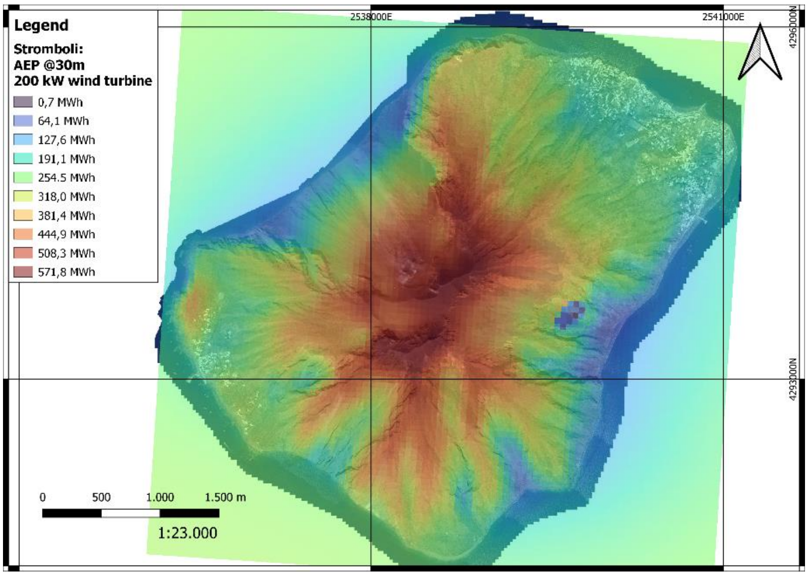
Map 111: Distances from residential zones | Stromboli



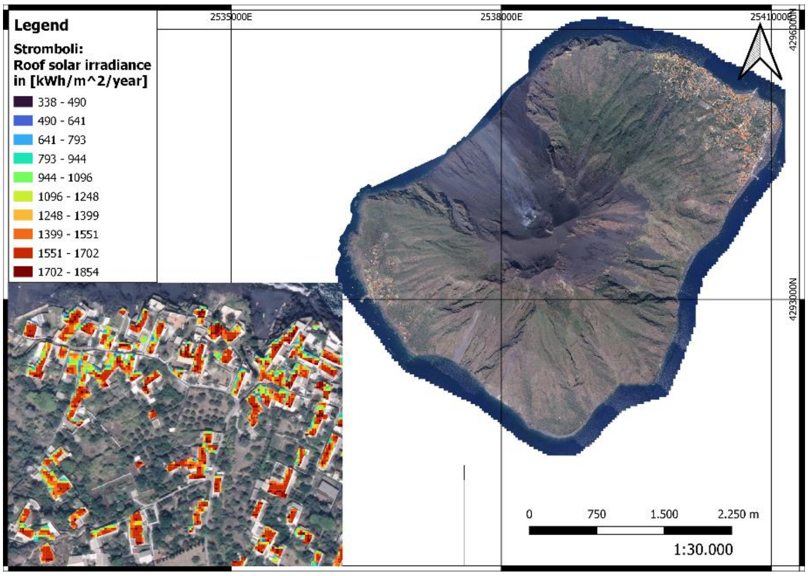
Map 112: Power density @30m a.g.l. | Stromboli



Map 113: Mean wind speed @30m | Stromboli



Map 114: Annual energy production 200 kW wind turbine @30m a.g.l. | Stromboli



Map 115: Solar irradiance on suitable roofs | Stromboli

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