Politecnico di Torino

INGEGNERIA ENERGETICA E NUCLEARE
A.A. 2021/2022
Sessione di Laurea Luglio 2022

Multi-scenario energy planning: development of a scenario setting and visualization tool for the Aegadian Islands.

Supervisors:

Prof. Giuliana MATTIAZZO

Ing. Riccardo NOVO

Ing. Claudio MOSCOLONI

Candidate:

Daniele FERRARA

Abstract

In order to mitigate the effects of climate change and limit the global temperature increase, the European Union is developing strong policies to support the energy transition, including the Clean Energy for EU islands initiative. This program entails the development of a transition agenda for small islands and promotes cooperation between the European Commission, the technical teams, and the local stakeholders and communities. One of the main challenges in this collaborative project is the definition of the desired energy system evolution, which usually requires several meetings between the involved parties. In this thesis, a scenario-planning tool was developed in order to help the setting and presentation of the scenarios. The multi-scenario tool was tested on the case study of the three Aegadian Islands, which are non-interconnected to the continental power systems and whose supply relies on diesel generation. The developed scenarios describe different working conditions of the islands energy systems, including different trends of energy demand increase (from 0 up to 5 %/year), introduction of electrical ferries, inclusion of different storage technologies (Li-ion batteries, hydrogen and liquid air energy storage), different levels of photovoltaic potential exploitation, utilization of various models of wind turbines. Also, scenarios are characterized by various constraints on the CO_2 emissions reduction, from 80% up to 100%. The comparison of the final results gives interesting points of view regarding the adopted constraints, suggesting the most feasible configurations for each island's energy system. Furthermore, the results demonstrate that an ambitious decarbonization is indeed feasible and desirable, achieving overall cost reductions of around 50% and CO_2 emissions reduction of over 90%. The work was developed to support the writing of the Aegadian islands transition agenda.

Acknowledgements

"Nulla impedirà al sole di sorgere ancora,
nemmeno la notte più buia.
Perché oltre la nera cortina della notte
c'è un'alba che ci aspetta."
Khalil Gibran

I would like to thank my supervisor Giuliana Mattiazzo who gave me the opportunity to undertake such ambitious project, giving space to my ideas. A special thanks to Riccardo Novo and Claudio Moscoloni for supporting me in the entire process. They are more than advisors, they are friends.

Table of Contents

List of Tables

List of Figures

Acronyms

DSO

Distribution system operator

EGD

European Green Deal

CETA

Clean Energy Transition Agenda

LP

Linear Programming

MILP

Mixed-Integer Linear Programming

GLPK

Gnu Linear Programming Kit

ZPS

Special Protected Area

ZSC

Special Area of Conservation

SIC

Area of community importance

IBA

Important Bird Area

RES

Rete Ecologica Siciliana

PAI

Piano Assetto Idrogeologico

DOC

Denominazione di Origine Controllata

DOCG

Denominazione di Origine Controllata e Garantita

DOP

Denominazione di Origine Protetta

IGP

Indicazione Geografica Protetta

STG

Specialità Tradizionale Garantita

DP Reg

Decreto del Presidente della Regione

DM

Decreto Ministeriale

PV

Photovoltaic

GIS

Geographic Information System

SITR

Sistema Informativo Territoriale Regionale

UMEP

Urban Multi-scale Environmental Predictor

GWC
: Generalized Wind Climate

DSM
: Digital Elevation Models

SR
: Solar Radiation

PR
: Performance Ratio

EC
: Energy Cost

GSR
: Generator-to-System Ratio

PVPP
: Photovoltaic Power Potential

PF
: Packing Factor

DR
: Daily Routes

LF
: Load Factor

DOM
: Domestic electricity demand

AUBT
: Ausiliari Bassa Tensione

IPBT
: Illuminazione Pubblica Bassa Tensione

RSD

Residential domestic demand

NRSD

Non-Residential domestic demand

ATSE

Activities and Services demands

LAES

Liquid Air Energy Storage

PEM

Polymer Electrolyte Membrane

Introduction

1.1 The importance of renewable energies in Europe

During the last decades the European Union decreased its primary energy production, encouraging the imports from third states; e.g. from 1990 to 2020 the natural gas imports doubled. The primary energy import is more than half of the total available energy, in fact, in 2019 the imported gross energy was about 61% of the total [1, 2]. Furthermore, the 2022 Ukraine crisis raised the question on the European energy dependency to other states and its supply stability. In reaction to the events, the European Parliament considered the possibility to increase the renewable energy target from 32% to 45% by 2030 [3]. It is not, therefore, an exclusively geopolitical problem, the climate change is putting increasing pressure on the energy transition as well. Rising temperature can cause ever larger forest wildfires, severe Great Barrier Reef bleaching, plants and animals extinction, and other non-negligible problems [4, 5, 6]. The main cause of the climate change is the warming of the atmosphere, due to the greenhouse effect [7]. Therefore, to mitigate these problems, it is necessary to act on the anthropogenic greenhouse gases, among them the most relevant is CO_2 . This could be done in two possible ways: reduction of carbon emissions and carbon capture.

1.2 Decarbonization pathways

In order to reduce the carbon emissions, the European Commission approved several renewable energy policy initiatives; the aim of these policies is to provide a framework for renewable energy projects, to increase the installed renewables among the European countries. In 2019, the European Commission presented the European Green Deal (EGD): a set of policy initiatives with the main ambition of making the European Union carbon-neutral by 2050 [8]. The EGD allocated about EUR 10 billion in the Innovation Fund, a fund opened in 2021 for large/mid scale projects, low-carbon projects included [9]. Another ambitious project which satisfies the European Green Deal requisites is "Clean Energy for EU islands", which aims to reduce the CO_2 emissions of 60 transition projects across 2400 European Islands, mobilizing more than 100 million euros [10]. This project aims to reduce the islands' dependence from energy import. Usually, little islands need to import diesel to power diesel generators. This process generates high emissions of CO_2 , to be attributed to the transport and the use of the primary energy source. If the islands increase the amount of energy produced by renewable sources, this carbon emission decreases drastically and, if enough power is installed, it could drop to zero. Furthermore, these upgrades would lead to an economical boost for the islands, reducing the cost of energy and also improving their air quality. The initiative is achieved through the collaboration between the Secretariat, the stakeholders, the technical team and the local communities of the islands. This is done with the realization of the **Clean Energy Transition Agenda** [11], a document which contains all the information regarding the transition roadmap. The agenda is composed as follows:

1. Description of the island geography/economy/population
2. Definition of the island energy system, including imports/exports of energy and its production/consumption
3. Analysis of the local renewable energies regulations
4. Calculation of the renewable energy power potential
5. Possible carbon reduction scenarios chosen together with the stakeholders
6. Roadmap for the realization of the new energy system

1.3 Motivations

The CETA document should be built through the collaboration between individuals and teams, which have a totally different working background. This could lead to misunderstandings and to the scheduling of several meetings. The technical group should conduct the study of the energy system of the islands and, in the meanwhile, it should set the conditions for the scenarios to be simulated. In order to do the latter, the technical team should arrange those conditions depending on the requests of the community and of the stakeholders. On the other hand, in order to give the requests to the technical team, those groups should know how the energy system could behave in some working conditions and how much its upgrades would cost. This interdependent collaboration could require several attempts before reaching the desired solution, increasing the time required to complete the tasks. In order to reduce the completion time of the tasks, this thesis introduces a new approach to the use of the modeling framework OSeMOSYS, by developing two software: one for the generation of multiple scenarios and the latter for the visualization of the results. The two software can help both the technical team and the stakeholders to understand how the energy system reacts to several stress conditions. Thanks to the first tool, it is possible to simulate conditions like: demand increments/decrements, technologies' performances degradation, addition/removal of technologies in the energy system, pollutants emissions ranges, RES penetration ranges, costs variations, addition/removal of storage technologies, and more. The second one could help the technical team to show the results to the decision-makers, by sharing them through a server and making it possible for the viewers to access them remotely from a browser, avoiding the necessity to install third-part software or to download the dataset locally. Furthermore, every user could view different results in respect to the others. In fact, the server would launch parallel instances for each user, making it possible to the user to freely choose the scenarios to plot, without compromise the visualization of other users. All these tools have been developed and tested while working on the CETA of the Aegadian Islands.

1.4 Thesis roadmap

In the introduction, it has been explained the actual situation in Europe regarding the RES share and the action taken in order to increase it in the energy mix. Furthermore, it has been explained what are the purposes of this thesis and what are the methodologies adopted in order to achieve them. The Chapter 2 gives details on the actual energy system of the islands. It also describes what are the renewable power potentials for each island, giving suggestions on where the renewable generators could be placed in the territories, in function of the actual legislation. In the Chapter 3 there is the explanation of the framework used for the simulations, OSeMOSYS, and a description of the islands' models. Furthermore, it introduces the multiple-scenarios configurations of the Aegadian Islands, describing the functions of their parameters. The Chapter 4 explains the frameworks of the developed software, how they work and what are their possible applications. In the Chapters 5 and 6 there are the results of the scenarios and the comparison between the storage technologies, and the final considerations on this thesis' work.

The energy system of the Aegadian Islands

2.1 The archipelago

Aegadian Islands is an archipelago located near Trapani, in the West of Sicily, South Italy. The archipelago (Figure 2.1) counts three main islands, Favignana, Levanzo and Marettimo, and other smaller islands which are almost uninhabited. The importance of building up a transition agenda for the islands is due to their total dependence on the primary energy import. In fact, none of the islands is connected to the national grid, they consequently produce themselves the electrical energy, by using diesel generators. On the other hand, the archipelago is in a well suited area in regards of the renewable sources availability. The islands are well exposed to wind during the year with mean speeds in the range of 5-12 m/s at a height of 50 meters, while the average global solar horizontal irradiation is 1800 kWh/m2/year ca. A marine protected area surrounds all the archipelago, therefore the area is not suitable for the installation of wave energy converters. The transition agenda regards the three main islands, but all of them differ in population, installed power, regulated areas and, consequently, in renewable power potential. For this reason, their study has been conducted separately for each one of them.

2.2 Environmental regulation

The Archipelago is a marine natural reserve, as declared in the ordinance of 27 December 1991 [12]; later defined as special area of conservation (ZSC) following the European Directive 92/43/ECC [13]. This means that Italy undertakes to protect the area with proper conservation measures, a condition that is incompatible with the installation of offshore renewable plants. On the other hand, the protection area covers partially the lands of the islands, opening to the possibility of renewable plants installation. Furthermore, there are other regulations in the lands to take under consideration. Their study proceeds as follows. It is important to clarify that this analysis requires that some regulations be ignored, even if this is not consistent

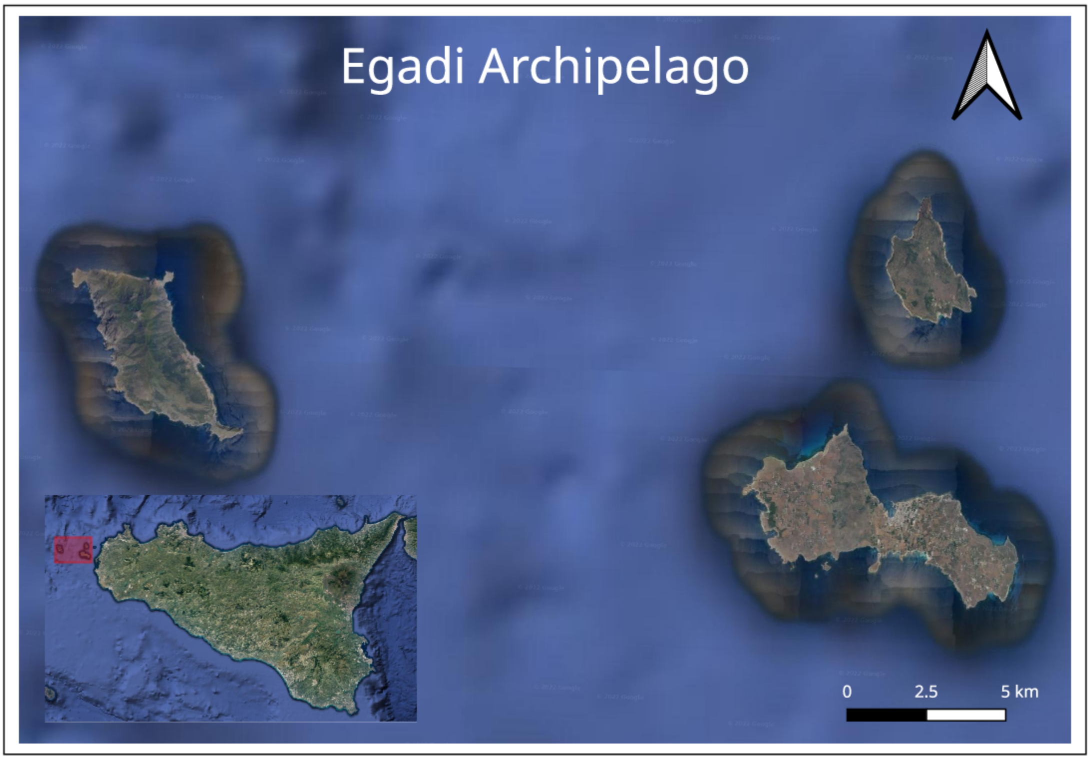


Figure 2.1: Overview of Aegadian islands. The archipelago is located on the west side of Sicily

with current legislation. The overruling of some laws is necessary because the main goal of decarbonization is the complete reduction of carbon emissions, reachable only if there is enough renewable power potential. Therefore, if there is a regulation that can be overcome, now or in the next few years, this possibility should be considered. In addition, the scenarios generated for the Aegadian Islands take into account the variability of the renewable power potential assuming more or less stringent environmental legislation. See Chapter 4 for further information.

2.2.1 Regulation on wind energy

The Ministerial Decree of 10 September 2010 gives the guidelines for the definition of wind turbines non-suitable areas [14]. Following these rules, the regions released a decree containing all the local regulations for the determination of the non-suitable areas. In Sicily, these regulations are contained in the Decree of 20 October 2017 [15]. The Decree regulates wind power turbines exceeding 20 kW of power, dividing them in three categories defined by the abbreviations: EO1 for the turbines with the nominal power lower than 20 kW, EO2 for turbines in the range 20÷60 kW and EO3 for the generators with nominal power higher than 60 kW. In this study, all the wind generators refer to the abbreviation "EO3", given that the smallest turbine is of 150 kW. Non-suitable areas:

a) areas characterized by hydrogeological risks

b) areas identified as landmarks, wooded areas, archaeological parks

c) areas of environmental interest as Special Area of Conservation (ZSC), Special Protection Area (ZPS), area of community importance (SIC), Important Bird Areas (IBA), Natura 2000 networks, Rete Ecologica Siciliana (RES), Natural Parks, Natural Reserves, Ramsar sites

d) the agricultural areas of particular value that have access to the regional funds for the valorization of the Sicilian excellences

e) areas under environmental regulatory constraint, archaeological regulatory constraint, humid areas regulatory constraint

Partially-suitable areas:

a) areas with hydrogeological regulatory constraint

b) areas that belong to PAI (Hydrogeological plan) in the zones of medium, moderate and low risk

c) areas of particular landscape value, areas near archaeological parks

d) areas intended for production of local products as biological, DOC, DOCG, DOP, IGP and STG products

Revision of the legislation

The regulations considered too fundamental to be ignored are:

- The distance between the wind generators and the houses should be at least of 200 meters (D.M. 10/09/2010)
- The turbines should be at least 6 times their height away from the inhabited areas (exception done for Marettimo, where the only available area is at 230 meters distance from the town)
- Areas characterized by high hydrogeological risk (class P3) and really high hydrogeological risk (class P4) (D.P. Reg 20/10/2017)
- Archeological parks and wooded areas (D.P. Reg 20/10/2017)

- ZPS and SIC/ZSC areas (D.P. Reg 20/10/2017)

Regarding the assumptions of which normative should be ignored, the very first normative ignored is the IBA area protection that impedes the installation of wind turbine over the entire Aegadian islands territory, covering integrally all the archipelago (see Figure 2.2). The other ignored normative is the prohibition to build new constructions at a distance below 150 meters from the shoreline.

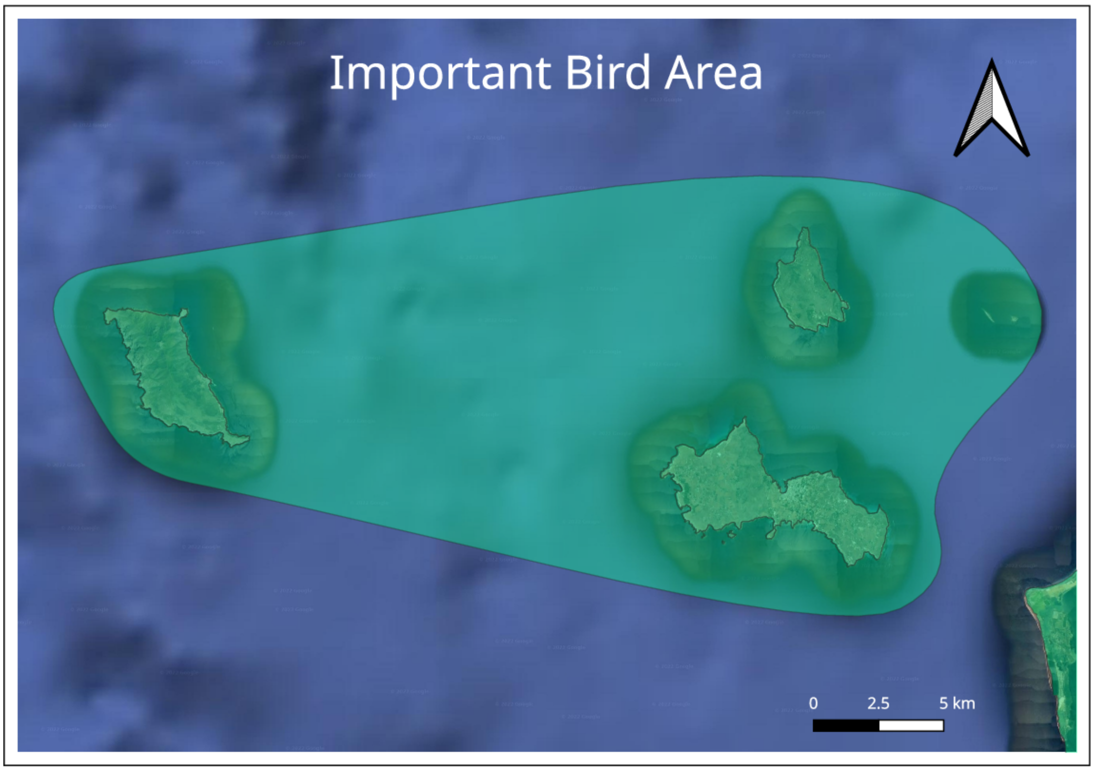


Figure 2.2: IBA area covering the archipelago

2.2.2 Regulation on solar photovoltaic energy

Photovoltaic regulations are generally more flexible than the ones intended for wind power plants, due to the less invasive nature of the generators. The reference normative is the regional decree of 17 May 2006. It gives guidelines for the installation of solar panels in function of their typology and their power, and it also defines what are the non-suitable areas for the installation. For the rooftop solar panels there aren't particular restrictions, but the main impediment is that they should not be visible from the streets; according to that they would have an inclination that could not be optimal. For ground PV, instead, the non-suitable areas should be considered only for the panels with nominal power higher than 10 kW, and they are defined as follows:

a) Integral reserve zones (A and B), natural parks, natural reserves

b) Special Protection Area (ZPS) and area of community importance (SIC) which contain priority habitats as defined in the directive n. 92/43/CEE

Sensible areas:

a) Areas of protection and control (C and D)

b) IBA areas

c) Buffer zones of wetlands

d) Buffer zones of two kilometers surrounding the non-feasible areas

e) Industrial zones in the range of two kilometers near the SIC areas

f) SIC areas that do not contain priority habitats as defined in the directive n. 92/43/CEE

g) The areas subjected to the landscape goods restrictions

Revision of the legislation

TRegional legislation requires that ZPS and SIC areas be complied with when installing ground-mounted photovoltaic systems with a rated power greater than 10 kW. In this particular case, the ZPS and SIC areas of the Aegadian Islands include priority habitats as defined in Directive 92/43/ CEE, for example the plant "*Brassica macrocarpa*". According to this, solar panels cannot be installed. Here it is assumed that all plants are placed on abandoned agricultural land and on the roofs of buildings after a detailed environmental assessment.

2.3 Methodology

All of the above regulations form the basis for determining appropriate locations for the installation of renewable energy power plants. To better understand where these areas are located, it is recommended to use GIS software. GIS stands for "Geographic Information System" and is a software used to display information in a coordinate system, model it and link it to surfaces. The software used here is QGIS (Figure 2.3) [16]. The areas governed by the normative can be found in the SITR Geoportal (SITR stands for 'Sistema Informatico Territoriale Regionale') in the format REST, WMS, WFS metadata [17].

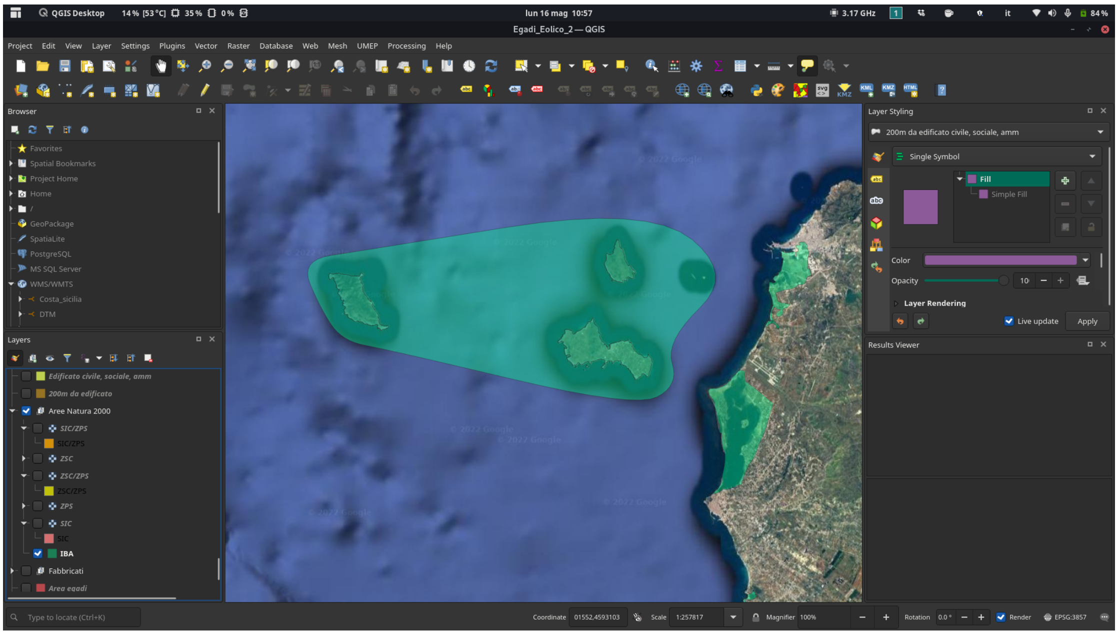


Figure 2.3: QGIS user interface. From left to right: layers selection, active layers, customization panel

2.3.1 Selection of the areas for renewable energy exploitation

After downloading all layers from the Internet and SITR, they are applied to a satellite base map, taken from Google Satellite. In Figure 2.4 an example of how layers look on the software.

The next step consists in overlapping the layers, where the empty area represents the area without legal restrictions. This one will be the zone where there could be

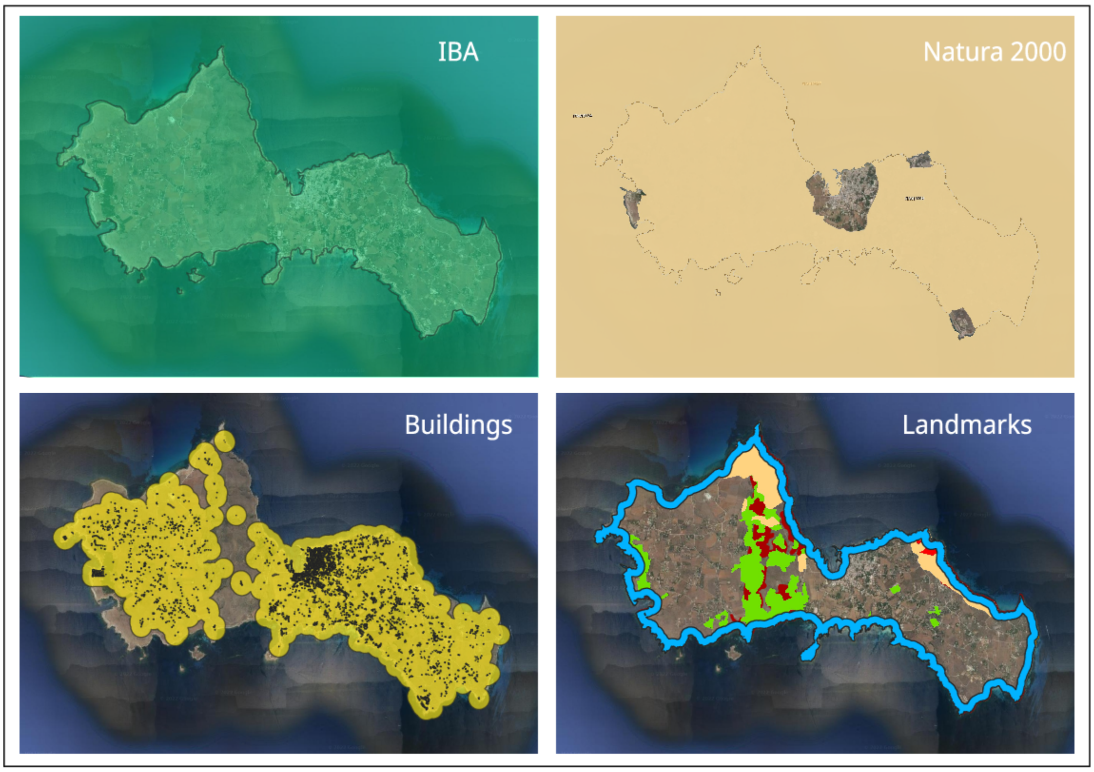


Figure 2.4: An example of how the layers representing the legislation look.

the installation of renewable power plants (see Figure 2.5). What happens next depends on what renewable technology should be installed in the area:

- **Wind turbines**: they require a special treatment because their efficiency is strictly dependent on the distancing between them in respect to the wind direction. A software has been used to analyze this aspect, WAsP [18].

- **Photovoltaic panels**: for PV panels the used approach depends on the type of installation. For the rooftop panels, there is another step done on QGIS, through the software UMEP [19]. UMEP stands for 'Urban Multi-scale Environmental Predictor' and it is used to calculate the solar radiation in areas where shadings are not negligible. Otherwise, for ground panels the approach is easier. After the selection of an area which can host the power plant, its dimensioning is determined after some approximation factors which counts for the distancing, the space for crossing of the vehicles, the inclination and other factors.

Figure 2.5: Example of an area where the installation of wind power plants is possible, after the assumptions on the regulations.

2.3.2 Wind turbines sizing

As mentioned earlier, the sizing of the wind turbines is done using the software WAsP [18]. WAsP is a software for the vertical and horizontal exploration of wind climate statistics in an area of interest. It simulates the energy production of wind sites as a function of turbine models, turbine placement at the site, and wind data [20]. The software requires the Generalized Wind Climate (GWC) file, which is downloadable from global wind atlas; it contains information regarding the wind climate of the analyzed zone as the wind speed, the temperature, the humidity, and others [21]. Afterward, in WAsP Map Editor it can be generated the vector map of the site of interest, which characterizes its orography and roughness. The vector map is fundamental for a correct analysis of the wind turbines performances. Their performing is strictly dependent on the characteristics of the terrain like the altitudes, the slope, the roughness and the obstacles.

The vector map together with the Generalized Wind Climate are useful to calculate the resource grid of the island, a map containing all the data required for

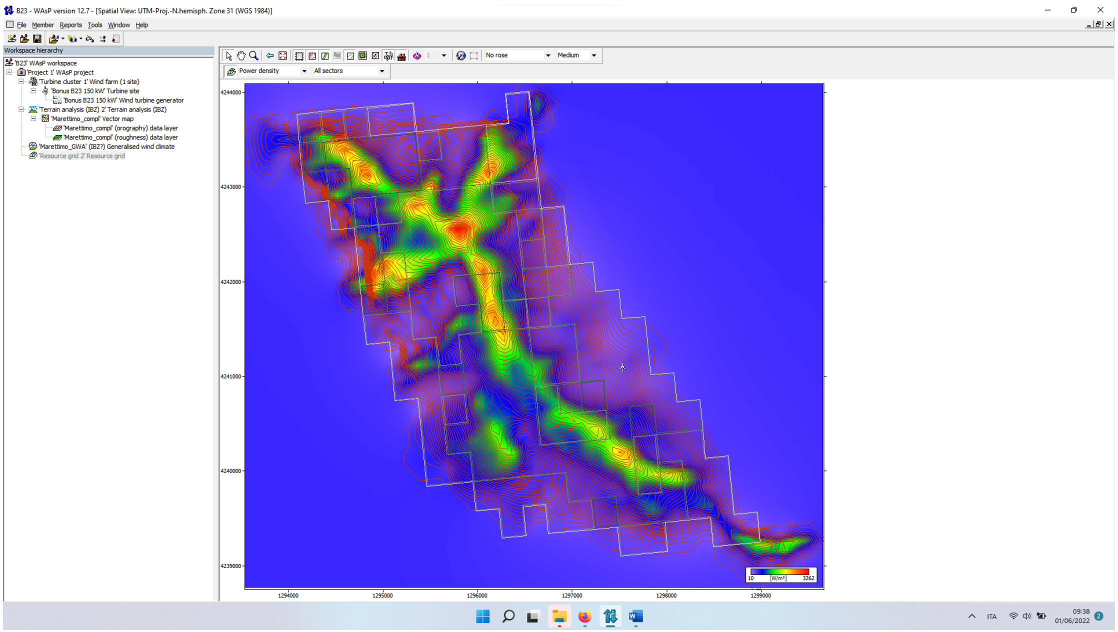
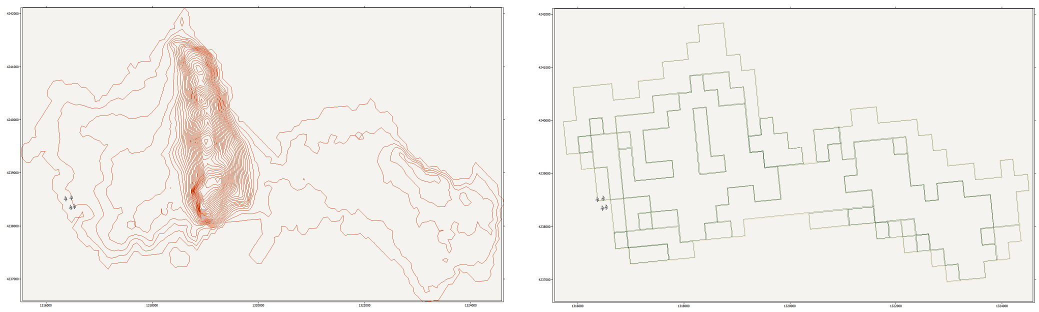


Figure 2.6: User interface of the software WAsP, for wind turbine site sizing

the wind turbine placing and dimensioning.



(a) Orography **(b)** Roughness

Figure 2.7: Examples of how vector map looks for Favignana island case study

At this stage, the last step consists in placing a turbine site where the legislation permits and then pair to it a turbine generator of the preferred size. Five turbine generators were used in this study: Bonus B23 150 kW, Vestas V90 3 MW, Enercon E126 7.58 MW, Enercon E53 800 kW and Enercon E82 3 MW [22, 23, 24, 25, 26].

If a turbine generator is not available on the tool database, it can be implemented with the software "WAsP Turbine Editor" [27], by inserting on the tables the power and the thrust coefficient related to the wind speed.

For sites containing more than one turbine, these should be placed with a correct spacing in order to reduce the wake losses and, consequently, increase the energy production. When more than one turbine are present on a site, the closer they are laterally and axially and the higher is the wake effect.
It consists in a reduction of the wind available energy, because absorbed by the turbines that are positioned ahead. According to the Italian normative, the distancing should be of 3-5 diameters laterally and 5-7 diameters in respect to the main wind direction (see figure 2.8). The prevailing wind direction can be obtained from the wind rose of the site, and it is the wind with higher mean speed values.

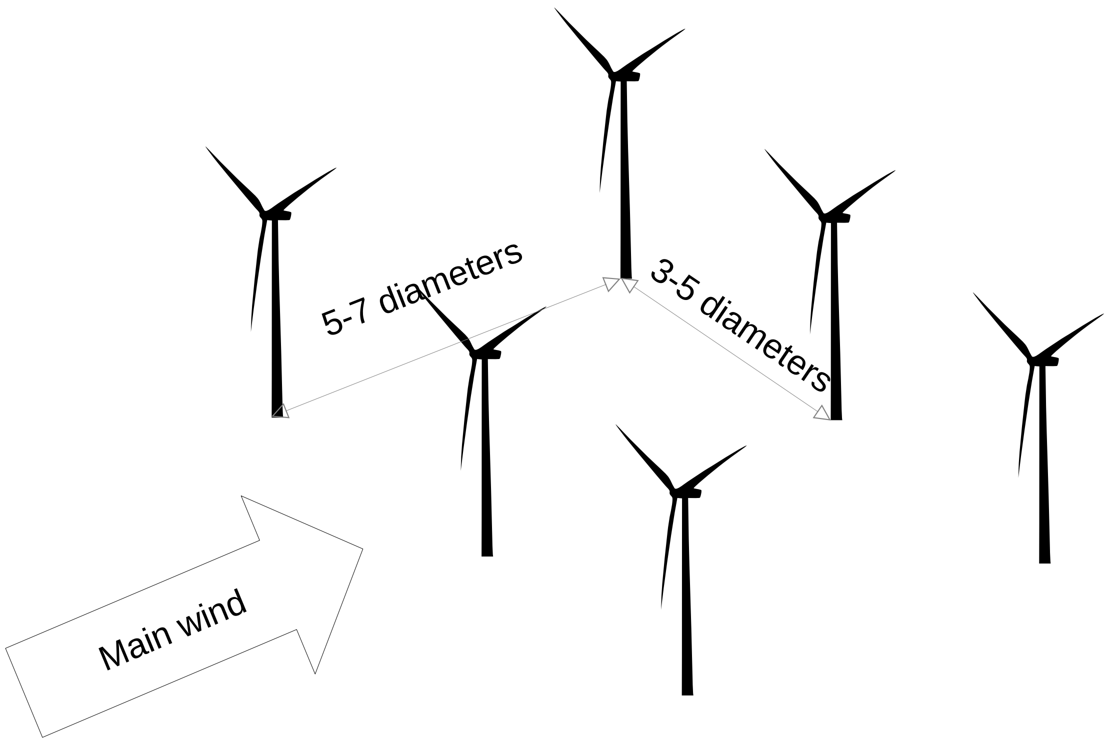


Figure 2.8: Distancing between the turbines in the same site [28].

After the sizing is completed, the simulation can be launched. The obtained results are the wake losses and the correlated total net energy produced by the site.

2.3.3 Sizing of rooftop photovoltaics

The installation of solar panels on the rooftops can surely help to reach a higher renewable power potential. In fact, if there are enough buildings on the island territory, the power potential of the rooftops solar panels could do the difference in fulfilling the energy demand. Firstly, not all buildings of Favignana can be used. In fact, the only buildings considered compatible with the installation of solar panels on the rooftops are the habitable buildings and the administrative buildings. The rooftops of graveyards and churches have been ignored. The rooftop's solar panels sizing was done through the plugin UMEP of QGIS and other post-processing elaborations [19]. The plugin develops a solar radiation map using as input the digital elevation models (DSM) of the terrain (Figure 2.9), the meteorological data (ERA5), the wall's aspect and the wall's height; the last two terms are obtained, after some calculations done on the plugin itself, from the DSM GeoTiff file.

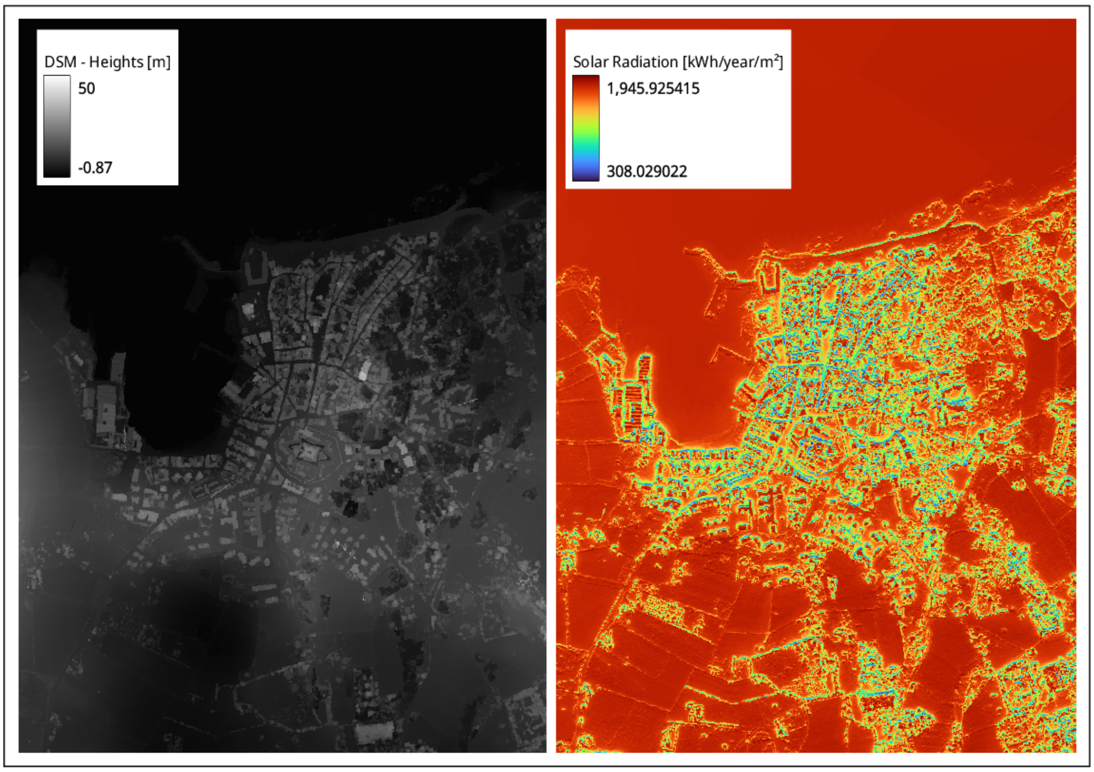


Figure 2.9: Favignana city center. Comparison between DSM and the solar radiation map calculated through it.

The next step consists in cutting off the surfaces that are not rooftops and the ones that have a low solar radiation value, because the payback time of the solar panels is directly correlated to the solar yield of them [29, 30], according to the following formula (M.C. Brito et al.):

$$Payback[year] = \frac{Panel\ Cost\ [\frac{€}{m^2}]}{SR[\frac{kWh}{m^2 \cdot year}] \cdot \eta \cdot PR \cdot EC[\frac{€}{kWh}]} \tag{2.1}$$

Where Panel Cost is the cost of the solar panel, SR is the yearly solar radiation per square meter, η is the panel efficiency, PR is the Performance Ratio, EC is the Energy Cost. The rooftops should have then a solar radiation higher or equal to the value of cutoff. In this case a value of 1200 kWh/m²/year has been chosen, in order to crop off from the rooftops, the parapets, the water tanks and other obscuring objects. In figure 2.10 the results of this process.

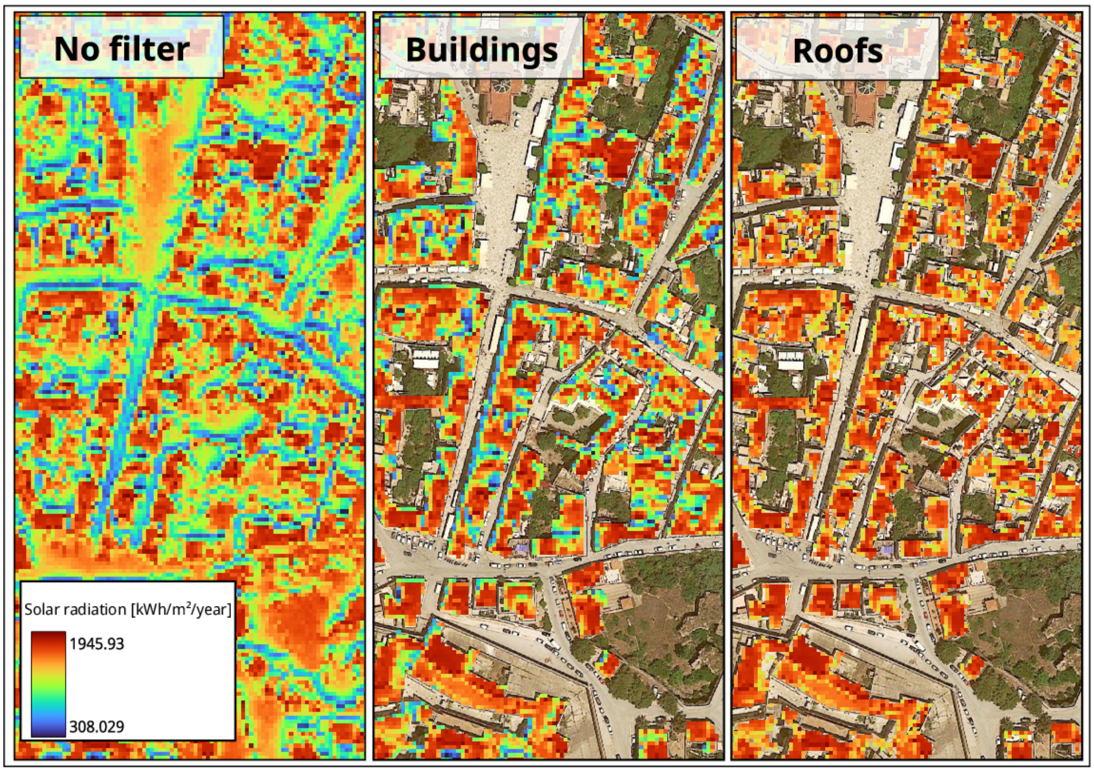


Figure 2.10: The three stages of crop of the yearly solar radiation map

Considering a panel cost of 300 €/m², a solar radiation of 1200 kWh/m²/year, an efficiency of 0.19, a performance ratio of 80% and an energy cost of 0.1555 €/kWh, the payback time would be about 10 years [31].

The resulting rooftops surfaces in the last tab of the figure 2.10 were then used to obtain the total renewable power potential of the islands, after the implementation of some corrective factors [32]. The solar panel surface is calculated through the equation:

$$S_{Solar\ Panel}[m^2] = \frac{S_{Rooftop}[m^2]}{cos(\theta_r) \cdot cos(\beta)} \cdot C_{RT} \cdot C_F \cdot C_{ST} \cdot C_{COV} \cdot C_{SH} \tag{2.2}$$

Where the terms are:

- $S_{Solar\ Panel}$: surface of the solar panel [m^2].
- $S_{Rooftop}$: horizontal surface of the rooftop [m^2].
- θ_r: tilt angle of the facades of the rooftop [°]. Given that the rooftops of the islands are horizontal, it is assumed equal to 0°.
- β: tilt angle of the solar panel in respect to the surface of the rooftop [°]. According to the analysis on PVGIS, the optimal one is $\sim 33°$ for all the islands [33].
- C_{RT}: rooftop-type correction factor. The rooftops of the islands, as mentioned before, are flat. This correction factor is 1.
- C_F: feature coefficient (for chimneys and HVAC systems). Assumed to be 0.7 [32].
- C_{ST}: solar-thermal correction factor, used to assume the presence of solar thermal panels on the rooftops. Assumed equal to 0.9 [32].
- C_{COV}: covering index coefficient, which represents the space between the solar panels and the walkable space. Assumed equal to 0.45 [32].
- C_{SH}: shadowing correction factor. It represents the usable fraction of the rooftops that is not subject to shadowing. Thanks to the precedent analysis on QGIS, this term has been ignored.

The result of these corrections applied on all the rooftops of the islands is the total area of PV panels that could be installed. If multiplied for the efficiency of the panels, this term indicates the total rooftop photovoltaic power potential.

2.3.4 Sizing of ground-mounted photovoltaics

The sizing of ground photovoltaic panels required a different and less complex approach. It required to find some uncultivated terrain on the same radiation map of the paragraph 2.3.3 and apply on their areas some correction factors, in order to obtain the usable area for the installation of solar panels [34]. This can be summarized in the equations:

$$Area_{PV}[m^2] = Area_{Site}[m^2] \cdot PF \cdot GSR \tag{2.3}$$

$$PVPP[kW] = Area_{PV}[m^2] \cdot \eta \cdot G_{STC}\left[\frac{kW}{m^2}\right] \tag{2.4}$$

Where:

- *PF*, packing factor: it represents the ratio between the effective surface occupied by the panels and the area occupied by the PV generator system, which includes the arrays and their distancing. It depends on various conditions as the shading criteria, the latitude (Φ), the declination angle (δ), the sun elevation (γ_s) the tilt angle (β) and on the azimuth angle (Ψ_s), according to the equation 2.5 and 2.6. In Martìn's work two shading criteria are mentioned. The first one avoids the inter-row shading at noon during all the year, which means that the plant should be dimensioned in the winter solstice, with a declination of -23.45°. The second shading criteria, instead, avoids shading for 2 hours before and after noon. The shading criteria used in this study is the first one.

  Sun elevation:
  $$\gamma_s = sin^{-1}[cos(sin(\Phi - \delta))] \tag{2.5}$$

  Packing Factor:
  $$PF = \frac{l}{d} = \left(cos\beta + \frac{sin\beta}{tan\gamma_s} cos\Psi_s \right) \tag{2.6}$$

- *GSR*, Generator-To-System area ratio: it is the ratio between the area of the PV generator system and the site area. It depends on the size and on the shape of the terrain, but in general it is in the range 0.7÷0.85. For a conservative approach, a value of 0.7 was chosen.

- *PVPP*, Photovoltaic Power Potential: total photovoltaic potential of the site area.

- G_{STC}, Global solar radiation on a horizontal surface. 1 kW/m^2 ca.

The estimation of the energy produced by the plant is performed by the "Photovoltaic Energy Potential" equation:

$$PVEP = PF \cdot GSR \cdot \eta \cdot I_a \cdot PR \cdot (1 - F_s) \tag{2.7}$$

I_a is the annual horizontal irradiation on the panel, also called solar radiation by the software UMEP, and it is the solar radiation that hits the surface during an average year. F_s is the shading factor, assumed equal to 0.05 [34].

2.3.5 Ferries

As often mentioned in this study, the multiple-scenarios simulator models the scenarios in function of several variables. One of the variables included in the simulations is the weighing of the ferries transport on the local energy demand of the islands. This is done in a perspective of energy transition to zero carbon emissions.

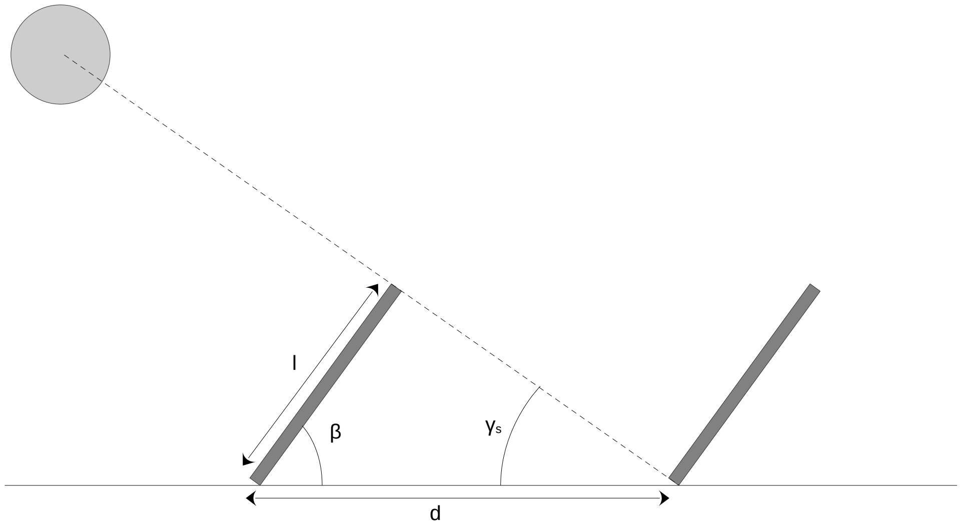


Figure 2.11: Spacing of the ground panels

In fact, despite the actual ferries refuel on Sicily mainland, their carbon emissions are strictly correlated to the fluxes from/to the islands, specially considering the tourism fluxes. So, if the objective of the stakeholders is also to drop to zero the carbon emissions of the ferries, the implementation of an electric ferry could be one of the available options.

Before dimensioning the electric ferries, it is necessary the study of the traditional ferries, in the context of the islands. it is done using a reference diesel consumption given by the ferries companies which are currently present in Sicily, Siremar and LibertyLines, and comparing it with an estimated diesel consumption. The developed methodology consisted in finding all the routes from/to each island during a month, through a website for marine traffic tracking [35].
The observed period falls in the low seasons months of November and December. In these two months the traffic through the archipelago is reduced, this is also confirmed by the timetables of the routes of both the companies [36, 37]. In the database of the routes were available all the routes, from, to and between the islands, including also the routes of non-passenger boats. After the selection of

the routes made only by the companies previously mentioned, a technical analysis of the ferries were done. Liberty lines mainly owns fast hydrofoils [38]; Siremar, instead, is the only company which owns ro-ro passenger ferries, that are slower than the ferries of the other company, but permit the transport of vehicles [39]. In order to reduce the computational time and the complexity of the models, only one type of ferry has been considered, obtained by calculating the average of the ferries available on the records. The resulting ferry has an average power of 3200 kW, but the other characteristics of the ferry like the travelling time, the average velocity and, consequently, the traveled distance and the energy consumed for each route, particularly vary between the islands. Each of these variable has been calculated by using the dataset downloaded from the routes-tracking website.

The destination ports of the routes are five, and the routes performed by the ferries between them, ignoring the direction, are only seven:

- Favignana - Trapani
- Favignana - Levanzo
- Favignana - Marettimo
- Favignana - Marsala
- Levanzo - Trapani
- Levanzo - Marettimo
- Marettimo - Trapani

These are direct routes between the ports, monitored through the database mentioned above, and they only refer to the low season period. From the timetables of the companies, it can be observed that there are, on average, two more daily routes per destination in the summer period, in respect to the number of routes during the low season. In the Table 2.1 the results of the analysis.

Ports	**Daily routes**	**Distance [nm]**	**Average velocity [kn]**	**Travel time [h]**
Favignana - Trapani	18	10	23	0.70
Favignana - Levanzo	11	3.8	22.3	0.23
Favignana - Marettimo	4	15.3	24.7	0.63
Favignana - Marsala	4	12	24	0.50
Levanzo - Trapani	8	8	27.3	0.30
Levanzo - Marettimo	4	13.2	27.5	0.53
Marettimo - Trapani	2	26	26.3	1.05

Table 2.1: Analysis on the observed dataset

The "daily routes" column includes all the roundtrips between the two ports. The scenarios simulation is done referring only to the energy system of one island per time, so the roundtrips should be reduced only to the ports of Favignana, Levanzo and Marettimo, without specifying the destination ports. As a consequence, the routes distances and consumption cannot be distinguished, so the only available information could be the average consumption per route. To achieve this, the trips were divided in two categories: island-mainland trip and island-island trip, and then added together with the following rule:

$$\text{Avg. island's daily routes} = \text{Routes}_{\text{Island-Mainland}} + \frac{\text{Routes}_{\text{Island-Island}}}{2} \tag{2.8}$$

The island-island routes are divided by two in order to avoid that the trips burden only on one island.

In the Table 2.2, the results of this analysis. The route characteristics (velocity, distance and travel time) are a weighted average over the number of routes between each couple of ports. For example, the average velocity for a generic Favignana route is calculated as follows:

$$Avg.V[kn] = \frac{V_{FT} \cdot DR_{FT} + V_{FL} \cdot \frac{DR_{FL}}{2} + V_{FMT} \cdot \frac{DR_{FMT}}{2} + V_{FMS} \cdot DR_{FMS}}{DR_{FT} + \frac{DR_{FL}}{2} + \frac{DR_{FMT}}{2} + DR_{FMS}} \tag{2.9}$$

Where, V is the velocity in knot and DR are the daily routes. The subscripts stand for:

- FT: Favignana - Trapani
- FL: Favignana - Levanzo
- FMT: Favignana - Marettimo
- FMS: Favignana - Marsala

The diesel consumption per route is calculated with the following equations.

Net energy consumed per route:

$$\text{Net Energy}\left[\frac{kWh}{route}\right] = P[kW] \cdot LF \cdot t_{Trip}\left[\frac{h}{route}\right] \tag{2.10}$$

Gross energy consumed per route:

$$\text{Gross Energy}\left[\frac{kWh}{route}\right] = \frac{\text{Net Energy}\left[\frac{kWh}{route}\right]}{\eta} \tag{2.11}$$

Port	**Routes [Routes/day]**	**Avg. distance [nm]**	**Avg. velocity [kn]**	**Avg. travel time [h]**
		LOW SEASON		
Favignana	29.5	9.47	23.12	0.58
Levanzo	15.5	7.18	25.55	0.30
Marettimo	6.0	18.17	26.17	0.74
		HIGH SEASON		
Favignana	39.50	9.66	23.19	0.57
Levanzo	23.5	7.54	25.74	0.32
Marettimo	14.0	19.29	26.19	0.78

Table 2.2: Routes relative to the ports of the islands. The other columns are a weighted average of the data available in the Table 2.1 in respect to the number of routes

Diesel consumption per route:

$$\text{Diesel Consumption}\left[\frac{t}{route}\right] = \frac{\text{Gross Energy}\left[\frac{kWh}{route}\right]}{1000 \cdot HHV\left[\frac{kWh}{kg}\right]} \tag{2.12}$$

In the Eq.2.10, P is the maximum power of the engine, LF is the load factor, and t_{Trip} is the travel time. The load factor is the ratio between the power generated by the engine and its maximum limit and for passengers ferries it varies in the range 40-100%, for this study a LF of 90% has been chosen [40]. For the calculation of the gross energy consumption 2.11, the efficiency of the diesel engine is assumed to be equal to 50% [41]. Through the equations 2.10 and 2.11 it can be calculated the net diesel consumption per route, assuming that the high heating value of the diesel is 12.46 kWh/kg [42].

For the electric ferry analysis, instead, it is taken as reference the Danish project "E-Ferry Project" [43]. The input data like the routes per day, the engine power, the load factor and the net energy consumption are assumed to be equal to the data calculated above. What is different in this case is the engine efficiency and an additional term which is the roundtrip efficiency of the batteries, the first assumed to be 95% and the latter is assumed equal to 86% [44, 43]. In the Table 2.3 the results.

The high season period is approximately 92 days long, according to the timetables of the company "Liberty Lines" [36]. According to that, the yearly consumption of the ferries could be calculated by multiplying the number of seasonal days for the daily consumption, obtaining a consumption of 5067 t of diesel approximately. The actual fuel consumption, during the year 2019, is instead of 4936 t, according

Diesel Ferry

	Energy Consumption [MWh/route]	**Diesel Consumption [t/route]**
Favignana	3.33	0.2671
Levanzo	1.79	0.1436
Marettimo	4.38	0.3518

Electric Ferry

	Electricity Consumption [MWh/route]
Favignana	2.04
Levanzo	1.1
Marettimo	2.68

Table 2.3: Comparison between the Diesel and the electric ferries, consumption per route.

to the data provided by the companies. By comparing the two values, it appears that they differ by only 2.65%. This means that the analysis, despite all the assumptions done, could be used for the estimation of the ferries consumption in the models. If the data provided by the companies were more detailed and they contained information such the number of routes, a more accurate analysis could be performed, in order to test the methodology above.

2.4 Favignana

Favignana is the most populous island in the archipelago, with 3407 inhabitants. It extends for 19.8 km^2; its terrain is mainly characterized by plain, the only exception is a hill, in the center of the island, that splits it from North to South (see Figure 2.12). Favignana, as the other islands in the archipelago, is highly frequented by tourists, especially in the summer period.

Figure 2.12: Favignana island on a satellite view

2.4.1 Energy System

Electricity Generation

None of the island in the archipelago is connected to the grid, in fact the main contributor to the electricity generation in Favignana is SEA diesel power plant, with an installed capacity of 12 MW [45]. Alongside the diesel power generation, there are few PV power plants for a total capacity of 361 kW, referring to the year 2021. The distribution covers all the island territory, through three electricity distribution lines. Two of them power the city center, the other one instead provides energy to the rest of the island.

Demand

Looking at the electricity demand of the island, there is an evident increase of energy request during the summer period, probably due to the tourism fluxes and to the use of air conditioners (Figure 2.13). The cumulative yearly demand of Favignana amounts to 15 GWh ca. in 2019, and it can be divided into three main categories:

- Residential domestic demand
- Non-Residential domestic demand
- Activities and services demands, which includes:
  - Activities
  - Accommodation business: Hotels, B&B, hostels etc.
  - Public services as lighting
  - Diesel running consumption (offices, pumps, lighting, etc.)
  - Other medium voltage users

The reason behind the inclusion of both the activities and the services in only one item is that in the bill tables there are not enough information to distinguish them.

Fossil fuels consumption

The only information available on the fossil fuel consumption are the amount of fuel consumed by the diesel generators, the fuel consumption of the ferries and the in-land diesel distribution, destined for the marine vehicles. Despite the presence of about 50 km of roads and one Eni gas station on the island, there aren't informations regarding the distribution of fossil fuels for automotive transport [46]. During 2019 the diesel consumption for electricity generation was of 3514 t. The ferry's diesel consumption is not directly bonded with the islands consumption of fuels, in fact the ferries refill on Sicily mainland; but it is important to include it in the analysis, because it is still a service for the islands. In fact, the islands can only be reached through the sea and, private boats aside, the ferries are the only mean to transport people and vehicles. Furthermore, they contribute to CO_2 emissions, and they should at least be considered during the analysis for CO_2 reduction. In this specific case, ferries consumption were introduced into the model of the island

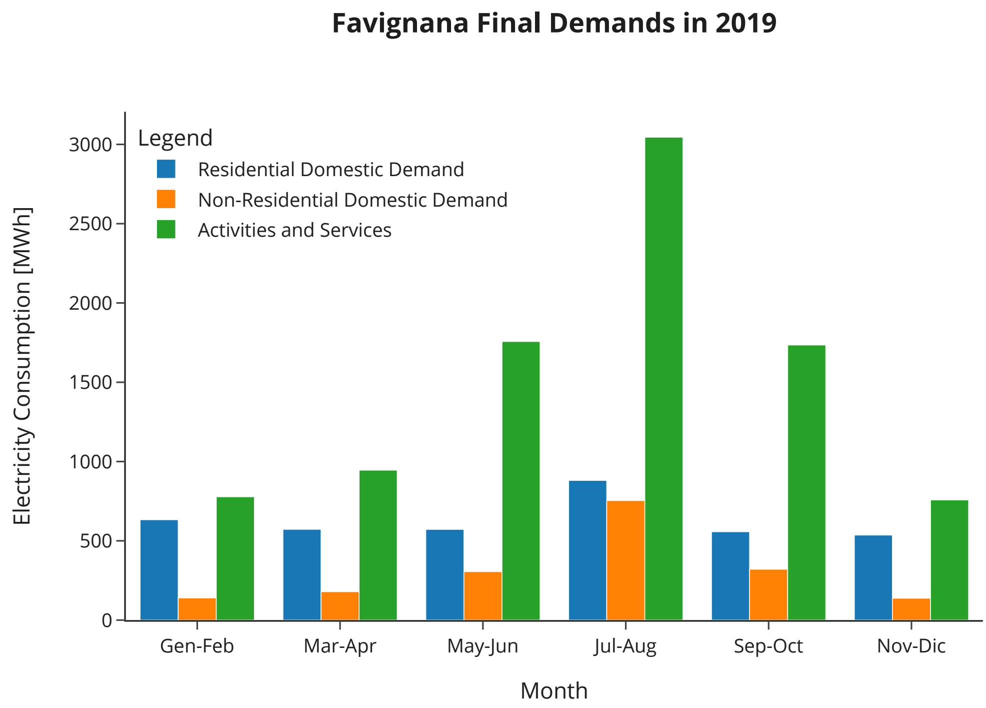


Figure 2.13: Electricity consumption in Favignana during 2019

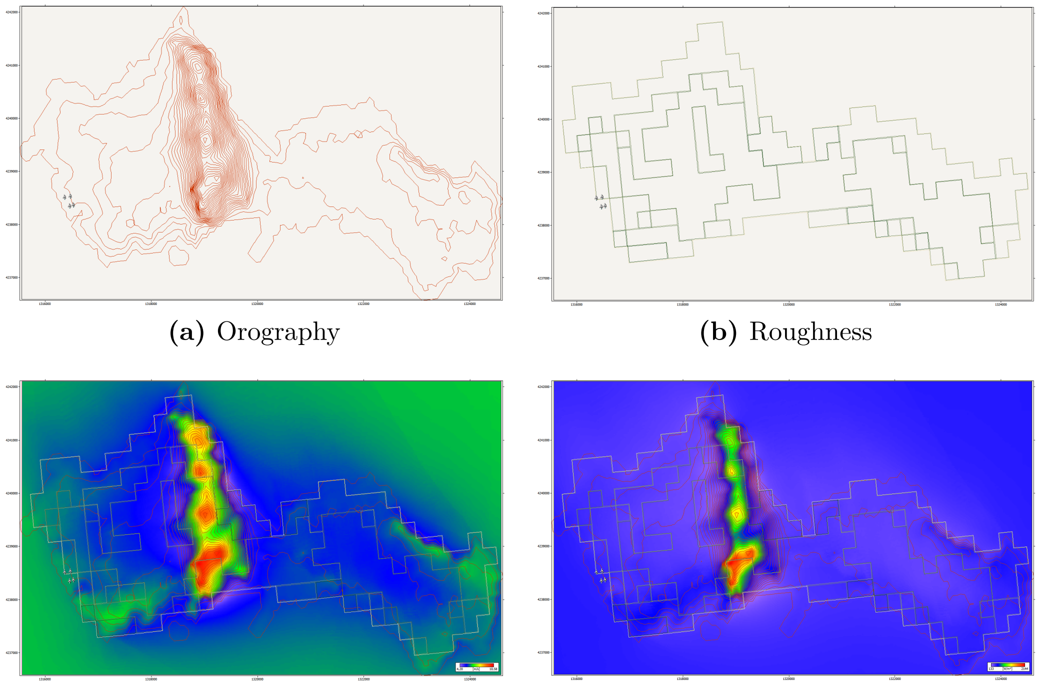
as a parameter of the scenario analysis. The 2019 ferry's consumption has been calculated referring to the methodology in the section 2.3.5, obtaining a value of 3129 t of diesel consumption related to Favignana.

2.4.2 Renewable power potential

Wind generators

In Favignana there is an abundance of wind energy, but the site of interest is unfortunately in an area where the wind is weak. In fact, the higher values of mean wind speed are placed on the top of the hill of the island, where the area is protected by Natura 2000 (Figure 2.14). The prevailing wind comes from South-Southeast with a frequency of 16.7% (see Figure 2.15).

The only suitable site is a portion of the west coast of the island, near a summer residence village (Figure 2.16). For the installation of the turbines, three turbine sizes were considered: small, medium and large (see Table 2.4).
The selection of three different turbines was done in order to achieve a more



(a) Orography (b) Roughness

(c) Mean wind speed (d) Power density

Figure 2.14: Most important wind-related characteristics of Favignana. To be noticed, the highest values of wind speed and power density are on the top of the hill.

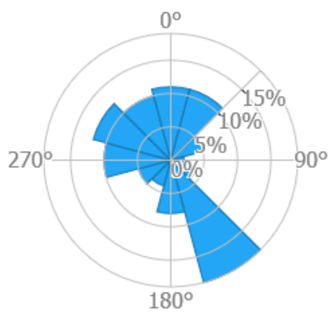


Figure 2.15: Wind rose of the island of Favignana [21]

accurate analysis of the energy scenarios of the island. In fact, the main function of the multi-scenarios tool is to simulate and compare the results of multiple energy scenarios. By introducing three different sizes of the turbines, it is possible to compare their costs and their contribution to the satisfaction of the annual demand,

and, afterward, help the stakeholders to choose the best solution they need.

Figure 2.16: Wind site of Favignana

Model	n° turbines	Nominal Power [MW]	Hub Height [m]	Rotor Diameter [m]	Energy Production [GWh/year]
Bonus B23	4	0.15	30	23	1.5
Vestas V90	1	3	80	90	8
Enercon E126	1	7.58	136	126	20.7

Table 2.4: Wind turbines models of Favignana

The annual production of the first model is of 1.5 GWh, of which 3% are wake losses, for the Vestas V90 it is of 8 GWh and 20.7 GWh for the E126 wind turbine.

Only the larger turbine can in theory full satisfy the annual demand of Favignana, the other two, instead, need to be accompanied by at least other forms of energy production. In any case, in a free carbon perspective, the energy portfolio should be a mix of different renewable energy sources. The turbine should indeed be accompanied by PV panels and storage systems.

Rooftop photovoltaics

Favignana, as already specified, is the most populous island in the archipelago. The buildings are in fact placed everywhere in the territory, with a higher density near the city center. On the island, the buildings compatible with the installation of solar panels on the rooftops are 2042, for a total rooftops' surface of 363429 m^2. But, applying a cutoff solar radiation of 1200 kWh/m^2/year, this number reduces to 309966 m^2. Afterward, as mentioned in the methodology paragraph, this surface should be further reduced with some correction factors. The calculated PV area is 105338 m^2, equal to 20 MW if considering an efficiency of 0.19.

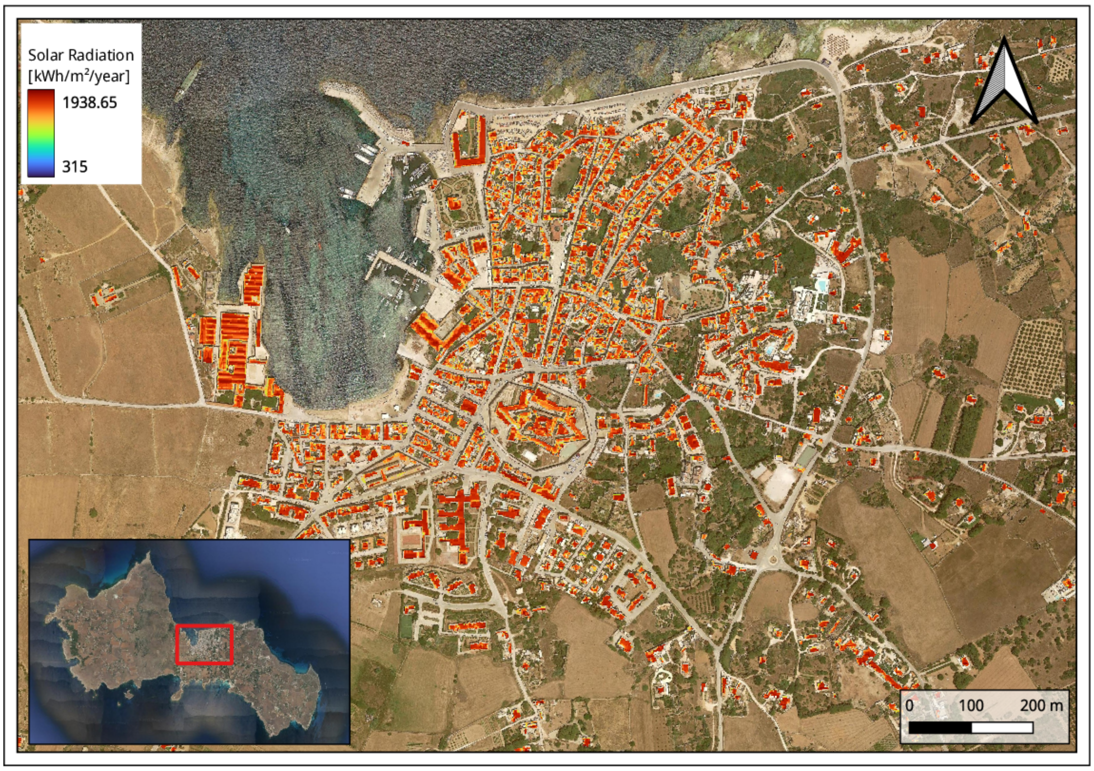


Figure 2.17: Solar radiation on the rooftops of Favignana

The average solar radiation on the rooftops, calculated on QGIS, is of 1634 kWh/m^2/year, which means that the energy production of the solar panels could be approximately of 28.12 GWh/year if it is assumed a system efficiency (electricity production + conversion) of 0.19*(1-0.14), where 0.19 is the efficiency of the solar panels and 0.14 corresponds to the system losses.

Ground photovoltaics

On the island of Favignana, there are several uncultivated lands; each one of them can be a potential terrain intended for the installation of photovoltaic panels, after an adequate environmental impact assessment. For obvious reasons, not all the free lands can be used for that, and it isn't either the purpose of this study. So, only three terrains were chosen in order to increase the renewable power potential of the island. The selection criteria consisted in finding one terrain, or more if near enough, that:

- It is distant from the coast, in order to reduce the visual impact.
- It has a gross area larger than ~11000 m^2, to have a power plant of 1 MW at least.
- It has a mean solar radiation higher than 1500 kWh/m^2/year.
- It is not cultivated.

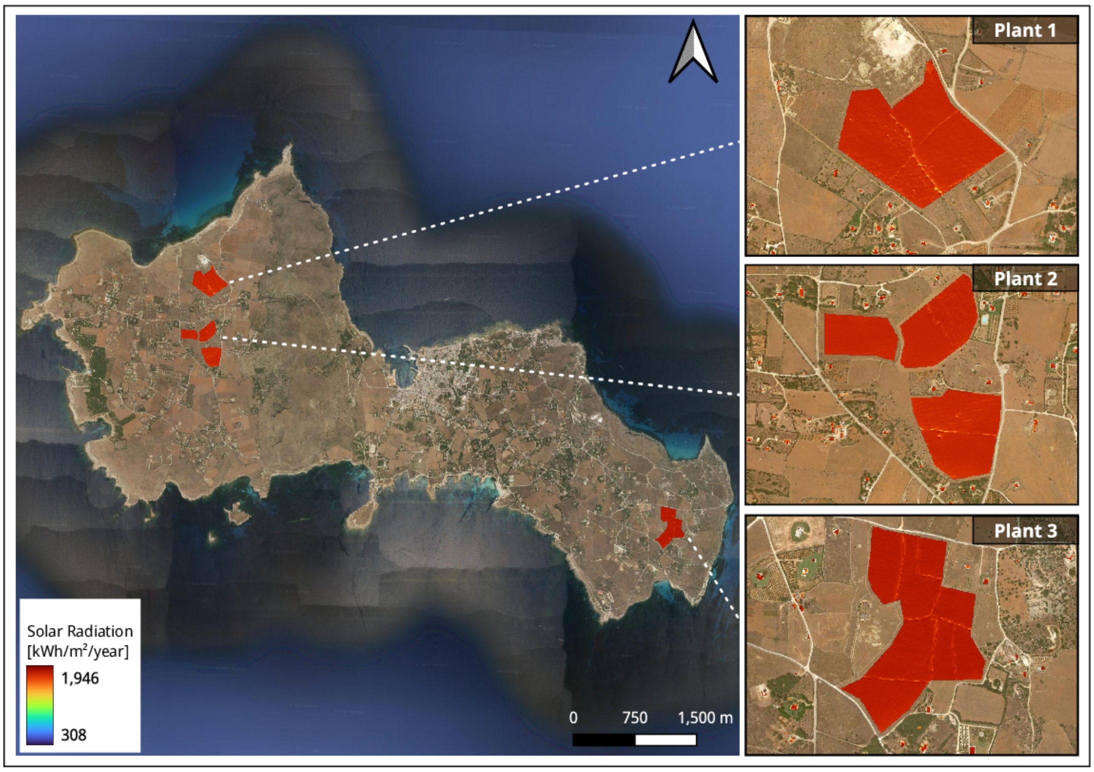


Figure 2.18: Ground PV power plants of Favignana.

	Land Surface [m²]	Generator to System Ratio	Packing Factor	Panels Surface [m²]	Efficiency	PVPP [MW]	Average solar radiation [kWh/m²/year]	PVEP [GWh/year]
Plant 1	90970	0.7	0.6688	42589	0.19	8.1	1757	12.22
Plant 2	102830	0.7	0.6688	48140	0.19	9.1	1780	14.00
Plant 3	92901	0.7	0.6688	43492	0.19	8.3	1820	12.93
TOT	**286701**	**-**	**-**	**134221**	**-**	**25.5**	**-**	**39.15**

Table 2.5: Supposed PV power plants in Favignana.

As can be seen from the Table 2.5 the estimated energy production can abundantly satisfy the energy demand of the island (∼15 GWh). But, the analysis above should not be considered as strictly dependent on the plant localization and sizing, for two reasons: the plants on the island can be smaller and located almost everywhere, and the sizing of the three plants above was done on the perspective of multi-scenarios simulation. In fact, the models use the maximum PVPP as a variable, varying it within the values BAU/33%/66%/100% of the PVPP calculated above. Furthermore, the oversizing of PV panels is a must, considering that the models also include the variables of annual increase of the demand of 5% and of the ferries inclusion in the island consumption. The latter, could weigh on the electricity demand if there is the constraint of CO_2 emissions reduction.

2.5 Levanzo

Levanzo island is the smallest island of the archipelago, with a surface of only 5.6 km^2 and 208 inhabitants. Characterized by a hilly territory, the island is an uncontaminated land located at north in respect to Favignana. It is a very popular tourist destination, particularly during the summer period. The island's territory is sparsely inhabited, with the vast majority of homes collocated in the town at south.

Figure 2.19: Satellite view of Levanzo island.

2.5.1 Energy system

Like the other islands of the archipelago, Levanzo is not connected to the grid and the majority of the energy demand of the island is satisfied through a diesel power plant. With a nominal power around 1.12 MW, the power plant is the only main source of energy of the island, only accompanied by some solar panels for a total installed capacity of 27.82 kW (2021) [47].

Demand

The cumulative yearly energy demand is of 691.5 MWh in 2019. According to the billed energy tables, it is divided in:

- DOM, domestic electricity demand. It contains both the residential and non-residential demands. In order to perform a similar analysis in respect to the other islands, it has been divided in the two shares, using as reference their ratio in Favignana island.
- AUBT, auxiliary low tension. It refers to the activities, the services and other users.
- IPBT, public illumination.

As specified above, the consumers categories have been reclassified in order to guarantee a better understanding of the results if compared to the other islands. Consequently, the two categories "AUBT" and "IPBT" collapsed in the category "ATSE" (Attività e Servizi) while DOM has been divided in the categories "RSD" and "NRSD".

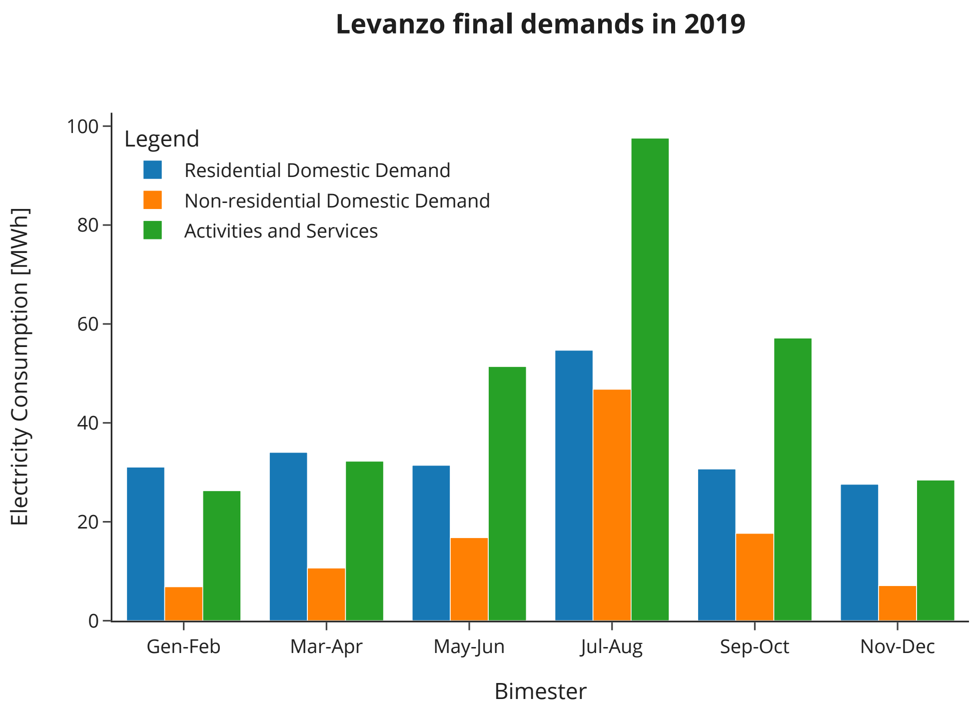


Figure 2.20: Levanzo final demands in the year 2019

Fossil fuels consumption

The island of Levanzo, unlike Favignana, has no roads. Of course there are vehicles, but since there is no gas station, they have to refuel in Favignana or in Sicily. The consumption of fossil fuels on the island is largely related to the generation of electricity by the diesel generators. In 2019, 171 tons of diesel were consumed for electricity generation, while diesel consumption for ferry traffic in the same year was 913 tons.

2.5.2 Renewable power potential

Despite the abundance of renewable energy sources available on the islands, they could not be fully exploited. Due to the island's hilly orography of the island and the presence of protected areas, wind turbines cannot be placed throughout the island's territory. PV panels can instead be placed in a few locations, e.g. on the roofs and on small undeveloped areas scattered around the island.

Wind generators

In Levanzo there aren't suitable places for the installation of wind turbines, as it is possible to see in the figure 2.22. But, apart from the restrictions, the island is rich of wind which could be potentially used for power generation. In fact, during the year the average wind speed on the island is 8 m/s ca. with a mean power density of 832 W/m².

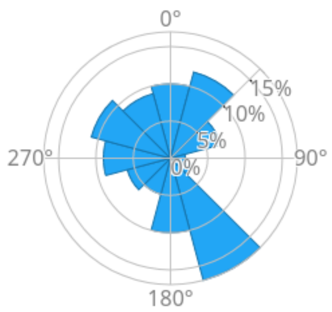


Figure 2.21: Wind rose of Levanzo.

Figure 2.22: Wind regulatory restrictions applied on Levanzo territory.

Rooftop photovoltaics

Levanzo is the island in the archipelago with the lowest number of buildings, of which 169 are eligible for the installation of rooftop solar panels. The total surface of the buildings' rooftops is of 19111 m^2, which reduces to 18133 m^2 if the filter of minimum solar radiation of 1200 kWh/m^2/year is applied. This is the surface available for the installation of solar panels, but it is not the effective area of them. To obtain that, another correction must be done, as specified in the section 2.3.3. The net panels surface would be then 6162 m^2, equivalent to 1.17 MW if it is assumed an efficiency of 0.19. With an average solar radiation of 1624 kWh/m^2/year and considering a panel efficiency of 0.19 and 14% of system losses, they could produce 1.63 GWh/year of electricity.

Figure 2.23: Solar radiation on the rooftops of Levanzo

Ground photovoltaics

For the sizing of the ground PV power plant, a terrain on the top of the town has been chosen. The choosing criteria, similarly to the case of Favignana, consisted in finding an uncultivated terrain which is far enough from the coast. Its surface is of 99187 m^2, which becomes 46685 m^2 after the application of all the correction factors, with an equivalent nominal power of 8.87 MW if it is assumed an efficiency of 0.19. The terrain is well exposed to the sunlight with an average solar radiation of 1755 $kWh/m^2/year$, which means it can produce up to 13.39 GWh/year if a system efficiency of 0.19*(1-0.14) is assumed [33].

Figure 2.24: An eligible area for the PV power plant of Levanzo

2.6 Marettimo

Characterized by a mountainous terrain, Marettimo is the island located at the east of the archipelago. It has 684 inhabitants, all mostly located in the town of Marettimo, in the east of the island. The rest of the territory is uninhabited, which makes the island a highly sought after tourist destination for a full-immersion journey in the nature. This adds difficulties to the sizing of the renewable power plants, trying to install them without spoiling the beautiful nature of the place.

Figure 2.25: Satellite view of the island of Marettimo

2.6.1 Energy system

Electricity generation

The electricity generation of the island of Marettimo is provided by the diesel power plant SELIS, by powering six diesel generators for a total nominal power of 1.8 MW [48]. To support the power generation of the diesel power plant, there are few photovoltaic plants in the island territory for a total installed power of 17 kW (at 2019). Because of the small size of the city, the electricity network consists only of one line, along the east cost of the island. This means that if it is required the installation of renewable generators outside the range of the network, the latter should be expanded. This study doesn't take in consideration this issue, but it is worth mentioning it.

Demand

During 2019 the electricity consumption of Marettimo amounted to ~2 GWh. The billed energy makes a distinction between the demands categories dividing them into:

- **Domestic**. It includes all the domestic consumption, residential and non-residential.
- **Non-Domestic**. Includes all the demands related to the activities, stores, B&B and others.
- **Public lighting**.

In order to remain in line with the analysis carried out for Favignana, the three categories mentioned above have been converted into the categories: residential demand, non-residential demand and activities and services. "Activities and services" incorporates both the voices, "non-domestic" and "public lighting", while "domestic" has been divided into "residential" and "non-residential" with the same proportions of Favignana (see figure 2.26).

Fossil fuels consumption

In Marettimo the fossil fuels consumption is mainly correlated to the production of electricity by the diesel generators, which consumed about 472 t of diesel in the year 2019. There aren't informations regarding the fossil fuels consumption for the transport sector, especially for the use of land vehicles. In Marettimo there is only a gas station, which refills only marine vehicles, for an amount of 91 tons of diesel and 41 tons of gasoline during 2019 [49]. In the other hand, being the island so hilly, the land transport could be really limited. The diesel consumption of the ferries, instead, are calculated with the methodology explained in the paragraph 2.3.5 and they amount to ~1026 t/year.

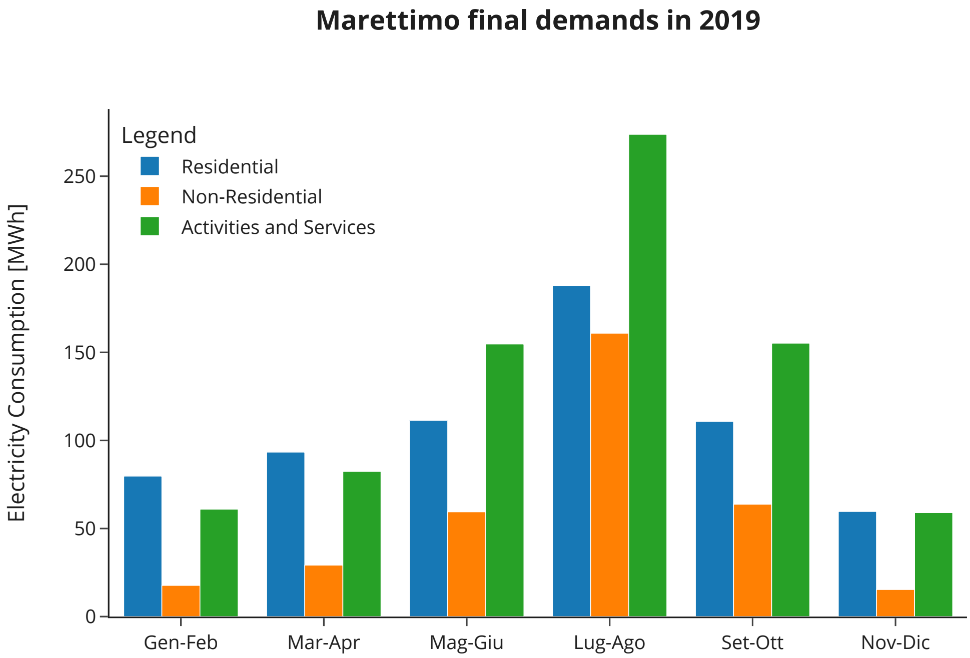


Figure 2.26: Final demands in Marettimo during 2019. The demand's increase relative to the summer period is probably correlated to the increase of tourism fluxes and to the use of air conditioning systems. To be noticed that only during the low seasons periods the activities demand is lower than the residential demand. However, it is always lower than the domestic demand (sum of residential and non-residential demands).

2.6.2 Renewable power potential

The island, similarly to the other islands of the archipelago, is rich of renewable sources, especially of wind energy. As could be seen in the paragraph, the orography of the island particularly privileges the wind energy production, with really high power densities proportionally to the mountain height.

Wind generators

In Marettimo there is only one site compatible with the installation of turbine generators and the wind data refers to it. In fact, due to the geomorphology of the island, the wind directions and their velocities change drastically in function of the location on the island. The site is located near the town on the east side of the island, and it is characterized by only one spot suitable for the installation of the turbine. So whatever is the size of the turbine, only one of them could be installed. For this site, due to its closeness to the town, three models of turbines have been simulated of three sizes: small, medium and large (see table 2.6).

Model	n° of turbines	Nominal Power [MW]	Hub Height [m]	Rotor Diameter [m]	Energy Production [GWh/year]
Bonus B23	1	0.15	30	23	0.244
Enercon E53	1	0.8	60	53	2.036
Enercon E82	1	3	69	82	5.846

Table 2.6: Wind turbines configurations of Marettimo

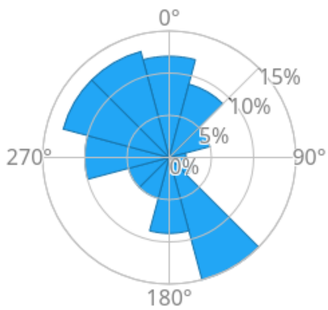
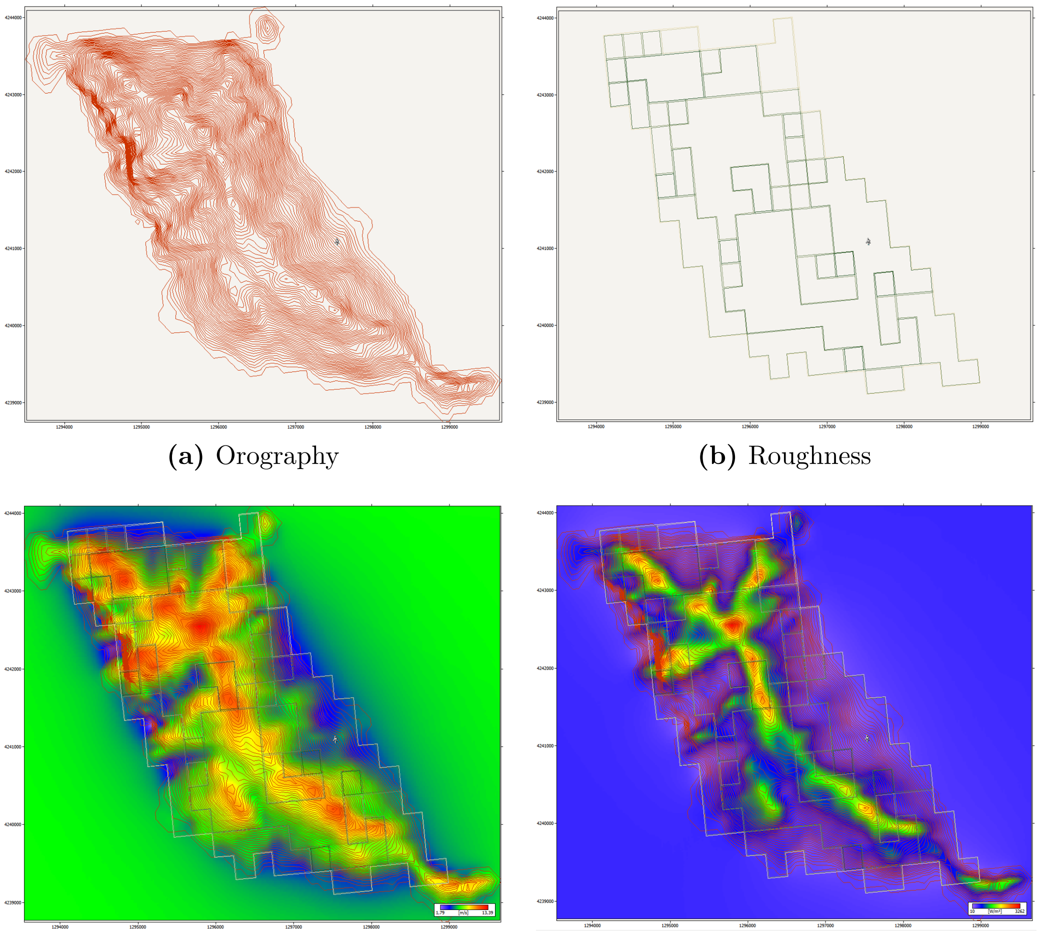


Figure 2.27: Wind rose of the wind site of Marettimo [21].

Figure 2.28: Suitable site for the installation of wind turbines on the island of Marettimo



(a) Orography **(b)** Roughness

(c) Mean wind speed **(d)** Power density

Figure 2.29: Most important wind-related characteristics of Marettimo.

The chosen turbines models are smaller than the ones of Favignana, due to their proximity to the town. The main issue is the noise generated by them and the visual impact that they could have on the inhabitants. So, despite the island is well exposed to the winds of the Mediterranean, it should complement other renewables power plants in its energy mix rather than only wind turbines.

As a supplement to the renewable energy generated by the wind turbines, there is the solar energy. Similarly to the other islands, also in Marettimo it has been calculated the photovoltaic power potential, of both the rooftops and the ground solar panels.

Rooftop photovoltaics

As already said, Marettimo has a population of only 684 inhabitants, mainly concentrated in the town, leaving the rest of the territory uninhabited. The buildings considered suitable for the installation of the rooftops solar panels are the civil and the administrative buildings, and they are 132. The total surface of the buildings is of 35986 m^2, which reduces to 27198 m^2 if the minimum solar radiation is set to 1200 $kWh/m^2/year$. This surface could be only partially used, due to the presence of obstacles on the roofs. In order to estimate the actual suitable surface for the installation of the rooftop solar panels, some correction factors were applied. The estimated total surface is of 9243 m^2 which is the 26% of the total rooftops surfaces. Assuming an efficiency of 0.19, the estimated power potential is of 1.76 MW. With an average solar radiation of 1522 $kWh/m^2/year$, they could produce around 2.67 GWh of electricity per year.

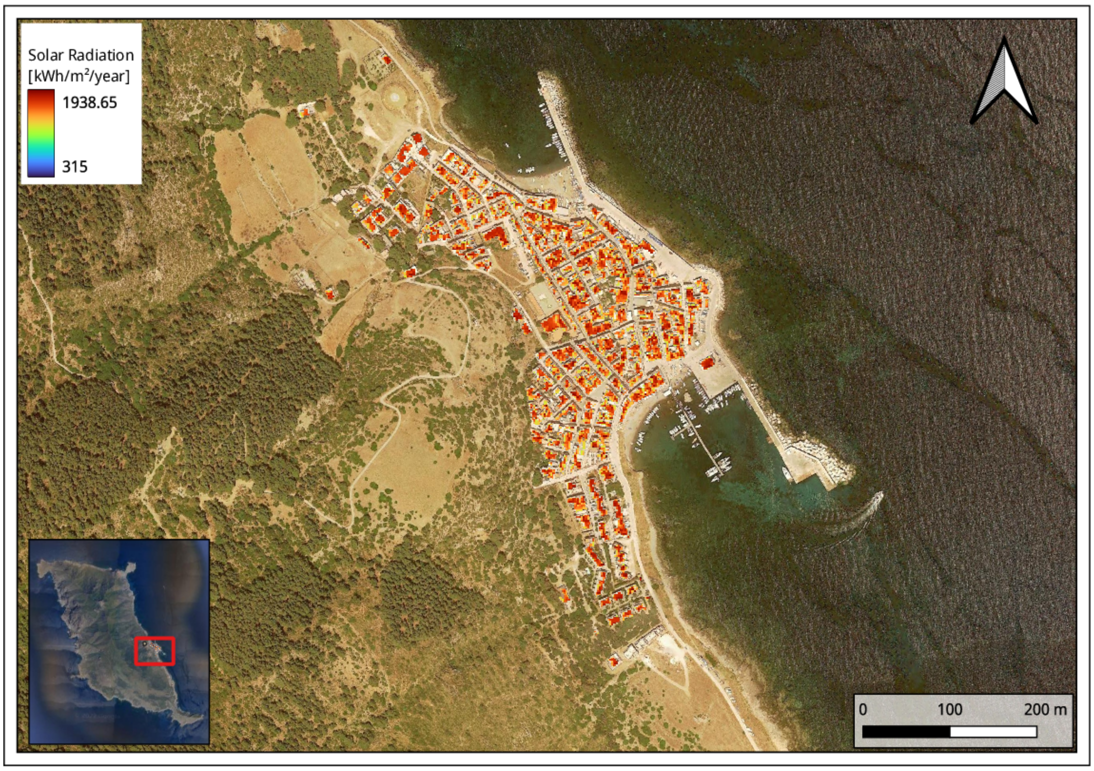


Figure 2.30: Solar radiation on the rooftops of Marettimo

Ground photovoltaics

Marettimo has its main territory covered by wooded areas (see figure 2.31), making it difficult to install ground solar panels. The only uncultivated land it seems to be close to the town, in the North-West side. It has a raw surface of only 11117 m^2, that reduces to 5204 m^2 after the application of all the correction factors explained in the methodology paragraph 2.3.4. The power potential associated to that area is roughly 1 MW and considering that the area is exposed to an annual solar radiation of 1553 kWh/m^2/year, it could produce about 1.32 GWh/year if it assumed an efficiency of 0.19 and a system loss of 14%. It has a low annual solar radiation due to the orography of the island. In fact, the island's mountains reach heights up to 686 meters and both the PV site and the town are located close to the side of the mountain. This prevents them to be reached by the sunlight during the afternoon hours, dropping down the energy yield of the panels.

Figure 2.31: Wooded area (green) of Marettimo.

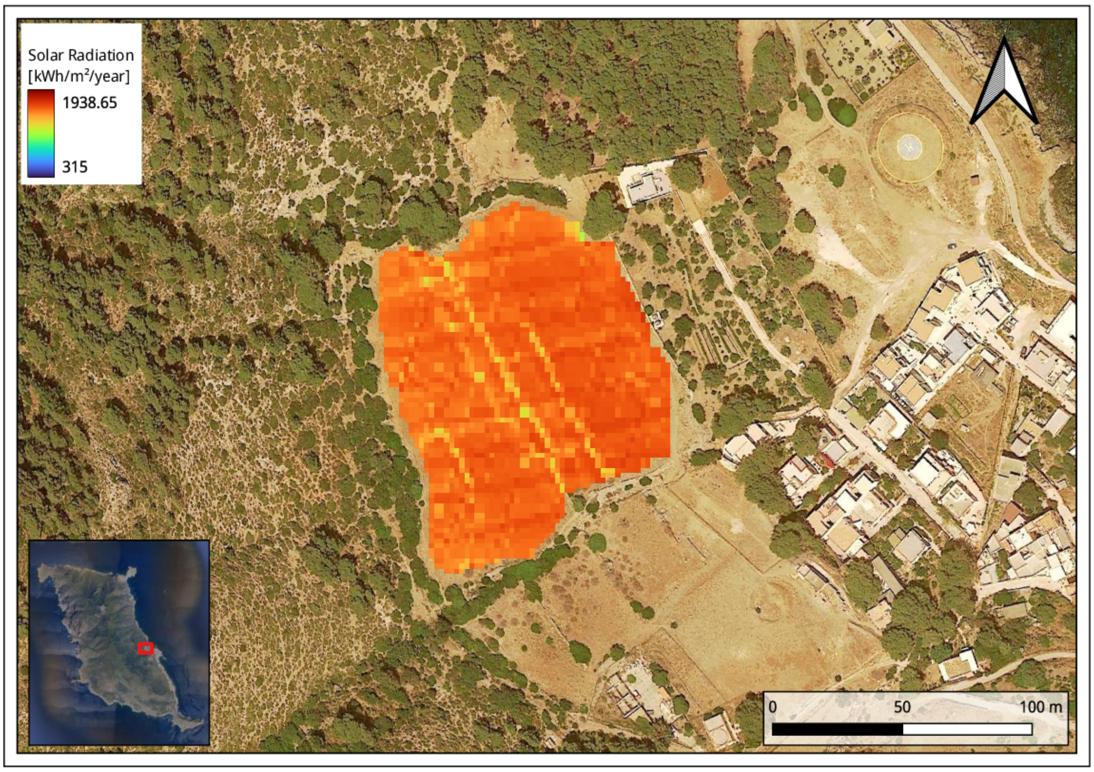


Figure 2.32: Eligible PV power plant of Marettimo

Scenario modeling

After having carried out the study of the energy system of the islands, it follows the scenario modeling part. This part of the study consists in modeling and simulating the energy scenarios of the Aegadian islands. There is a wide range of software available for energy modeling, some are commercial as HOMER [50], some are proprietary software and some are open source like OSeMOSYS and oemof [51, 52]. All these tools have different frameworks and different approaches to the case study: the top-down, the bottom-up or both [53]. The top-down approach is to study the energy system by looking at it as an aggregate, from an economic point of view. This type of model examines the economics of the system without considering the specific technologies and demand profiles. Instead, it examines what the impact of a policy change would be. The bottom-up approach goes in the opposite direction. It consists of studying the energy system as specifically as possible by considering all the technologies and the demand curves. This type of study could provide more specific information about the energy system and its behavior. The first approach is more suitable for modeling large energy systems such as countries or continents, while the second approach is more suitable for studying small energy systems that strictly depend on the demand profiles and technologies used. In this work, the bottom-up approach was used to study the energy scenarios of Aegadian Islands. As mentioned before, the bottom-up model includes a set of parameters that contain information about the technologies and the demand profiles of the energy system. After applying some constraints, the techno-economic objective function is minimized to find one or more possible solutions. Due to the complexity of the system, the solutions cannot usually be determined directly. On the contrary, the energy scenarios generally require LP or MILP techniques to be solved. These stand for "Linear Programming" or "Mixed-Integer Linear Programming." These types of problems require specific solvers to get to the solution, requiring multiple complex iterations. As for scenario modeling frameworks, there are several available solvers in this case as well, some of which are: GLPK [54], which is open source, IBM ILOG CPLEX© [55], free for academic use, OCTAVE [56], LP _SOLVE and Gurobi [57, 58]. For the models simulated here, we mainly used the solver IBM ILOG CPLEX©, which implements optimizers based on both primary and dual simplex algorithms. It is one of the most widely used software for solving linear optimization problems. CPLEX can solve linear programming (LP), mixed integer linear programming (MILP) and also quadratic programming (QP) objective functions [59, 60]. All of these operations are performed on a time scale with a time step resolution that depends on the application domain and can span a range of years or decades. Obviously, the smaller the time step or the more years considered in the model, the more computational power is required. The goal of this analysis is to create a robust model of the energy system that behaves as similarly as possible to reality in order to estimate the behavior of the system after the constraints and new technologies are implemented.

3.1 Methodology

The model to be simulated should be built to be compatible with the framework of OSeMOSYS. OSeMOSYS, like other linear programs, requires the definition of sets, parameters and variables [61]. The sets represent the structure of the model by defining them:

- **Years range**. List of the years computed by the model.
- **Technologies**. Defining all the technologies names.
- **Time slice**. Each time slice represents a fraction of the year.
- **Fuel**. It consists of a list of all input and output vectors used by technologies. These are not fuels per se, but more generally what is used or produced by the technology. It is up to the modeler to define what the fuels are. For example, they might be electricity, fossil fuels, transportation units, ferry trips, and others.
- **Emission**. List of pollutants to be considered in the study.
- **Mode of operation**. It defines the number of operating modes of technologies. For example, a cogeneration plant has two modes of operation. The first outputs electricity. The second generates heat.
- **Region**. List of the regions of the model. The regions can trade fuels between them, for example the electricity
- **Season**. Each year in the model is divided into seasons. It is up to the modeler to decide how many seasons to include in the year, depending on their importance.

- **Day Type**. It can be used to differentiate the days of a week (for example, week day and weekend).
- **Daily Time Bracket**. It defines how many time-bracket are present in a day.
- **Storage**. List of the storage facilities to be included in the model.

The parameters are the numerical inputs that the model uses for the simulations. They include both the definitions of some elements of the above sets (e.g., the time slices in a year) and the constraints to be applied to the model. There are 54 parameters in total, but they can be divided into the following macro categories:

- **Global**. Probably the most important parameter contained in this category is the year split. The year split contains all the time slices values, each of them represents a portion of the year. Due to the complexity of the models, the time resolution is crucial in terms of computational time. In fact, the smaller it is, the higher is the computational time. Other parameters contained in this category are other relative to the time, and others which define the trades between the regions and the discount rate of the costs.
- **Demands**. They define the demands for each commodity, making a distinction between the cumulative yearly demands and those demands that are instead specified in each time slice of the year.
- **Performance**. All the parameters related to the performances of the technologies (capacity factors, availability, inputs, outputs, and others).
- **Technology Costs**. It is self-explaining. This category contains all the parameters related to the technologies costs (capital, fixed and variable costs).
- **Storage**. All those parameters which define the storage characteristics (which technology recharge them or which is powered by them, their levels, their costs, etc.).
- **Capacity Constraints**. Capacities of the technologies, like their total capacity for each modeled year or the maximum capacity investment and others.
- **Activity Constraints**. Constraints related to the upper and lower limits of the activities of the technologies. The activity represents the products generated by a technology.

- **Reserve Margin**. All those parameters related to the reserve margin of the model and to which technologies contribute to it. The reserve margin is the excess of available power supply in respect to the actual power required by a network. It is necessary in order to prevent lack of power in a system.
- **RE Generation target**. The parameters which define what technologies are renewable ones and what is the target of renewable production year by year.
- **Emissions**. Parameters related to the emissions of pollutants, defining which technologies produce them and defining the emissions limits of them.

Based on the parameters generated above, the OSeMOSYS software generates several equations and inequalities and solves them using a solver to minimize the objective function of the net present cost. The solver can be GLPK or IBM ILOG CPLEX©, the latter being more powerful than the former. The results of the simulations are the variables. They are mainly defined on an annual scale, but some of them are more precise and can be visualized for any time slice. The output variables include information about the total installed capacity of the technologies and their activities, as well as other variables related to the storages and the commodities.
The most used variables in this study are the following:

- **Total capacity annual**. Cumulative installed capacity for each technology, per year.
- **Total technology annual activity**. Activity done by each technology in the year domain.
- **Accumulated new storage capacity**. Cumulative capacity for each storage facility, per year.
- **Annual emissions**. Emissions of each pollutant in the years.
- **Capital Investment**. Total capital investments of each technology per year.

3.2 Energy system model

The Chapter 2 helped to understand the actual energy system of the islands of the archipelago, but it is not enough to provide information on how it could be improved. In fact, that's where it should be done the scenario planning. The energy scenarios study can be conducted on the basis of a reference energy system (RES). In the case of Aegadian islands (except Levanzo, which doesn't allow the installation of turbine generators) it is composed as in figure 3.1. Each box represents a technology, the vertical lines are instead the energy commodities, while the horizontal lines are the energy flows. To be noticed, that the energy flows/commodities could not be necessarily energies per se. In fact, in the case of the ferry, its commodity represents the demands of routes, while its flow lines are diesel in input and route in output.

The technologies can be distinguished in three categories:

- **Import**. A technology that imports a fuel from outside the energy system. It is characterized by only an output flow (or more). They are the technologies upstream the RES, providing all the fuels used by it. In the case of Aegadian islands the import technologies are "IMP_DSL" and "DSL_EXT" which are the diesel imports, the first for the system, the latter for only ferry use. The explanation to this differentiation is that the diesel consumption of the ferry should not be included in the island's diesel consumption.
- **Export**. This kind of technology doesn't have input flows, but only output ones, as the import tech. This is used when there are commodities exports in the energy system or when the technology is a renewable one, because it generates the output flows from an uncountable resource (solar energy, wind energy, wave energy, geothermal energy etc.)
- **Conversion**. The conversion technologies are those which convert the input flows into output flows. For example, the diesel power plant converts the diesel into electricity.

The technologies could have more than one output flow, each one of them represent one fraction of the conversions happened in the technology, with the foresight that their sum should be 1. For example, the output flows of a CHP plant are electricity and heat. In another example, the outputs of a refinery could be diesel, gasoline and methane (or even more). To be noticed that the outputs should be always useful; in fact, the wasted ones aren't considered as outputs.

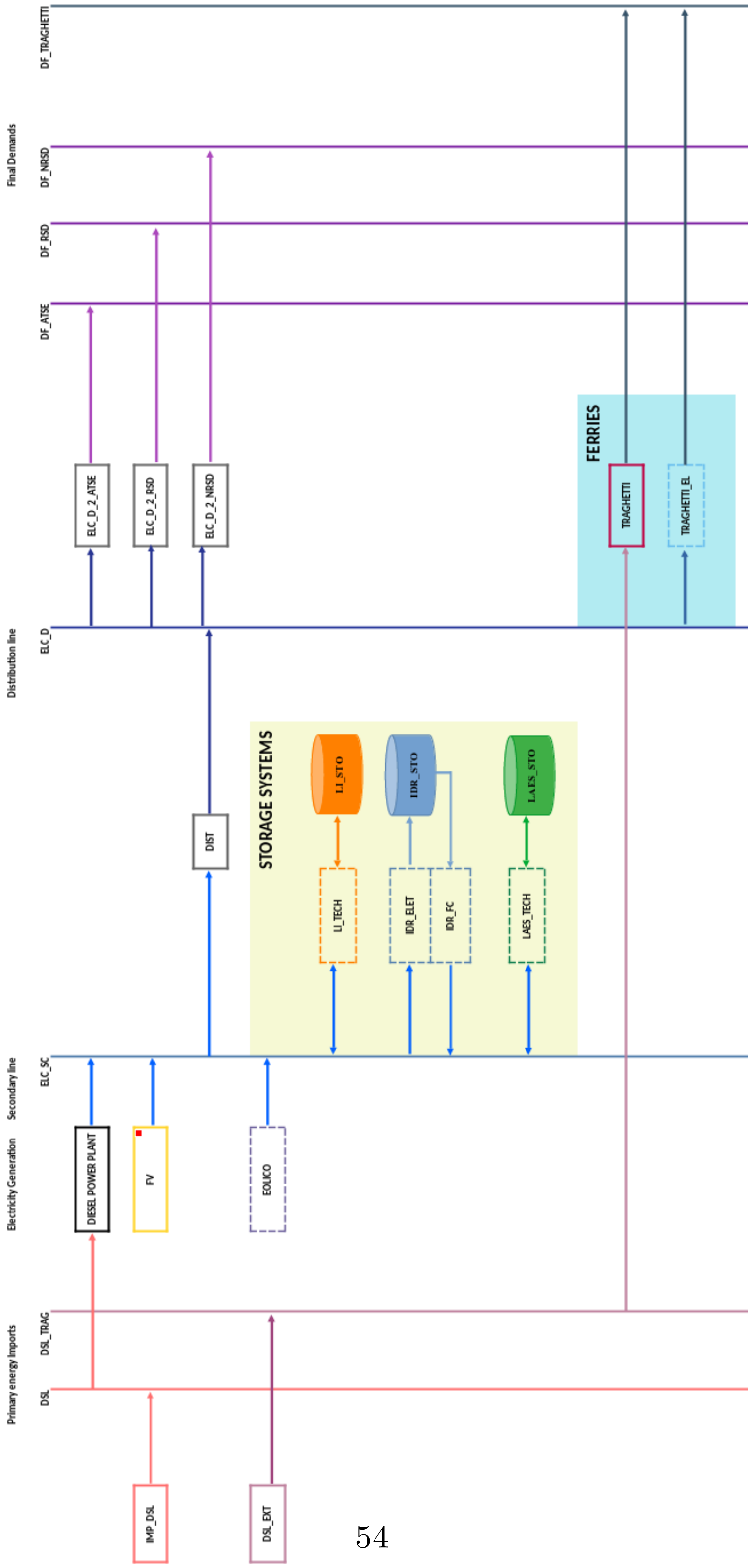


Figure 3.1: Reference Energy System of Aegadian islands. The diesel power plant name changes between the islands (*"CEN_SEA"* for Favignana, *"CEN_ICEL"* for Levanzo and *"CEN_SELIS"* for Marettimo). The dotted lines represent the new technologies implemented in the energy system.

3.2.1 The model

Before entering into the technical details of the structure of the models, it is necessary to explain what are the technologies introduced in them. Furthermore, the models' parameters have been written by using the technical specifications collected for each technology.

Diesel generators

Thanks to the data provided by the local companies of the islands, the diesel generators' parameters have been obtained from that data. One of the informations obtained from it is the generator efficiency, which translates into "output activity ratio"/"input to activity ratio". The input activity ratios of the plants are 0.236 t/MWh_e for Favignana, 0.2366 t/MWh_e for Marettimo and 0.251 t/MWh_e for Levanzo. Regarding the operational life of the plants, instead, it has been assumed equal to 16 years [62].

Wind turbines

The wind turbines' models used by the models are five in total: Bonus B23, Vestas V90, Enercon E53, Enercon E82, Enercon E126. The purpose of this selection of turbines is to compare different sizes during the scenario planning.

Bonus B23

This is the only turbine which is in common between the models of Favignana and Marettimo, and it is also the smallest one. With a rated power of 150 kW, and a hub height of 30 meters, it can be used to increase the installability along the islands' territories. This can only be achieved if the actual legislations, especially the ones relative to NATURA2000, are relaxed. Technical details in the table 3.1.

Bonus B23 - Techincal specifications	
Rated power [kW]	150
Cut-in wind speed [m/s]	3.5
Rated wind speed [m/s]	12.5
Cut-out wind speed [m/s]	25
Rotor diameter [m]	23
Swept Area [m^2]	415
N° of blades	3
Material	Glass fiber
Power Density [W/m^2]	361.4
Type	Asynchronus
Voltage [V]	400
Grid connection	Thyristor
Hub height [m]	30
Type	Lattice
Total weight (tower + rotor) [t]	26

Table 3.1: Bonus B23 datasheet [26]

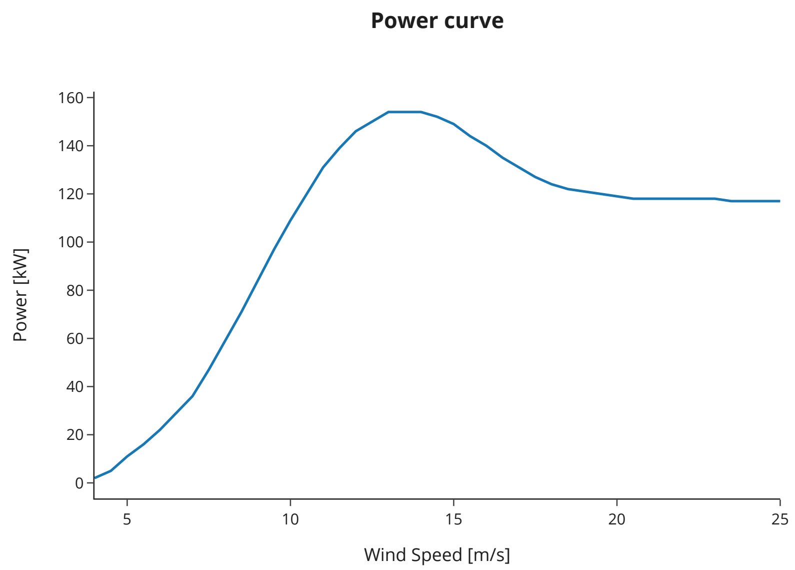


Figure 3.2: Bonus B23 power curve [26]

Vestas V90

This turbine is the medium-sized turbine adopted in the model of Favignana.

Vestas V90 - Techincal specifications	
Rated power [kW]	3000
Cut-in wind speed [m/s]	4
Rated wind speed [m/s]	15
Cut-out wind speed [m/s]	25
Rotor diameter [m]	90
Swept Area [m²]	6362
N° of blades	3
Material	Glass fiber
Power Density [W/m²]	471.5
Type	Asynchronus
Voltage [V]	1000
Grid connection	OptiSpeed
Hub height [m]	80
Type	Steel tube
Total weight (tower + rotor) [t]	396

Table 3.2: Vestas V90 datasheet

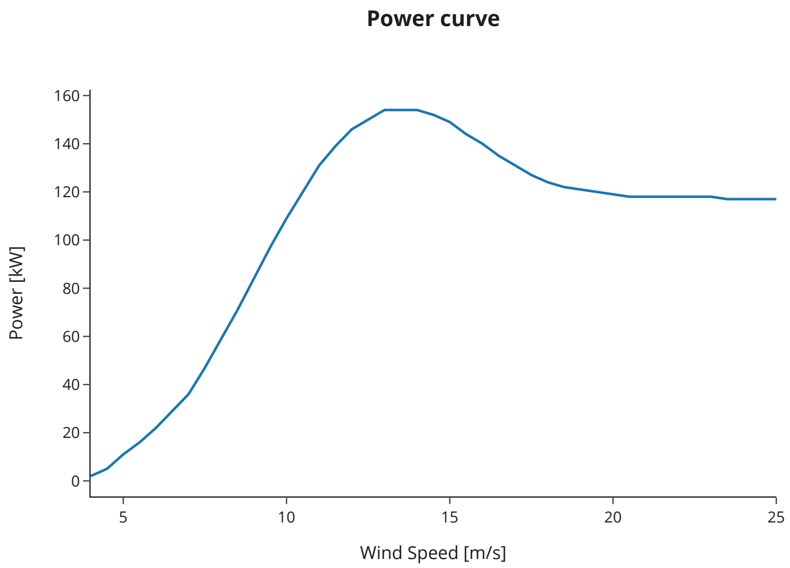


Figure 3.3: Vestas V90 power curve [26]

Enercon E126

The E126 is the biggest turbine modeled in Favignana. It is too large for the site chosen in the island, but it has been inserted in the models in order to compare the results and in order to assume how the energy system would behave after its installation.

Enercon E126 - Techincal specifications	
Rated power [kW]	7580
Cut-in wind speed [m/s]	3
Rated wind speed [m/s]	16.5
Cut-out wind speed [m/s]	34
Rotor diameter [m]	127
Swept Area [m^2]	12668
N° of blades	3
Material	Glass fiber
Power Density [W/m^2]	598.4
Type	Synchronous
Voltage [V]	690
Grid connection	IGBT
Hub height [m]	135
Type	Concrete

Table 3.3: Enercon E126 datasheet [22]

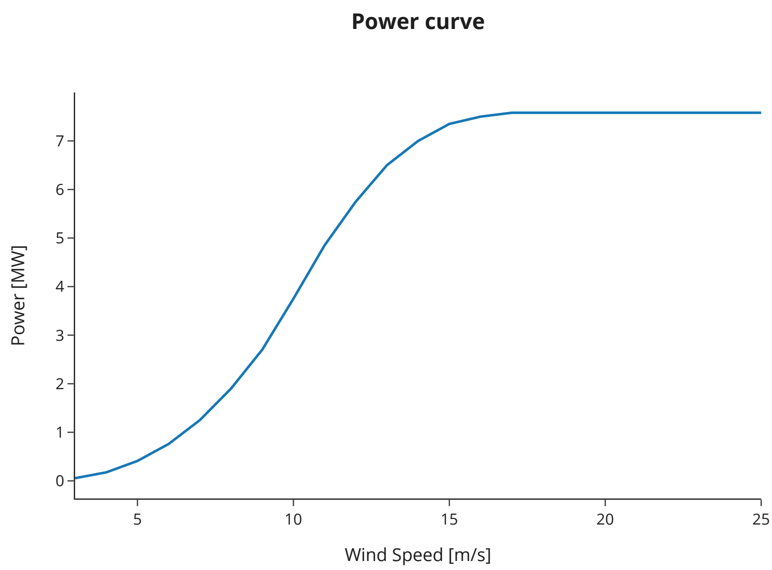


Figure 3.4: Enercon E126 power curve [22]

Enercon E53

Medium-sized turbine adopted in the models of Marettimo. Due to the nearness between the site and the town, this turbine, and the smallest one, are the most suggested turbines to be placed in that location.

Enercon E53 - Technical specifications	
Rated power [kW]	800
Cut-in wind speed [m/s]	3
Rated wind speed [m/s]	12
Cut-out wind speed [m/s]	34
Rotor diameter [m]	52.9
Swept Area [m²]	2198
N° of blades	3
Material	Glass fiber
Power Density [W/m²]	364
Type	Synchronous
Voltage [V]	690
Grid connection	IGBT
Hub height [m]	60
Type	Steel tube

Table 3.4: Enercon E53 datasheet [23]

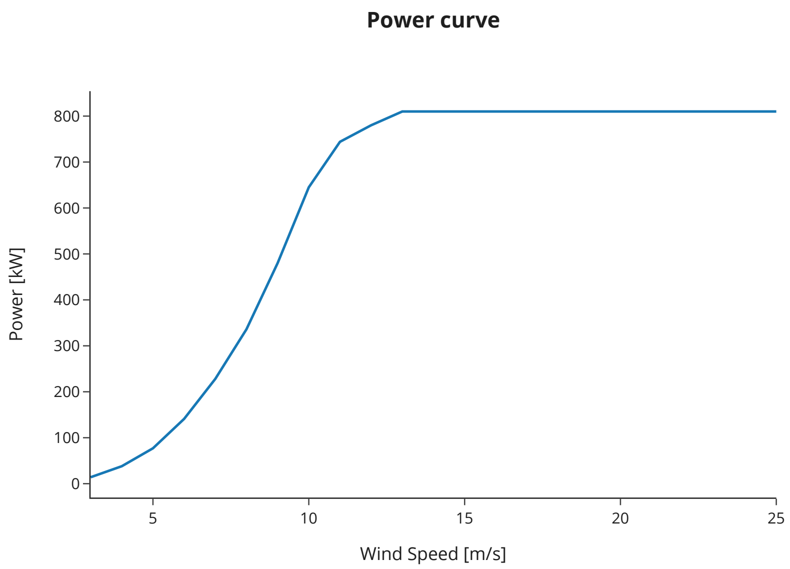


Figure 3.5: Enercon E53 power curve [23]

Enercon E82

This is the largest turbine used in the models of Marettimo although it is not suitable for a location so near to the town. In fact, a turbine of this size would generate too much noise. Nevertheless, the objective of the introduction of multiple models is to compare different sizes of turbines, considering also that in the future the legislation could change and therefore a turbine can be installed elsewhere.

Enercon E82 - Technical specifications	
Rated power [kW]	3000
Cut-in wind speed [m/s]	3
Rated wind speed [m/s]	16
Cut-out wind speed [m/s]	34
Rotor diameter [m]	82
Swept Area [m²]	5281
N° of blades	3
Material	Glass fiber
Power Density [W/m²]	568.1
Type	Synchronous multi-pole
Voltage [V]	690
Grid connection	IGBT
Hub height [m]	69
Type	Steel tube

Table 3.5: Enercon E82 datasheet [24]

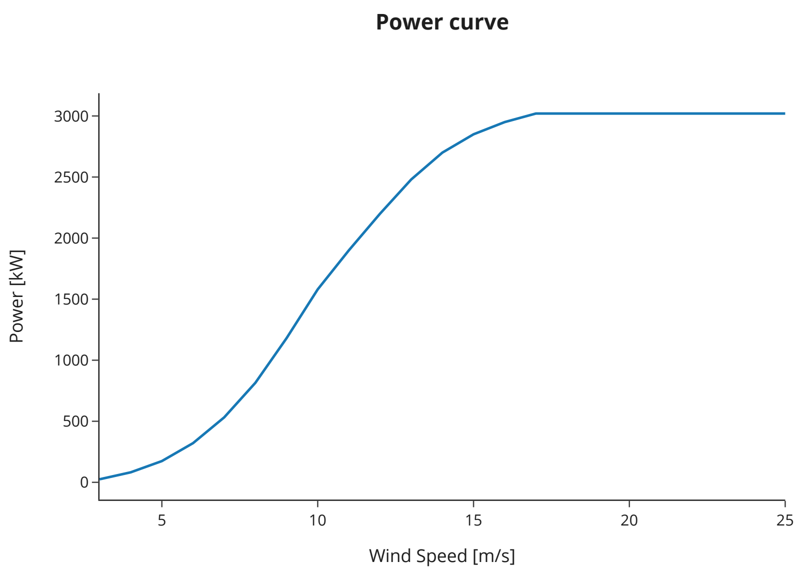


Figure 3.6: Enercon E82 power curve [24]

As it is possible to see in the plots above, the behavior of the wind turbines changes drastically between the models. Their hourly capacity factors have been extrapolated from Renewables Ninja web site, which makes possible to select the model of the turbine and the site where it is installed [63].

Solar panels

The solar panels chosen for the models are of monocrystalline type. A commercial monocrystalline panel has an efficiency of 15-22%, in the model it has been considered equal to 19% [64]. The capacity factors of the solar panels were calculated from the European website PVGIS, which stands for Photovoltaic Geographical Information System. The tool automatically choose the best angles for the panels in order to improve the energy generation. A system loss of 14% has been assumed.

Ferries

In order to simulate the behavior of the ferries in the models, their technology has been created on purpose on the basis of the methodology in the section 2.3.5. When a new technology is inserted in OSeMOSYS, it is important to define some parameters related to the performances. In the case of the ferries the most important parameters are two: the "Capacity to activity unit" and the "Input Activity ratio". The first one represents how many routes can a ferry do, if it works all daylong. It has been calculated dividing 8760 by the time spent for a single journey + 15 minutes of rest. The second parameter represents, instead, the quantity of input required to obtain 1 unit of output (the route). In the table 3.6 the results.

Model	Capacity to activity unit [Routes/y]	Diesel Ferry Input Activity Ratio [t/Route]	Electric Ferry Input Activity Ratio [MWh/Route]
Favignana	10582	0.2671	2.04
Levanzo	15624	0.1436	1.10
Marettimo	8667	0.3518	2.68

Table 3.6: Ferries performances parameters

Storages

Liquid Air Energy Storage

The liquid air energy storage (LAES) is a storage system which converts the electricity into liquid air. It is a promising way to storage energy thanks to its high energy density and to its independence on the geomorphology of the site of installation [65, 66]. Generally, a LAES plant has a round-trip efficiency around 50%, but it could be increased up to 80% by recovering heat from both the stages of liquefaction and of electricity production. A roundtrip efficiency of 70% was chosen for the models. Thanks to their long lifespan (30+ years), this kind of plants could be a good choice in order to provide continuity of service to an isolated power grid [65].

Li-ion batteries system

Lithium batteries are one of the storage systems easier to install. As the LAES system, they don't depend on the geomorphology of the site of installation, ensuring their installation also on an island territory. With a really high round-trip efficiency, around 86%, they are one of the most efficient storage systems, but one of their cons is the relative short lifetime of the cells, around 10-15 years [67, 68, 69].

Hydrogen Storage System

The last storage system introduced in the model is represented by the hydrogen energy vector. The hydrogen is assumed to be produced by PEM electrolyzer and later converted into electricity thanks to PEM fuel cells. The system thus conceived has a roundtrip efficiency of 47%. Despite its low roundtrip efficiency, especially if compared to the other storage systems, hydrogen has other advantages, as the high versatility of its applications. The lifetime of the technologies correlated to it are slightly different. The PEM electrolyzer has an estimated lifetime about 60000 h, while the fuel cell has a lifetime of 40000 h. Assuming 4 hours/day of functioning for the first and 6 hours/day for the latter, their lifetime would be around 30-40 years for the electrolyzer and 18 years for the fuel cell; while the lifetime of the hydrogen tanks is assumed to be around 20 years [69, 70].

Each island of the archipelago has been simulated individually, in order to reduce the model complexity. The models created for the islands are pretty similar, there are only differentiations on the names of the diesel power plants and on the adopted technologies for the wind turbine generators. In fact, as it is possible to observe in the chapter 2, the wind site's locations are different in the case of Favignana and Marettimo. The site of Favignana is far enough from the town and this contributes to reduce the visual/noise impact on the citizens, giving the possibility to install bigger wind generators. In the case of Marettimo, instead, the wind site is too near the town, and despite the distancing of 200 meters is satisfied, the turbine cannot be too big, or it would have a really high visual/noise impact.

3.2.2 SETS

Fuels

The fuels used by the models are of three type: fossil fuels imports, the electricity vectors and the commodities. The fossil fuels are represented by the diesel import (DSL), used by the islands' diesel generators, and by the ferry's diesel consumption (DSL_TRAG), used externally to the energy systems. The electricity vectors are the secondary line (ELC_SC), downstream the generation, and the electricity distribution line (ELC_D) which feeds the users. The electricity generated by the power plants, and distributed by the distribution line (ELC_D) satisfies the domestic residential demand (DF_RSD), the domestic non-residential demand (DF_NRSD) and the activities/services demands (DF_ATSE). The ferries commodities are instead satisfied by the ferries technologies (DF_TRAGHETTI).

Storages

The storages system implemented in the models are three: Li-ion batteries (LI_STO), Liquid Air Energy Storage (LAES_STO) and hydrogen storage (IDR_STO). The introduction of three different storages in the energy system aims to make a comparison between them, observing the final costs and capacities. In fact, the scenarios are simulated by combining the installation of one storage type at a time.

Technologies

- **Fossil fuels imports**. They define the imports of fuel consumed by the energy system, the diesel (IMP_DSL) and the ferries diesel (DSL_EXT). The ferries diesel should be distinguished from the in-land consumptions, because the ferries refill outside the energy system, that's why there are two different technologies for the diesel import. There aren't other fuels because, as already explained in the chapter 2, there is lack of data of their consumption.

- **Generation**. The generation technologies are the diesel power plant, "CEN_SEA" for Favignana, "CEN_ICEL" for Levanzo and "CEN_SELIS" for Marettimo, the rooftop/ground solar power plants (FV) and the wind turbines (EOLICO_XX). For the wind turbines there is one technology for each turbine model used by the island, substituting XX with the model acronym. For example, in the model of Favignana there are three different sizes of turbines: small, medium, and large (see table 2.4, and they are defined by the technologies: EOLICO_B23, EOLICO_V90, EOLICO_E126, EOLICO_E53, EOLICO_E86.

- **Electricity distribution**. Defined by only one technology, the distribution line (DIST). It takes the electricity from the generators and distributes it to the users with some losses.

- **User feeding tech**. Dummy technologies that connect the commodities (DF_RSD, DF_NRSD, DF_ATSE) to the electricity distribution network (ELC_D_2_RSD, ELC_D_2_NRSD and ELC_D_2_ATSE).

- **Storages technologies**. The technologies which convert the electricity and send it to the storage facilities and vice versa. In the models there are 4 storages technologies, the rectifiers and the inverters for the Lithium-ion batteries (LI_TECH), the LAES power plant (LAES_TECH), the electrolyzer for hydrogen production (IDR_ELET) and the fuel cells and the inverters for its conversion into electricity (IDR_FC).

- **Ferries**. Two technologies to simulate the traditional and electric ferries (TRAGHETTI and TRAGHETTI_EL)

Regions

There is one model for each island, and because of their limited territory size, only one region has been considered for each one of them. "FAVI_1" for Favignana, "LEVANZO" for Levanzo and "MARET" for Marettimo.

Modes of operation

In OSeMOSYS, in the most cases the storage systems are simulated by using two modes of operation of the technology to which they are connected. In the Aegadian's models, both the Li-ion and LAES storages use only one technology (LI_TECH and LAES_TECH), making it necessary to use them in two modes of operation: "charging" and "discharging".

Emissions

In all the Aegadian's models the only pollutant is CO_2 (CO2).

Time context

All the models have been simulated within the same range of years (2021-2053) and with the same time slices. Each time slice is defined by an acronym "S*D*T*" where S is the season, D is the day type and T is the daily time bracket. Each year of the model is firstly splitted in seasons, the season are splitted in day types and then each day of the day type is divided in time brackets. The combinations of these three splitting levels made the time slices; each one of them represents a year fraction. The seasons used in the models are 6, one for each bimester, with only one day type, while the daily time brackets are 10. Combining them, 60 time slices are obtained (see table 3.7).

Bimester	Season
Jan-Feb	S1
Mar-Apr	S2
May-Jun	S3
Jul-Aug	S4
Sep-Oct	S5
Nov-Dec	S6

Start hour	End hour	Time bracket
0	3	T1
3	6	T2
6	8	T3
8	10	T4
10	12	T5
12	14	T6
14	16	T7
16	18	T8
18	21	T9
21	24	T10

Table 3.7: Seasons and time brackets used in the models of Aegadian islands.

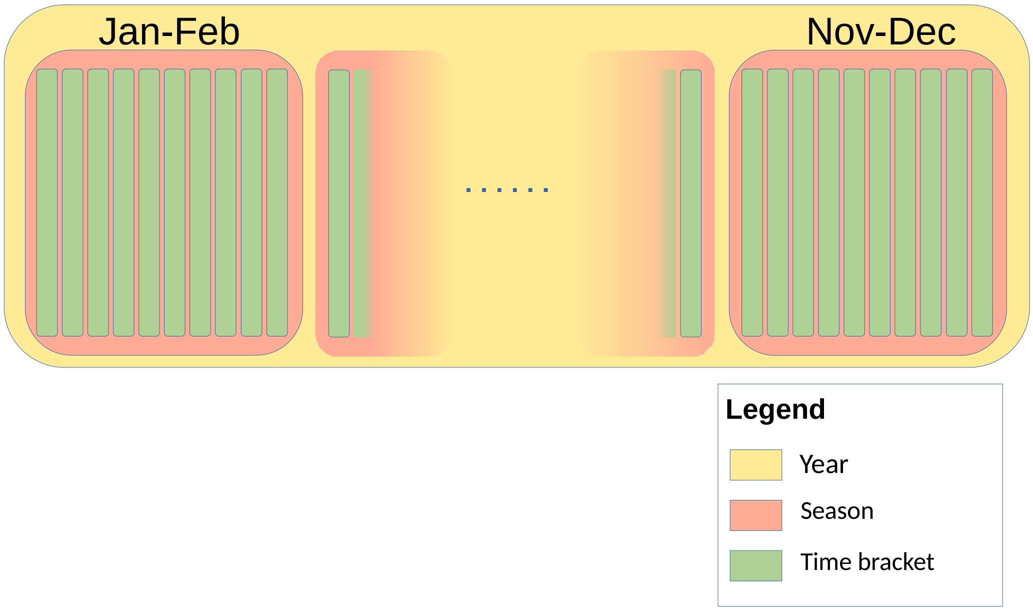


Figure 3.7: Year splitting in the models of Aegadian's islands.

3.2.3 PARAMETERS

Global parameters

The year split has been calculated by dividing the length (in hours) of each timeslice by the total number of hours in a year (8760 h). The day split, similarly to the year split, is calculated by dividing the length of the daily time brackets by the number of hours in a year. Furthermore, the discount rate and the depreciation method are set to 5% and to "sinking fund depreciation" respectively.

Demands

The demands have been sized according to the data collected in the study of the islands' energy systems (see 2). These demands correspond to the commodities "DF_RSD", "DF_NRSD", "DF_ATSE", and "DF_TRAGHETTI". For the electricity demands (in MWh), the sizing has been done by taking the billed energies' data and distributing it in the year by following the electricity production plot of the diesel power plants. For the ferries demands (in n° of routes), instead, the demand has been calculated by checking the timetables of the ferries companies and combining them with the data obtained with the methodology in the paragraph 2.3.5.

Performance

The performance parameters strongly depend on the type of the adopted technology. Their values have been extrapolated mostly from the literature, while others have been calculated with the methodology described in the chapter 2. They are summarized in the table 3.10.

Technology Costs

In the models, the technology costs could be constant in the years, or they could vary. For most of the technologies adopted in the models, the costs are assumed to be constant, while for PV panels and wind turbines they are assumed to decrease [71]. They are summarized in the table 3.8.

	Capital costs	**Fixed costs**	**Variable costs**
Diesel imports	**-**	-	1.77 k€/t
Diesel PP	1023.5 k€/MW	30.705 k€/MW/y	0.019 k€/MWh
PV	628_{2020} - 330_{2050} k€/MW	8.16 k€/MW/y	-
Wind Turbine	1325_{2020} - 1118_{2050} k€/MW	14.575 k€/MW/y	0.003 k€/MWh
Li plant	1596 k€/MW	3.916 k€/MW/y	0.006 k€/MWh
Electrolyzer	1691 k€/MW	12.91 k€/MW/y	0.0056 k€/MWh
Fuel cell	1234.4 k€/MW	11.92 k€/MW/y	0.00044 k€/MWh
LAES plant	1851.2 k€/MW	46.28 k€/MW/y	0.0052 k€/MWh
Diesel Ferry	5000 k€/Ferry	1472 k€/Ferry/y	-
Electric Ferry	16255 k€/Ferry	1472 k€/Ferry/y	-

Table 3.8: Technologies' costs in the models of the Aegadian's islands [72, 66, 69]

Storage

The storage systems in the models are, as already said, three: lithium battery, hydrogen and LAES. The lithium battery requires only one technology, which performs both the charge and the discharge. So when 'LI_TECH' is in mode of operation '1' it charges the storage, otherwise, when it is in mode of operation '2' it draws energy from it and injects it in the electricity network 'ELC_SC'. The same happens with the liquid air energy storage. For the hydrogen storage a different approach was used, because of the substantial difference between the technologies related to it. It is connected to the electrolyzer 'IDR_ELET' during the charge phase and to the fuel cell 'IDR_FC' during the discharge phase. The storages' state of charge is set to zero when they are installed.

Storage	**Lifetime [y]**
LI_STO	10
IDR_STO	20
LAES_STO	30

Table 3.9: Lifetime of the storages.

Capacity constraints

The renewables power potential limits calculated in the chapter 2 need to be inserted in the model, in order to have a more realistic approach when the solver installs renewable power plants. In fact, we know for sure that the available surface for the installation of wind turbines is really limited by the actual normative, also if few laws are relaxed. For the photovoltaic power potential, instead, the assumptions were of different footprint, and the available surfaces could be larger or either smaller. Those limits are set through the 'TotalAnnualMaxCapacity' parameter. Because of the presence of one technology for each model of turbine, they could not be installed simultaneously, due to the presence of only one site in both the islands of Favignana and Marettimo. This means that it should be created one scenario for each model of turbine, setting the turbine's 'TotalAnnualMaxCapacity' to the value of the power potential measured in the chapter 2, while setting the same parameter of the other turbines to zero. Leaving the model free to invest any quantity of technology potential each year could mislead the interpretation of the results (see figure 3.8). The other technologies subject to the investment constraint are all the electricity generation technologies, with an investment limited to 2 MW/year [73] The capacities of one technology unit are set only for the wind turbines, in function of their size and for the ferries, because it is not possible to install a half ferry.

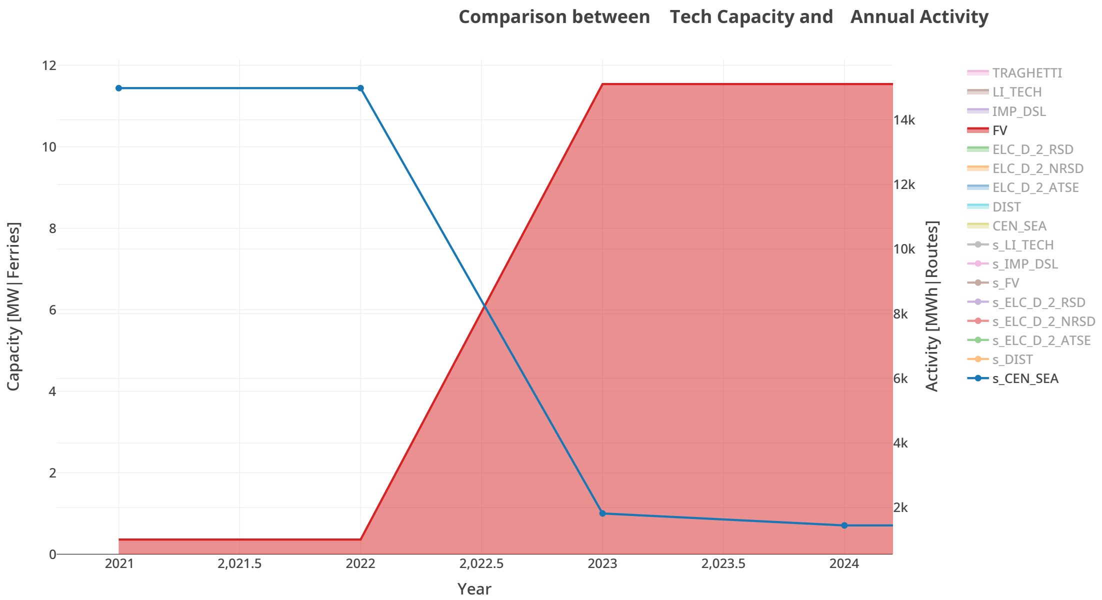


Figure 3.8: Comparison between the PV capacity investment (red area) and the Diesel power plant activity (blue line) if the investment constraints are not applied, in one of the Favignana's scenarios.

Activities constraints

The activities constraints were used in order to disable the technologies in the scenarios simulated, setting them to zero. Generally speaking, they are not built for that use, but in all the simulated scenarios it didn't seem necessary to limit the technologies activities.

Reserve margin

The reserve margin is the excess of installed capacity in respect to the peak demand. It has been set to 1.2 and associated to the fuel 'ELC_SC'. The technologies which contribute to the capacity increase are instead the diesel power plants.

Renewable generation target

The renewable technologies in the models are the PV panels and the wind turbines, while the tagged fuel is the generators-side electricity network "ELC_SC". The target has been set to zero.

Emissions

The renewable's generation target, if applied, forces the system to use the tagged renewable technologies to satisfy the electricity demand, but this doesn't reduce the emissions of the technologies disconnected from the network (vehicles, ferries, cooking in the households, etc.). In order to solve this issue, rather than a renewable generation target, it has been set a CO_2 emission limit. In fact, in this way when the system is forced to reduce the pollutants, it tries to satisfy all the demands using only CO_2 free technologies (renewable generators and electric ferries in this specific case). The emissions of CO_2 are bounded to the imports of diesel ('IMP_DSL' and 'DSL_EXT'), in a ratio of 3.15 tons of CO_2 per ton of diesel imported [74].

Technology	Input fuel	Input to activity ratio	Input unit	Output fuel	Output to activity ratio	Output unit	Capacity to activity unit	Unit	Lifetime [y]
IMP_DSL	-	-	-	DSL	1	[t]	999999	-	-
DSL_EXT	-	-	-	DSL_TRAG	1	[t]	999999	-	-
DPP[1]	DSL	[2]	[t]	ELC_SC	1	[MWh]	8760	[(MWh/y)/MW]	16
FV	-	-	-	ELC_SC	1	[MWh]	8760	[(MWh/y)/MW]	20
EOLICO[3]	-	-	-	ELC_SC	1	[MWh]	8760	[(MWh/y)/MW]	20
DIST	ELC_SC	1	[MWh]	ELC_D	[4]	[MWh]	999999	-	-
LI_TECH	ELC_SC	1.16	[MWh]	ELC_SC	1	-	8760	[(MWh/y)/MW]	30
IDR_ELET	ELC_SC	2.13	[MWh]	-	-	-	8760	[(MWh/y)/MW]	30
IDR_FC	-		-	ELC_SC	1	[MWh]	8760	[(MWh/y)/MW]	18
LAES_TECH	ELC_SC	1.67	[MWh]	ELC_SC	1	-	8760	[(MWh/y)/MW]	30
ELC_D_2_RSD	ELC_D	1	[MWh]	DF_RSD	1	[MWh]	999999	-	-
ELC_D_2_NRSD	ELC_D	1	[MWh]	DF_NRSD	1	[MWh]	999999	-	-
ELC_D_2_ATSE	ELC_D	1	[MWh]	DF_ATSE	1	[MWh]	999999	-	-
TRAGHETTI	DSL_TRAG	[5]	[t]	DF_TRAGHETTI	1	[Route]	[5]	[(Routes/y)/Ferry]	30
TRAGHETTI_EL	ELC_D	[5]	[MWh]	DF_TRAGHETTI	1	[Route]	[5]	[(Routes/y)/Ferry]	30

Table 3.10: Main parameters of the technologies of the Aegadian's models.

[1]. The diesel power plant name changes between each model of the islands: CEN_SEA for Favignana, CEN_ICEL for Levanzo and CEN_SELIS for Marettimo.

[2]. The input to activity ratio varies depending on the involved diesel power plant. 0.236 t/MWh for SEA, 0.251 t/MWh for ICEL and 0.2366 for SELIS.

[3]. For the wind turbines there is not only one technology, but one for each turbine model. See the paragraph 3.2.2 for more info.

[4]. The losses of the distribution network vary between the islands. For example, Favignana has the longer network, with consequent higher losses. It is 0.936 for Favignana and 0.976 for both Levanzo and Marettimo.

[5]. The ferries parameters change drastically between the islands, due to the different time spent for the single routes (see table 3.6).

3.2.4 Scenario settings

In order to simulate multiple scenarios, it has been created one model for each island. Inside the model there are all the settings used to generate the scenarios, following the procedure described in the section 4.1. The scenarios have been created in order to make it possible for the stakeholders to freely choose what are the conditions to impose to the models. The conditions are related to the performances of the energy system, developed in order to stress the solver to find solutions also when the conditions are particularly challenging. For example, in this way it is possible to verify how the system responds if the maximum photovoltaic power potential halves. As already explained in the chapter 2, the islands' suitability for the installation of renewable plants is tricky, due to all the legislation currently in force. It follows that one of the parameters characterizing the scenarios should be the renewables' penetration, in order to simulate the impossibility to install some generators where before it was considered feasible. Another customization implemented in the models is the CO_2 target, which can be easily varied in order to simulate conditions where it is less or more stringent. In fact, in some cases if the CO_2 emissions target is too strict, the solver may not find a converging solution or it could be uncomfortable in terms of costs or in terms of installed capacities. Because of the presence of three different storages systems, another implemented parameter is the possibility to choose which storage use in the model, making it easy to compare the costs and the capacities of different storages technologies. The last customizable parameters introduced in the models are the annual increase of the electricity demand and the modeling of the ferries. With the first, it is possible to simulate an increase of the demand, maybe including on it all those utilities fed with fossil fuels that switch to electrical power and that are not included in the models (vehicles, boats, home cooking, etc.). The second is instead used in order to choose if to simulate or not the ferries. This was introduced into the models for a reason: the traditional ferries produce CO_2 emissions that could be estimated by the models; if there is a certain CO_2 emissions target, the solver replaces the traditional ferries with the electric ones in order to satisfy the constraints. But, if the stakeholders don't want to implement electric ferries, by using this parameter, the ferries are not simulated at all, so the solver could reach the solution in any case.

Photovoltaic power potential parameters

Since they are available in all the islands, the photovoltaic power potential (PVPP) parameter is present in all the models. It sets the maximum solar panels capacity of the scenario, and it consists of 5 values: BAU/33%/66%/100%/999; where BAU is the business as usual, so the solar panels capacity is the same as it currently is, the percentage values set the maximum capacity to a fraction of the maximum rooftop+ground PV capacity calculated in the chapter 2, while 999 sets the maximum capacity of the scenario to 999 MW, making it possible to simulate the conditions where there is no constraint in the installation of solar panels in the islands.

Wind turbines parameters

These parameters are active only on the models of Favignana and Marettimo, because only on those islands there were found suitable terrains for the installation of wind turbines. Because of the limited size of the terrain, only one medium-large size of turbine can be installed in them, so the parameter sets which turbine the user wants to install. The possibilities are 0/Turbine_model/999. Similarly to the PVPP parameter, 999 stands for 999 MW so the model can simulate the conditions where there aren't installation limits of wind turbines.

Storages parameters

The storages' parameters are four 'Disconnect all'/'Only Lithium'/'Only LAES'/'Only Hydrogen', so the different systems could be easily compared, in techno-economic terms. It would be good also to simulate their combinations, but it increases drastically the number of scenarios to be simulated, not affordable if the simulations are run in a personal computer.

CO_2 emissions parameters

The CO_2 parameters are 'no limits'/'20%'/'10%'/'0%', and they set the emissions target that should be reached within the last year The percentage values set the limit to a fraction of the initial emissions values. For example, during the first year the emissions are 100 tons, so if the chosen limit is '20%', the scenario's emissions should drop to 20 tons within 2050.

Ferries modeling

This parameter could assume two values '1'/'0' and it disables the ferries in the models. If they are modeled and if the CO_2 target is strict enough, the solver would install electric ferries in order to reduce the CO_2 emissions. If the stakeholders don't want a similar approach to the transition process, there would be available the scenarios where the ferries are disabled.

Demands parameters

The annual increase of demand could assume two values '0%'/'5%', when it is set to zero there isn't an increase of the demands and they remain constant during the years. When it is 5% instead, they increase annually of 5% in respect to the first modeled year. 5% has been chosen because during the last year the demand will be of 4.5 times bigger than the first modeled year, so it could 'contain' those increments related to an increase of the tourism fluxes or to the transition of the fossil fuel vehicles to the electric ones, or it may include all those demands that should be satisfied by the electric system.

	N° of combinations						
	PVPP	**Wind turbine model**	**CO2 Emissions**	**Storage**	**Ferries modeling**	**Demand increments**	**Scenarios to be simulated**
Favignana	5	7	4	4	2	2	2240
Levanzo	5	-	4	4	2	2	320
Marettimo	5	7	4	4	2	2	2240
TOT	-	-	-	-	-	-	**4800**

Table 3.11: N° of available combinations for each parameter. In the last column, the total number of scenarios, obtained by multiplying the combinations. Each scenario employs from 5 to 9 minutes to be simulated. So, if they run in series, the Aegadian's islands' models would require from 16 to 30 days to complete.

Development of scenario making and visualization tools

4.1 Multi-scenario tool

Once the model is created, the multiple scenario simulation part begins. The simulation tool was developed in Python, inspired by the work of Riccardo Novo. The goal of the tool is to automate as much as possible the creation of multiple parameter files, simulate them and collect the results. A configuration Excel file was created for the creation of the scenarios. It consists of three main sections: model sheets, time slice sheets and time series sheets.

4.1.1 Model sheets

Each sheet represents a model in which each row represents a scenario to be simulated. The columns contain two types of information: the structure of the scenario and the parameters of the scenario.

Scenarios' setup

The setup columns are:

- **Skip**. When set to 'x', the scenario is skipped. It is designed to reduce the computation time of the models when some scenarios fail. The scenarios are ordered from best to worst. So if one scenario fails, the next worst scenarios will surely fail too, and skipping them drastically reduces the computation time.
- **Overwrite parameters file**. If this option is set to 'yes', the parameter file of the calculated scenario will be overwritten. This option should be set to 'no' if the parameter file was changed after its creation.
- **Time series columns**. The "time series sheet" column allows you to specify which time series sheet to read for each scenario. This can be useful to

compare different demands or technologies' capacity factors between scenarios. However, if the sheet is not available or if the "time series elaboration" option is set to 'yes', a new time series sheet will be created. To create it, the scenario searches for the time series file specified in the "Timeseries_file" column.

- **Solver**. If multiple solvers are available, through this column it is possible to specify which solver is used by each scenario. This could be used to make a comparison of the computation times of different solvers. The solvers actually supported are GLPK and CPLEX©.
- **Reference year**. This is the first year to be modeled. It is also the reference year of the time series data.

Scenarios' parameters

The columns are divided in function of which parameter they modify:

- **AI.XX**. Annual increase of the demand/capacity factor 'XX'. This is done by taking the time series related to that demand/CF and increasing it cumulatively year by year. Useful to simulate different conditions of demand increase/decrease, or if the parameter is related to a technology, it could be used to impose the technology degradation (capacity factor reduction).
- **MF.XX**. Here, 'MF' stands for multiplication factor. This parameter acts on the demand/CF time series related to 'XX', by multiplying it by the multiplication factor specified in the cell.
- **DIS_STO.XX**. Boolean parameter which permits to disconnect the selected storage. If multiple storage are present in the models, this parameter could be used to combine them.
- **ACT_UPL.XX**. This parameter could be used to set the activity upper limit of the technology 'XX'. Unfortunately, OSeMOSYS doesn't have a parameter for disabling/enabling a technology. The only way to do it is to reduce to zero its activity upper limit. So, this parameter could be also used in order to disable some technologies.
- **EMITARG.XX**. This parameter modify the parameter "Annual Emission Limit" of the pollutant 'XX' and it could contain a string or a number. The string can be in the format "t;r;m", where t is the target (0 emissions of CO_2 for example), r is the reference value (the emissions at the beginning of the modeled period) and m is the method. The methods implemented in this algorithm are two: linear and stepY. With the linear method, the target is reached linearly through the years, starting from the reference value. Otherwise, with the

method 'stepY' the target is reached by reducing/increasing it every 'Y' years (step2 every 2 years, step5 every 5 years and so on).

- **MAXCAP.XX**. It sets the maximum installable capacity of the technology 'XX' by acting on the OSeMOSYS parameter 'Total Annual Max Capacity'.

- **TotAnnMaxCapInv.XX**. This parameter modifies the parameter 'Total Annual Mac Capacity Investment' which represents the maximum capacity which could be installed year after year. Sometimes, in the scenarios there could be a relaxation of the limit of the maximum installable capacity, in order to simulate scenarios where there aren't limits of installation. But, if the capacity investment is still limited, the solver could not reach a converging result. For example, let's assume to have a number of years to be modeled equal to 30 and the capacity investment is limited to 2 MW/year. In this way, the total capacity that the model could ever reach is of 60 MW, by the last year. If there is no limit of maximum capacity and if it is required by the solver to reach a capacity higher than 60 MW, the model would not converge anyway.

- **CAPCOST.XX and FIXCOST.XX**. Both modify the cost parameters of the technology 'XX', the capital costs and the fixed costs respectively. As the EMITARG parameter, also this parameter could work with a string in the format "t;r;m", in order to make it possible to vary the costs of a technology in the years.

	A	B	C	D	E	F	G	H	I
3	Short_name	SKIP	Overwrite_param_file	Timeseries_elab	Code_type	Timeslice_sheet	Timeseries_sheet	Timeseries_file	Solver
4	BAU_Scenario	x	yes	yes	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
5	Free_Scenario	x	yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
6	CO2Calibration001	x	yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
7	CO2Calibration004	x	yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
8	CO2Calibration005	x	yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
9	Scenario0001		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
10	Scenario0002		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
11	Scenario0003		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
12	Scenario0004		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
13	Scenario0005		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
14	Scenario0006		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
15	Scenario0007		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
16	Scenario0008		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
17	Scenario0009		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
18	Scenario0010		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
19	Scenario0011		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
20	Scenario0012		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
21	Scenario0013		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
22	Scenario0014		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
23	Scenario0015		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
24	Scenario0016		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
25	Scenario0017		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
26	Scenario0018		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
27	Scenario0019		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
28	Scenario0020		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
29	Scenario0021		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
30	Scenario0022		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
31	Scenario0023		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
32	Scenario0024		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
33	Scenario0025		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
34	Scenario0026		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
35	Scenario0027		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
36	Scenario0028		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
37	Scenario0029		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
38	Scenario0030		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
39	Scenario0031		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
40	Scenario0032		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
41	Scenario0033		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex
42	Scenario0034		yes	no	OSeMOSYS	SIMPLE3	TS_FAV_1reg	TS_FAVI_1REG.xlsx	cplex

Figure 4.1: Example of a model sheet (Favignana).

4.1.2 Timeslices sheets

In each time slice sheet (see Figure 4.2), there is a time configuration that can be used for the model. Here you can configure the number and length of seasons, day types, daily time brackets and years to be simulated. The user could freely choose which time configuration to use for each simulated scenario. In the case of the Aegadian Islands, the selected time slice sheet is called "SIMPLE3" and consists of 6 seasons (bimesters), 1 day type, 10 daily time brackets, and a year span that goes from 2021 to 2050. The time brackets are of two sizes: 2 hours for the hours in the 6AM-6PM range and 3 hours for the remaining hours. This time division was chosen to increase the accuracy of the model during the daily hours when the solar panels are in operation.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Setting	Bimestrial																
2	Code	OSeMOSYS																
3	Description	4 seasons, 1 daytype																
4																		
5	**SEASON**	**Start day**	**End day**		**DAYTYPE**	**Type**		**DAILYTIMEBRACKET**	**Start hou**	**End hour**		**N_season**	**N_daytyp**	**N_DB**	**_Timeslices**		**Start year**	**End year**
6	1	1	59		1	All days		1	0	3		6	1	10	60		2021	2050
7	2	60	120					2	3	6								
8	3	121	181					3	6	8								
9	4	182	243					4	8	10								
10	5	244	304					5	10	12								
11	6	305	365					6	12	14								
12								7	14	16								
13								8	16	18								
14								9	18	21								
15								10	21	24								

Figure 4.2: Example of a time slice sheet (SIMPLE3).

4.1.3 Time series sheets

The time series sheet is the source of the time series used by the scenarios. Each scenario could freely choose a different time series sheet, making it possible to 'feed' the models with different demand/capacity factors profiles.

	A	B	C	D	E	F	G
1	**Timestamp**	**DEM.FAVI_1.DF_ATSE**	**DEM.FAVI_1.DF_RSD**	**DEM.FAVI_1.DF_NRSD**	**TECH.FAVI_1.FV**	**TECH.FAVI_1.EOLICO_B23**	**TECH.FAVI_1.EOLICO_V90**
2	**2021-01-01 00:00:00**	0.53072129495544	0.43195265107133	0.0954773109507668	0	0.695	0.695838666666667
3	**2021-01-01 01:00:00**	0.519970034836639	0.423202229042259	0.0935431481138269	0	0.783	0.788628
4	**2021-01-01 02:00:00**	0.474032832510846	0.385814062190782	0.0852789978105378	0	0.841	0.856444666666667
5	**2021-01-01 03:00:00**	0.435914728453272	0.354789838633173	0.0784215113886596	0	0.87	0.897493333333333
6	**2021-01-01 04:00:00**	0.408059190872737	0.332118290648765	0.073410271311133	0	0.871	0.900223666666667
7	**2021-01-01 05:00:00**	0.399262705320991	0.324958854443164	0.0718277744445458	0	0.87	0.897196666666667
8	**2021-01-01 06:00:00**	0.432493872960926	0.352005613442105	0.0778060959405423	0	0.86	0.881492666666667
9	**2021-01-01 07:00:00**	0.433959953886218	0.353198852809705	0.0780698454183067	0.14426	0.841	0.849988333333333
10	**2021-01-01 08:00:00**	0.491137109972577	0.399735188146119	0.0883560750511239	0.41862	0.812	0.80759
11	**2021-01-01 09:00:00**	0.562975075311849	0.458203917158536	0.101279799461587	0.59197	0.786	0.773065666666667
12	**2021-01-01 10:00:00**	0.583011514624162	0.474511521849074	0.104884375657703	0.69387	0.759	0.740924666666667
13	**2021-01-01 11:00:00**	0.569328092654778	0.463374621084805	0.10242271386523	0.68913	0.721	0.695428
14	**2021-01-01 12:00:00**	0.552223815193048	0.449453495129469	0.0993456366246471	0.70371	0.676	0.645669333333333
15	**2021-01-01 13:00:00**	0.493091884539632	0.401326173969586	0.0887077410214768	0.6424	0.639	0.608126333333333
16	**2021-01-01 14:00:00**	0.464258959675569	0.377859133073445	0.0835206679587737	0.48714	0.609	0.579928666666667
17	**2021-01-01 15:00:00**	0.498467514599033	0.405701384984121	0.0896748224399468	0.26244	0.556	0.538845666666667

Figure 4.3: Example of a time series sheet (Favignana).

4.1.4 Structure of the code

Once all the scenarios are set, the models could be launched. The code is built in a pyramidal structure, starting from the main code and propagating into the sub-codes (see figure 4.4).

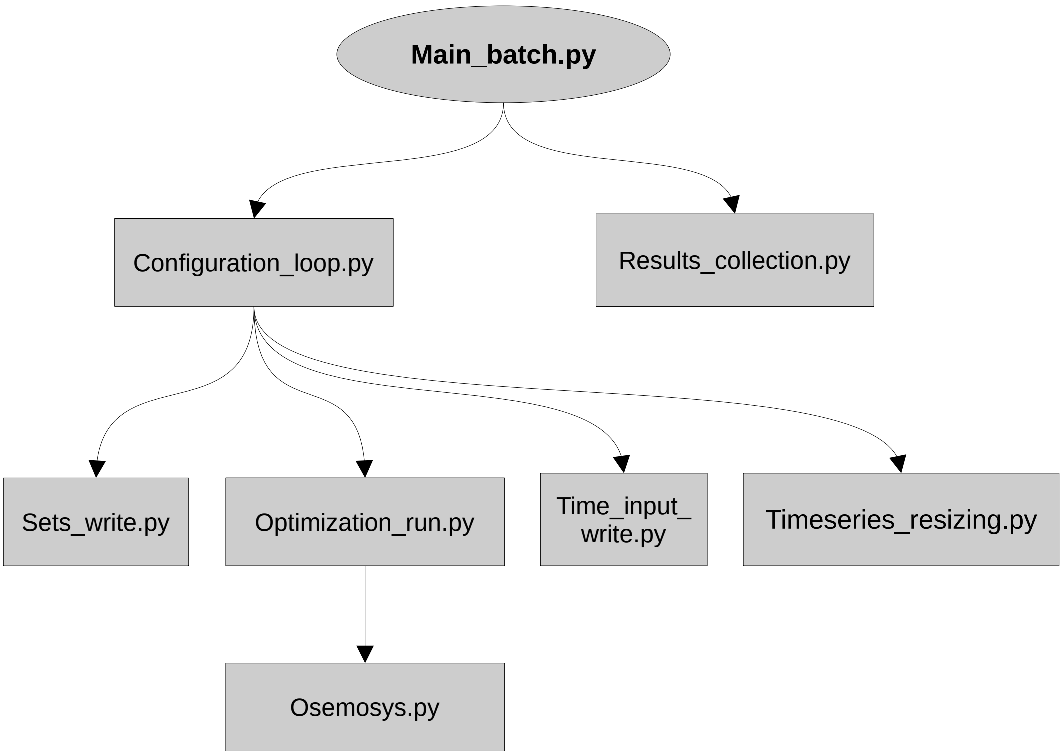


Figure 4.4: Structure of the developed code.

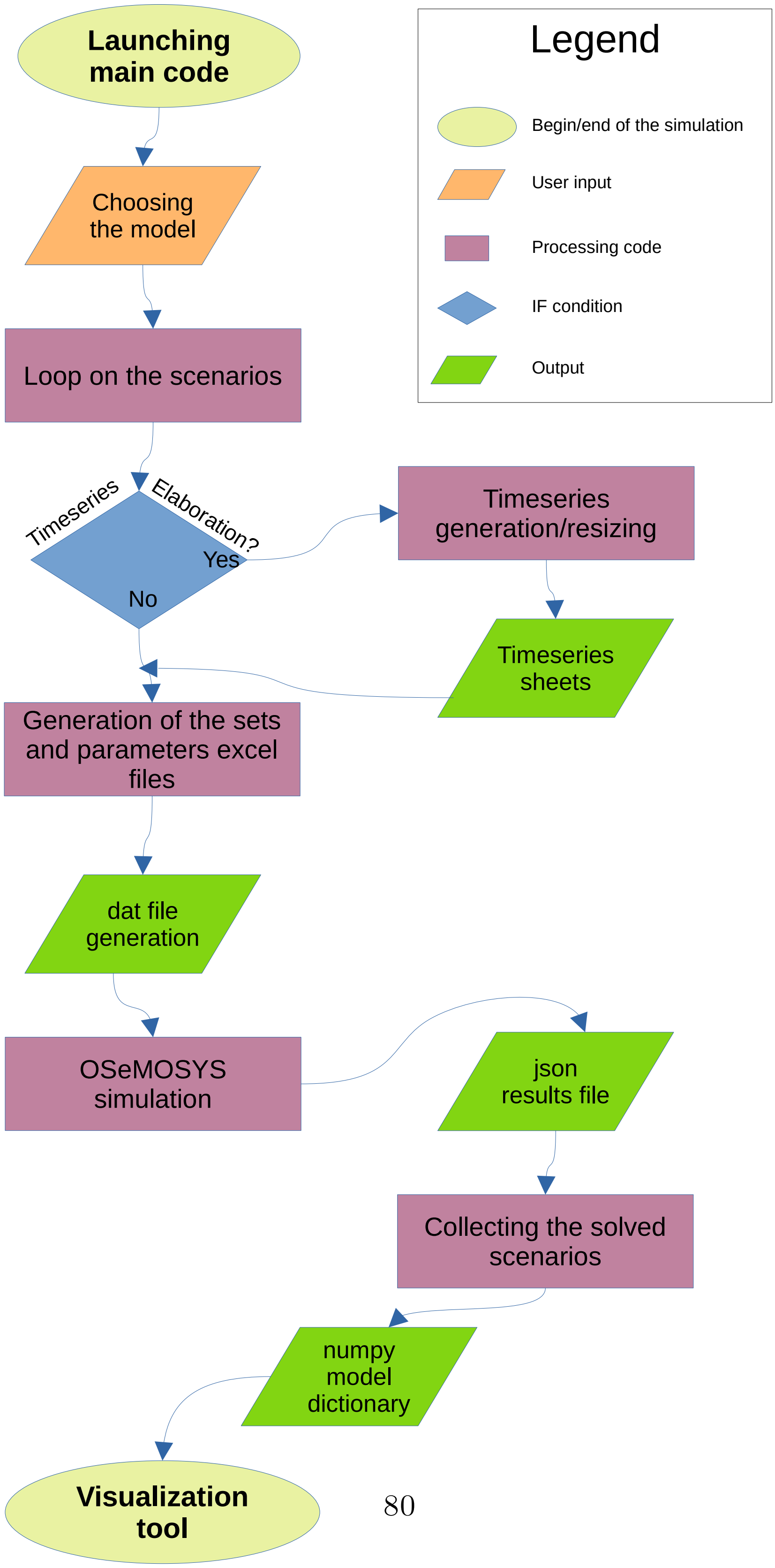


Figure 4.5: Flowchart of a simulation.

Main_Batch.py

This is the main code of the tool. When it is started, the code reads the 'Configurations' Excel file, which contains all the information about the models (see section above) and sets up the whole environment for the simulations, such as defining the directories and importing the other functions. Once set up, it looks in the configuration file for the sheets 'MOD.', each of which represents a model (or in this case, an island). It then asks the user which model he wants to start. At this point, the main code switches to the configuration loop.

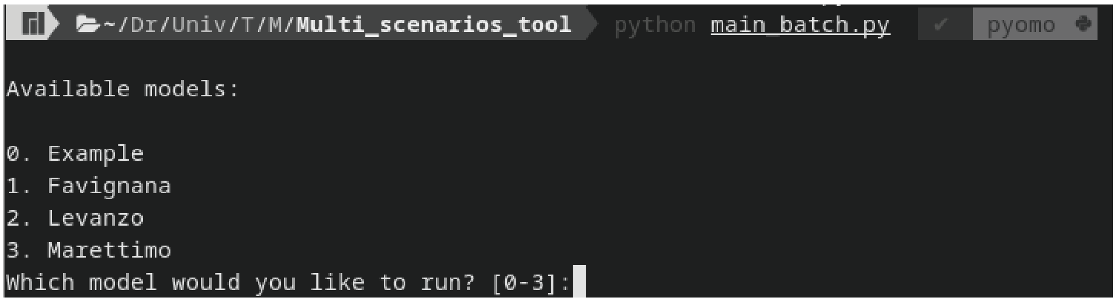


Figure 4.6: Launching the tool.

Configuration_loop.py

The selected model contains several scenarios, each with different settings. The configuration loop reads these settings with a for loop and starts simulating the scenario. In this part, the time series file is created or read if it already exists. Another code 'Timeseries_resizing.py' is required to create the time series sheet. Once the collection of all the scenario data is complete, the program generates the sets file by running 'sets_write.py', creates the Excel file of the parameters with 'time_input_write.py', and then simulates the scenario with 'optimization_run.py'. When the simulation is complete, the program starts calculating the next scenario.

Timeseries_resizing.py

If no time series sheet is available or if it is requested by the user himself, this code generates the time series of the selected scenario. To do that, it first reads an Excel file containing all the time series in different formats, and resizes them so that they are all the same size. If the time series has more than 8760 values, it means that the time steps are shorter than one hour and therefore it should be reduced in size. If it is a demand, the values belonging to one hour are summed; if it is a capacity factor instead, they are averaged. If the time series contains less than 8760 values, it means that the time step is larger than one hour and it should be scaled up. In this case, two approaches can be chosen: direct scale up or virtualization.

Direct scale up

When the "direct scale up" happens, the demands are just distributed evenly from the larger time step to the smaller one; while the capacity factors are copied, since the larger time step could be assumed as the average of the values belonging to the smaller time step. For example, if the time step is of 24 hours, and it is a demand of 24 MWh, when it scales up it is converted into 24 time steps of 1 hour, each one of them representing 1 MWh. But this approach doesn't give information to the solver on what happens in the most intense hours. It just sees a homogenous demand. The same is applied on the capacity factors. This is the reason why it has been built a code for the virtualization of the time series.

Virtualization

The virtualization is a free choice of the user, and it consists in setting the virtual profile of the demand/capacity factor along the hours of the day; then the code automatically create the time series by following that profile. This approach is util when it is known the demand in a month scale, but it is necessary to know how the demand impacts in some hours of the day. For example, some models of the Aegadian islands simulate the ferries journeys and, when they are switched to the electric ferries, they could require electricity from the islands' electricity network. Because of the high number of routes done per day, the ferries recharge after every journey, having a high impact on the electricity demand [43]. So, instead of having their demand distributed equally during the day, it is preferable to make it corresponds to the routes hours, referring to the companies timetables.

Time_input_write.py

This code generates the parameters for each scenario, in function of the conditions declared in the configuration file. To do that, it refers to a template parameters file, which contains all the parameters necessary for the model to converge, but they are defined for only one year. The time_input_write reads it and modify it by introducing the customizations declared in the configuration file, if available, or by simply copying the first year into the successive years. Obtaining then a complete parameter file, which will be successively saved.

Optimization_run.py

After the generation of the sets and of the parameters files, the next part consists in creating a .dat file which contains the information useful for OSeMOSYS to simulate, done by the 'optimization_run' code. After that, it begins the simulation, which generates an output json file containing all the results.

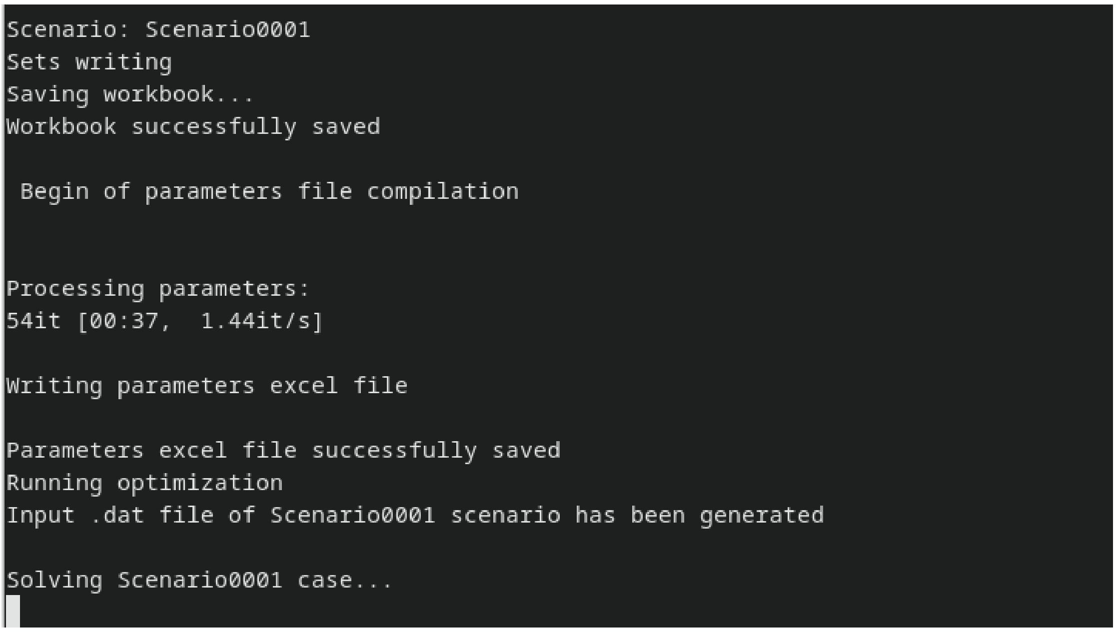


Figure 4.7: How the terminal appears when the simulation is running.

Results_collection.py

When all the simulations of the model's scenarios are done, the 'results_collection' script iterate between all the results folders, collecting the results from the json files. The model's scenarios are saved in a dictionary, creating a sub-dictionary for each one of them. Under each scenario there are as sub-dictionaries as the number of the output variables (Total installed capacity, storages variables etc.), and each one of them contains a DataFrame for each region present in the model (see figure 4.8). When the collection is completed, the code saves the results in a numpy file, ready to be read by the visualization tool.

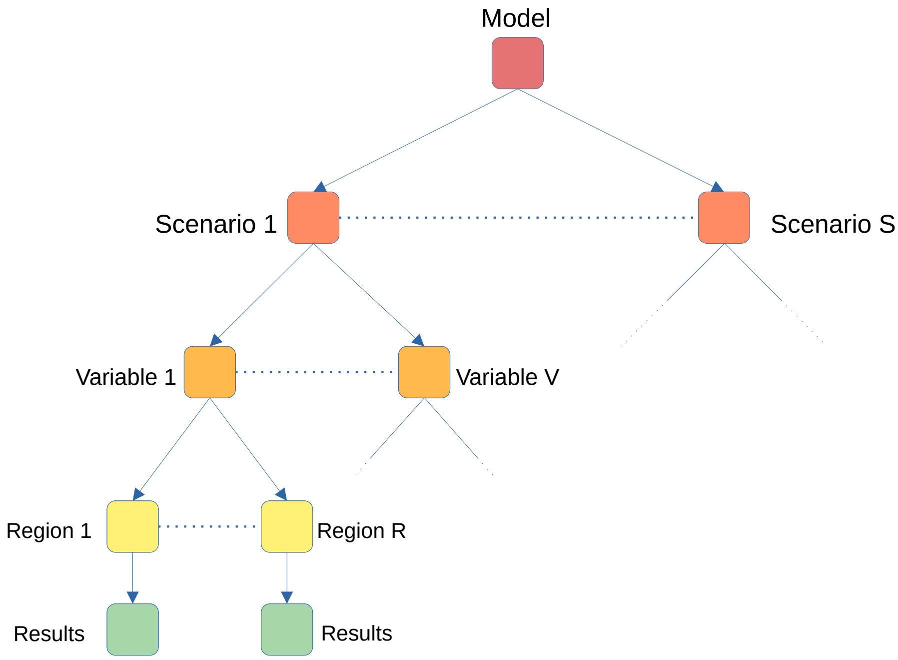


Figure 4.8: Structure of the results dictionary.

4.2 Visualization tool

The visualization tool, as the multi-scenario tool, has been built in Python language code. But for its realization, it has been used the Dash library [75]. Dash, as the company claims, is a language code useful for the realization of graphic dashboards, accessible especially by the decision-makers. In fact, the potential of dashboard consists in running it on a server while permitting the user to connect to it remotely and play the session without influencing the other users' sessions. For these reasons, Dash can be very promising to easily show to the stakeholders the results of the scenarios, leaving them free to choose the conditions of the scenario to plot. The Dash package uses a mix of HTML and Python language, in fact the resulting dashboard would be run in HTML and can be only viewed by browser. The App is divided in two sections: Layout and Callbacks.

4.2.1 Layout

Here happens the customization of the application's user interface, by introducing the tree of the components which could be of two type: HTML components or dash components. The firsts are components translated from HTML to the Python language; so they could be html.Div, html.Button, html.H1, etc., doing the same function they do in HTML. The dash components are instead some components implemented by the dash library itself, they generally have a different purpose than the HTML's ones. For the realization of the layout, it has been taken as inspiration the layout of an open source application of Dash [76]. The user interface has been divided in three sections, composed by twelve vertical columns in total, with fixed width but variable length. Two sections are placed in the left and right sides, each one of them with a width of three columns, while the last section has been placed in the center of the interface, having a width of six columns. In this way, the section on the right has been used for the customization of the viewer options (scenario's selection, variables selection, plot settings etc.); the section on the left has been used for the secondary data visualization, while the section in the center has been used to plot the main graph.

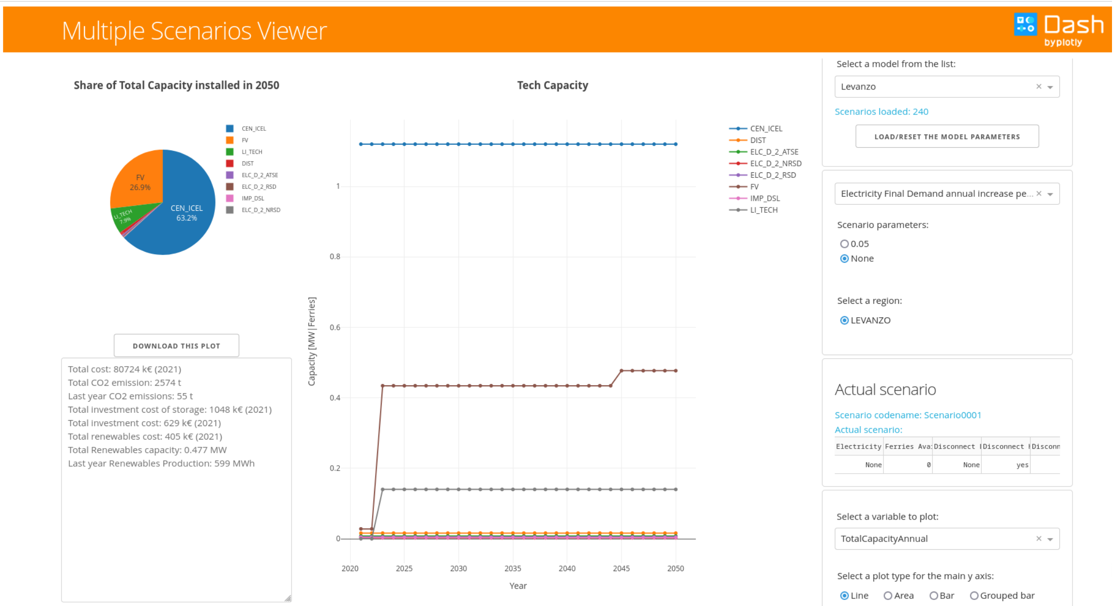


Figure 4.9: User interface of the multiple scenarios' viewer.

[

```
    drc.Card([
            dcc.Dropdown(id='options-list'),
            html.Button('Confirm',
                        id='confirm-button',
                        style = {'textAlign':'center',
                                 'margin':'10px',
                                 'display':'none'}),

            html.A(id='param-name',
                   style={'display':'none'}),
            drc.NamedRadioItems('Scenario parameters',
                id='param-options',
                labelStyle={
                    'margin-right': '7px',
                    'display': 'block'
                }),
            drc.NamedRadioItems('Select a region',
                                id='select-region',
                                style={'display':'block'},
                                inline=True),

            ])
```

Listing 4.1: Example of the code used for the generation of the scenario's selection card

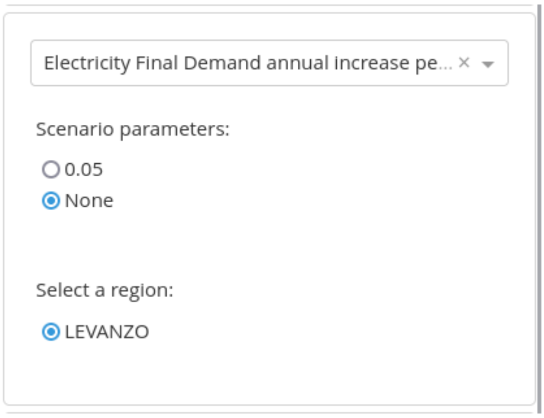


Figure 4.10: How the card generated by the code 4.2.1 appears.

4.2.2 Callbacks

The callbacks represent the interaction that the user has with the program. Every time the user interacts with the user interface, by clicking a button or by choosing an item from a dropdown menu, the callback to which it is associated that input, intervenes. The callbacks are composed by three components: Inputs, Outputs and Functions. The inputs are, as mentioned before, what triggers the callback; the Function is a function definition which makes the needed computation and returns the Outputs. All the Outputs voices should interact with a layout item (distinguished by an id), allowing the transformation of the user interface, for example by plotting a graph, by writing something, by disabling some user interface buttons and so on, with infinite possibilities. Because of Dash's muliple-users nature, every variable generated in a callback should remain inside it; so in this way, each user generates its own variables without getting involved in variables conflicts. But, the viewer should permit the variable to escape a callback, for example when the scenarios are loaded. In fact, because of their big size (in the case of Favignana the file size is of 2 GB) they could not be loaded every time the user interacts with a component, slowing down the system. It is then preferred to pre-load them, and then to call them every time a callback requires the reading of the scenarios. This issue has been solved generating a global variable for the loaded scenarios, callable from every callbacks, and by using the dash component 'dcc.Store'. This component allows to pull out data from the callbacks, by loading them in this 'container' which would be different for each user, so without losing the multi-tasking of the tool. To permits their uses, the dataframe that should be exported, should be firstly converted into the json format.

4.2.3 App functioning

Once the user loads the scenaios of the selected model, the options bonded to it are generated and inserted inside a dropdown menu. When the user interacts with the menu, the values of the options are listed below it, permitting the user to choose the option he prefers. Once all the options have been chosen, the program iterate through the available list of the scenarios, by removing the ones which don't satisfy the options. At the end of this iteration, it should remain only one scenario, that would be the one that should be plotted. To choose scenario's variable to plot, the user can interact with two dropdown menus, one for the main y-axis, and the other for the secondary y-axis. Once the scenario has been founded by the tool and the variable has been set, the program searches for the dataframe bonded to these two conditions in the scenarios' dictionary, following the structure in the figure 4.8, and then plot it in the main chart. The secondary chart, on the left, plots the results of the last year for that scenario, so to make it easy to understand what is the results' share at the end of the model's computational period.

Results

The simulations of the Aegadian Islands models took about 1 month and were performed using four personal computers with average hardware. After some adjustments and the removal of the non-converged scenarios, the total number of scenarios was ∼1800 for Favignana and Marettimo islands and 240 for Levanzo. The non-convergent scenarios are those where the conditions were too strict, for example when there is a demand increase and a strict CO_2 target, but the renewables power potential is really limited, so the solver cannot find a feasible solution. An interesting result of this approach is not only the comparison between scenarios of the same model, but also the comparison between the models themselves. This is because, despite the energy systems being quite similar, the way in which the solver installs the storage/ RES technologies differs drastically. An interesting approach would be to compare the storage technologies. To do this, the scenarios with maximum photovoltaic power potential (PVPP), medium-scale wind turbine, no ferries, and constant demand were selected, and then the rated power of storage was compared to its capacity at the end of the model period for each technology and for each CO_2 emission target.

As expected, the rated power and capacity of the storage increase when the CO_2 emission target is stricter, reaching their maximum when the emissions' limits are zero. According to the results, lithium exhibits an interesting behavior. When the CO_2 emission reduction target is the lowest (-80% of emissions), the lithium storage has the lowest rated power and capacity; however, when the emission target is more stringent, this behavior reverses and results in the lithium storage having the higher rated power and capacity values. This could be due to the fact that it has the highest efficiency and lowest cost, especially fixed cost, among the modeled storage technologies. Among the available storages, the lithium storage does not require as much regular maintenance. The lithium storage also has the shortest operational lifetime (10 years versus 30 years for the other storages). Thus, if the emissions target is not particularly stringent, the solver determines that it is not worth installing lithium storage due to cost. However, if the target is more stringent, the solver installs more lithium storage than renewable energy technologies because it is cheaper and reduces curtailment. But this doesn't explain the higher overall

costs of the lithium-based models in respect to the other storage technologies (see its behavior in Favignana case 5.2). The reason of this contradiction stands in the storage lifetime. In fact, because of the short operational life of the lithium storage, it would be better to install bigger capacities of it taking advantage of its low prices. Let's see this under another perspective. When the model requires zero carbon emissions within the last year (2050), the solver should choose between increasing the rated power of the renewable plants (therefore increasing the investments costs) or install more batteries that cost less, in order to better use the already available renewable power plants (curtailment reduction). Clearly, the only way to really understand this "paradox" is seeing the attempts done by the solver in order to reach this solution.
So in summary, when the Li-ion battery storage is considered in the system, the rated power of the renewable sources is lower if compared to the other storages configuration. Furthermore, the Li-ion batteries have short responding time among the other modeled storage technologies. Considering the size of the islands networks and their isolation from the mainland network, a faster dispatchable power source as the Li-ion storage could increase the stability of the network. So, the Li-ion storage has been taken as reference storage for the other plots.

5.1 Favignana

The behavior of the Li-ion storage described above is confirmed by the plot of the Favignana RES penetration, which shows, in the carbon-free scenario (green), a low overall cost reduction (-50.8%) but with also the lowest rated power for the RES technologies (16.78 MW), see figure 5.2. Being Favignana the biggest island in the archipelago, with the highest demands, its storage systems reach capacities up to 37.45 MWh with a rated power of 4.95 MW (Li-ion batteries) when the CO_2 target is set to zero (green symbols on figure 5.1).

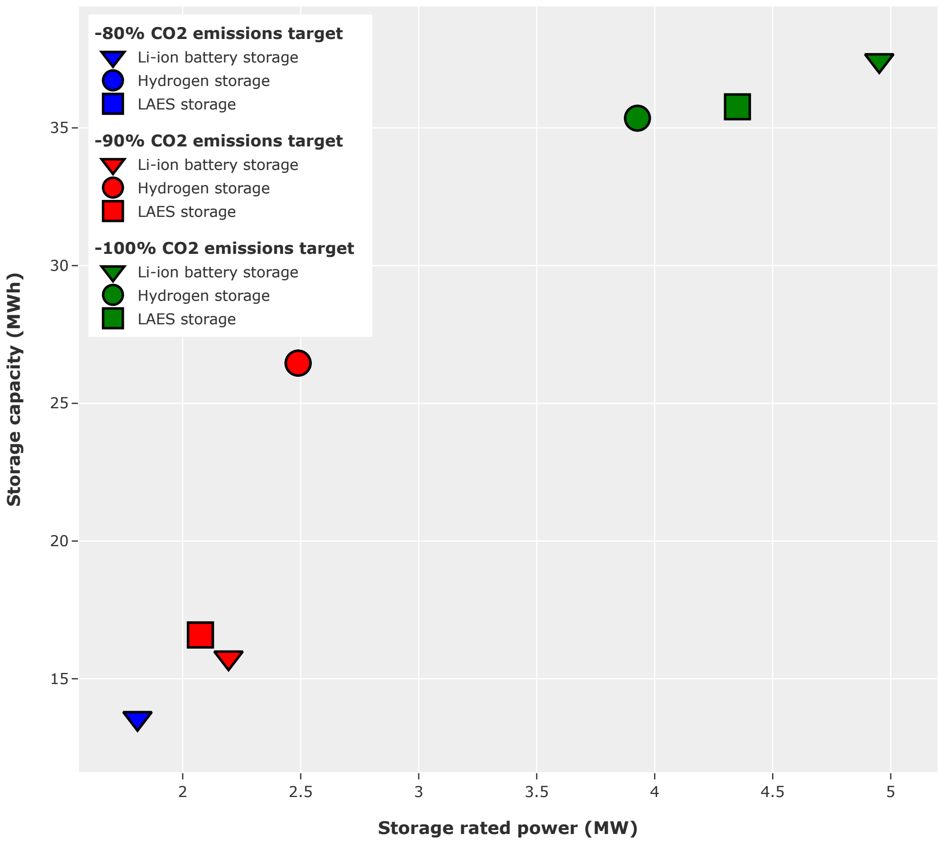


Figure 5.1: Correlation between storage capacity and storage rated power in function of the CO_2 target and of the type of storage (Favignana)

In the figure 5.2 it is plotted the correlation between the RES penetration and the overall cost reduction, in respect to the total costs of the BAU scenario equal to 122 M€ in Favignana model's period. According to the results, in Favignana model there would be a costs reduction, also when the CO_2 emissions target is of zero emissions within the 2050. Given that the results in the plot refer to the scenarios where the demand is constant, these results are still encouraging in view of a future energy transition.

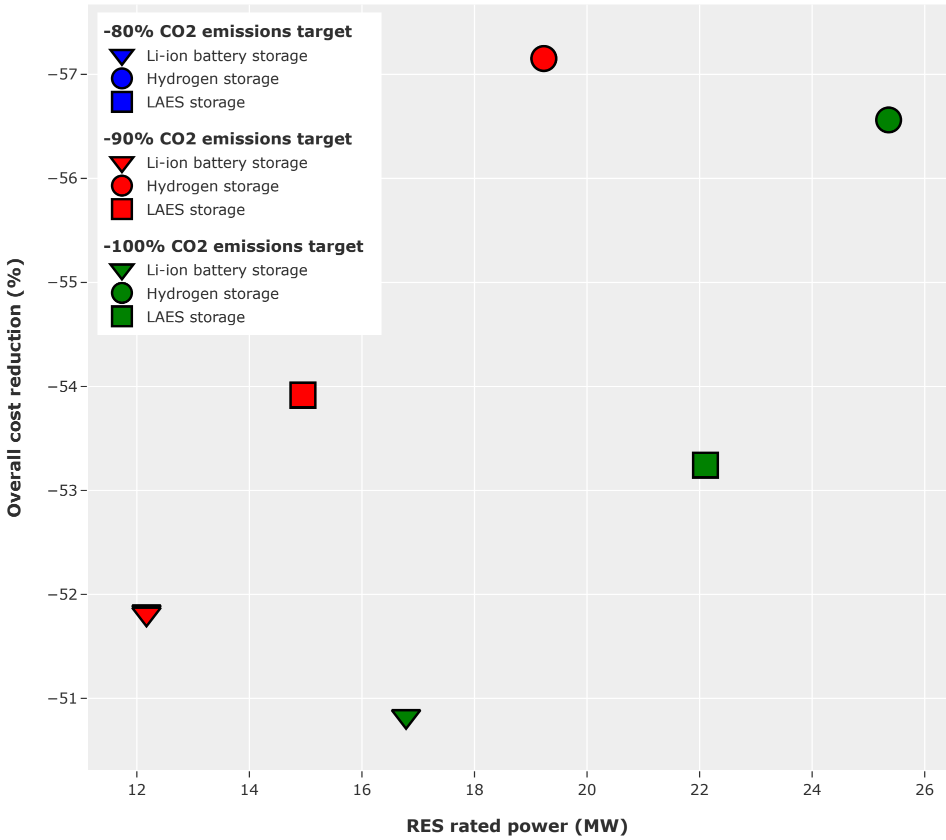


Figure 5.2: Correlation between the rated power of the renewable technologies and the overall cost reduction, in function of the CO_2 target and of the type of storage (Favignana)

In order to understand what are the differences between the scenarios in which the demand increments and those that have a constant demand, they have been compared in the graph 5.3. The straight line represents those points where the renewable energy production equals the electricity final demand. If the emissions target is zero, the points should lay under the line, meaning that there is more energy production than electricity final demand. The production should not equal the demand, because there are energy losses in both the distribution line (6.35%) and in the storage systems (14% in the Li-ion battery). If instead the emissions target is higher than zero, the demand could be higher than the RES power generation, because in any case the remaining energy would be supplied by the diesel generators. According to the graph, in Favignana there could be enough RES power generation in order to satisfy the demand, in any scenario associated with the demand's increments.

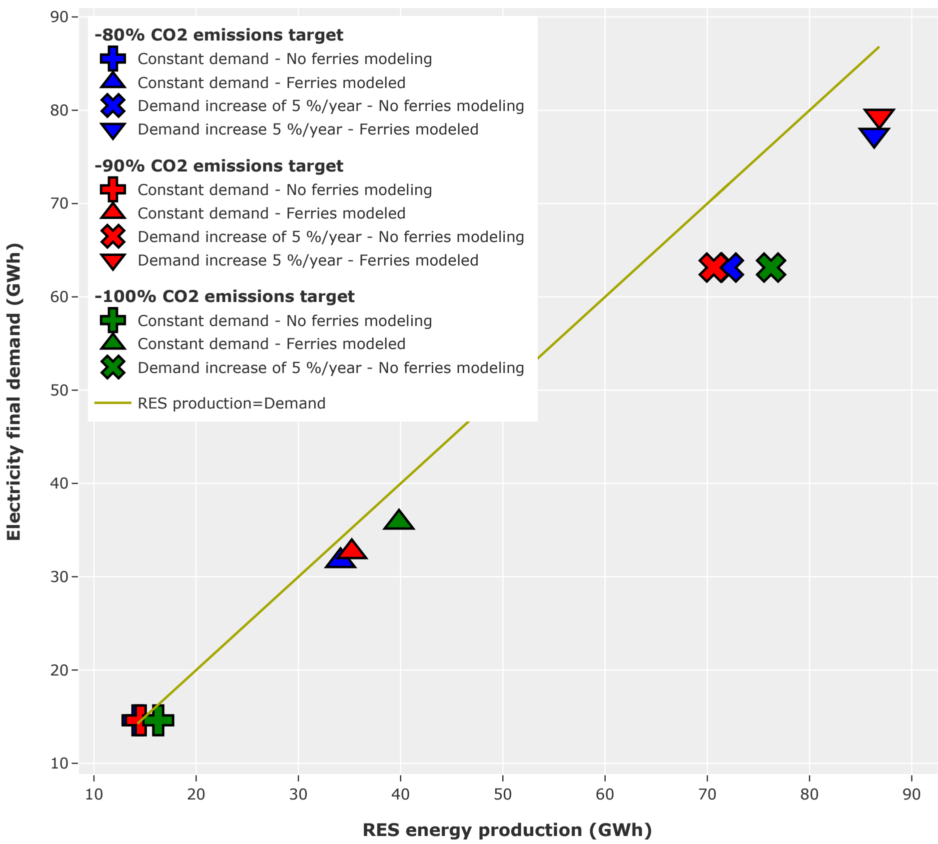


Figure 5.3: Last year renewable energy production and electricity final demand, in function of the CO_2 target and of the demand increments (Favignana).

According to the results hereby, the Favignana energy system should support an increment of demand. To verify that, two scenarios have been extrapolated from the viewer tool. The first one has constant demand, Li-ion battery storage, full PV power potential, medium-sized turbine and full decarbonization target. The second, instead, has the same characteristics of the first scenario with the exception that it has an annual increase of the demand of 5 %/year.

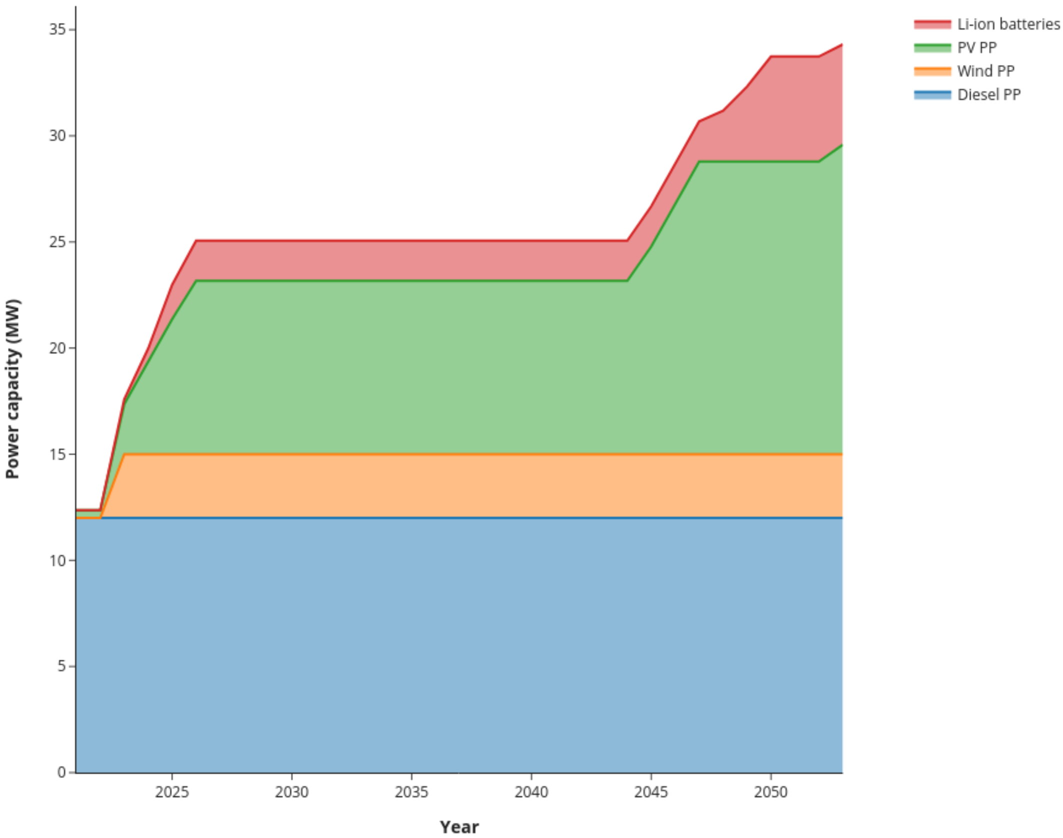


Figure 5.4: Power capacity in Favignana when the demand is constant and the CO_2 emissions target is zero. The constant slope between 2027 and 2045 means that the CO_2 target requirements are satisfied. The solver, in fact, installs enough renewables power plant at the beginning of the simulation probably because it would reduce the overall costs.

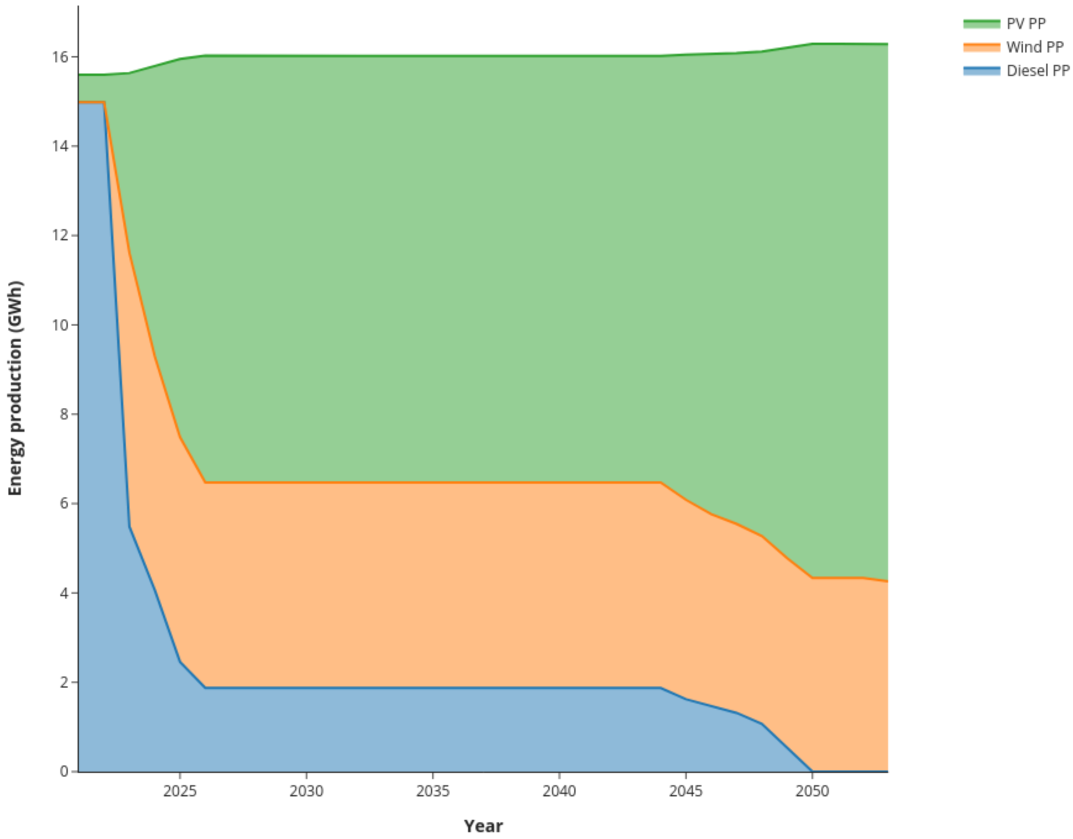


Figure 5.5: Energy production in Favignana when the demand is constant and the CO_2 emissions target is zero. As it is possible to see, there is a little increment in the generated power. This could be associated to the installation of the storage in the system. The storages, in fact, have energy losses in both the phases of charging and discharging.

When the demand increases, the system responds differently. Similarly to the scenarios above, there is an investment in the technologies during the first modeled years, but after that, the installed power capacity keep an approximately constant slope. Nearly the year 2040 the slope changes and the rated power of the storage technology increases more rapidly than the power capacity of the solar panels. An explanation to that behavior could be the capacity factor curve of the solar panels. In fact, they could still produce enough energy in order to satisfy the demands, but their ability to cover the peak demands is still limited to the capacity factor curve. So in the hours in which the capacity factor is lower, the PV panels cannot satisfy the demand and so the Lithium storage intervenes. This could lead to quicker increase of the rated power capacity of the Lithium storage.

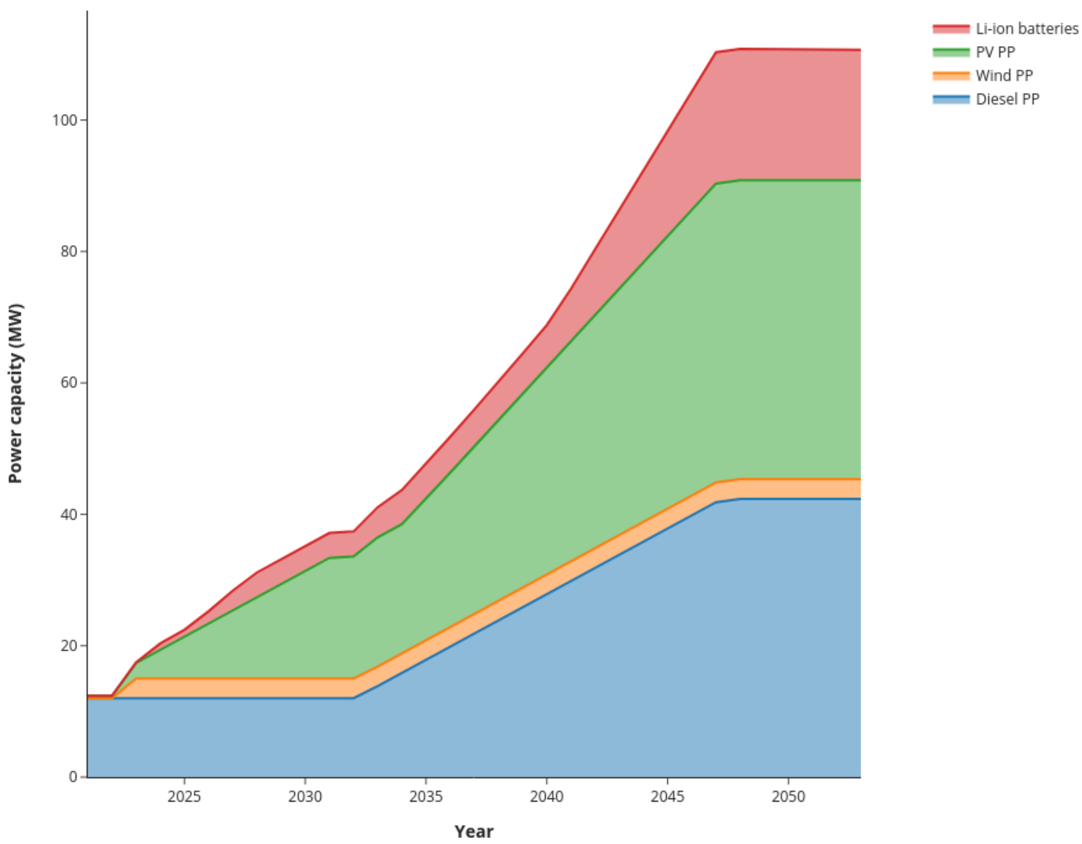


Figure 5.6: Power capacity in Favignana when the demand annually increases and the CO_2 emissions target is zero.

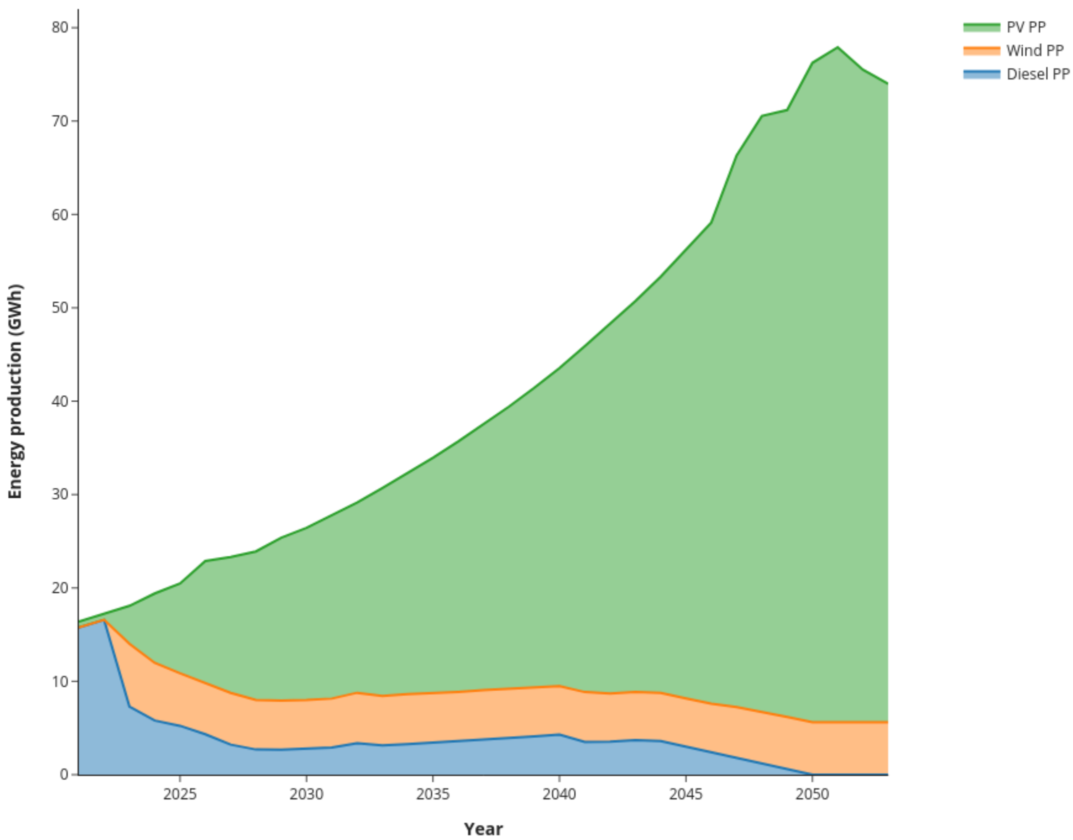


Figure 5.7: Energy production in Favignana when the demand annually increases and the CO_2 emissions target is zero

5.2 Levanzo

Levanzo has the lowest demands among the Aegadian Islands. Thanks to its high PVPP, those demands are easily satisfied in almost all the simulated scenarios. As it is possible to see in the figure 5.8 the storages don't reach capacities comparable to the other islands. In fact, they nearly reach the 2 MWh of storage's capacity in the carbon-free scenarios, as it could be seen observing the green symbols. The Lithium storage is the one with the highest rated power and installed capacities among the other technologies, reaching a capacity of 1.76 MWh and a rated power of 0.2 MW.

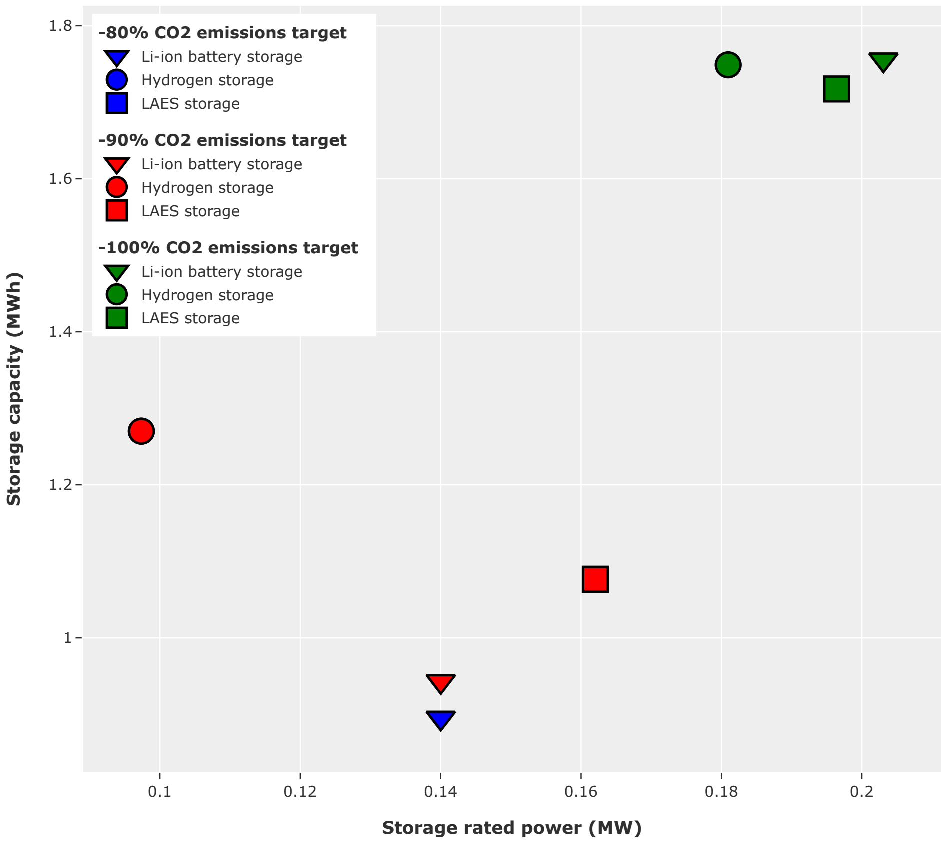


Figure 5.8: Correlation between storage capacity and storage rated power in function of the CO_2 target and of the type of storage (Levanzo)

Similarly to Favignana, also in Levanzo there is around -50% of overall costs reduction. An interesting result is the overall costs reduction of the scenarios having the hydrogen as storage systems. According to the results, those scenarios in Levanzo have higher costs reduction rather the other storages systems, even in the scenario with zero carbon emissions. But, differently from Favignana scenarios, in this case the RES rated power of the scenario having the hydrogen storage is similar to the one having the Li-ion battery as storage. This suggests that hydrogen could be the best storage solution in Levanzo. But despite that, the storage system used as reference for the plotted scenarios is still the Li-ion ones, because of its better response times.

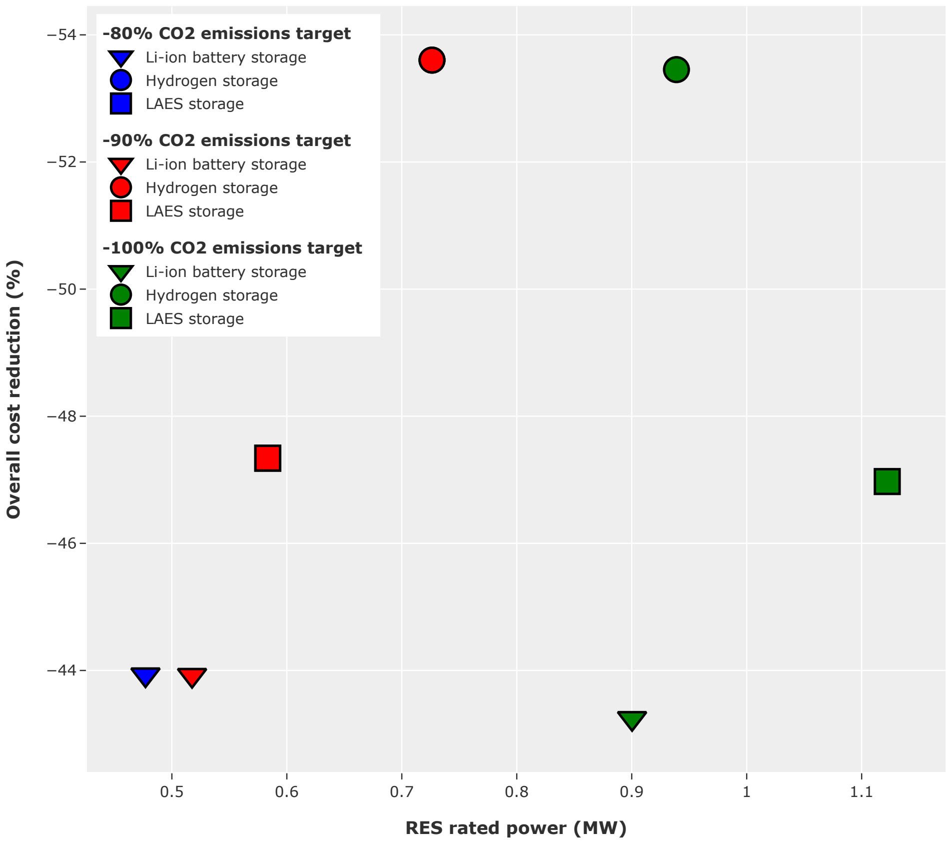


Figure 5.9: Correlation between the rated power of the renewable technologies and the overall cost reduction, in function of the CO_2 target and of the type of storage (Levanzo)

Comparing those scenarios which have an increase of the annual demand to those having constant demand, it is possible to see how the Levanzo model responds to the demands increments. Observing the curve in the figure 5.10, the Levanzo RES energy production always satisfies the electricity final demands, also in those scenarios where there are both the ferries modeling and the electricity demand annual increase.

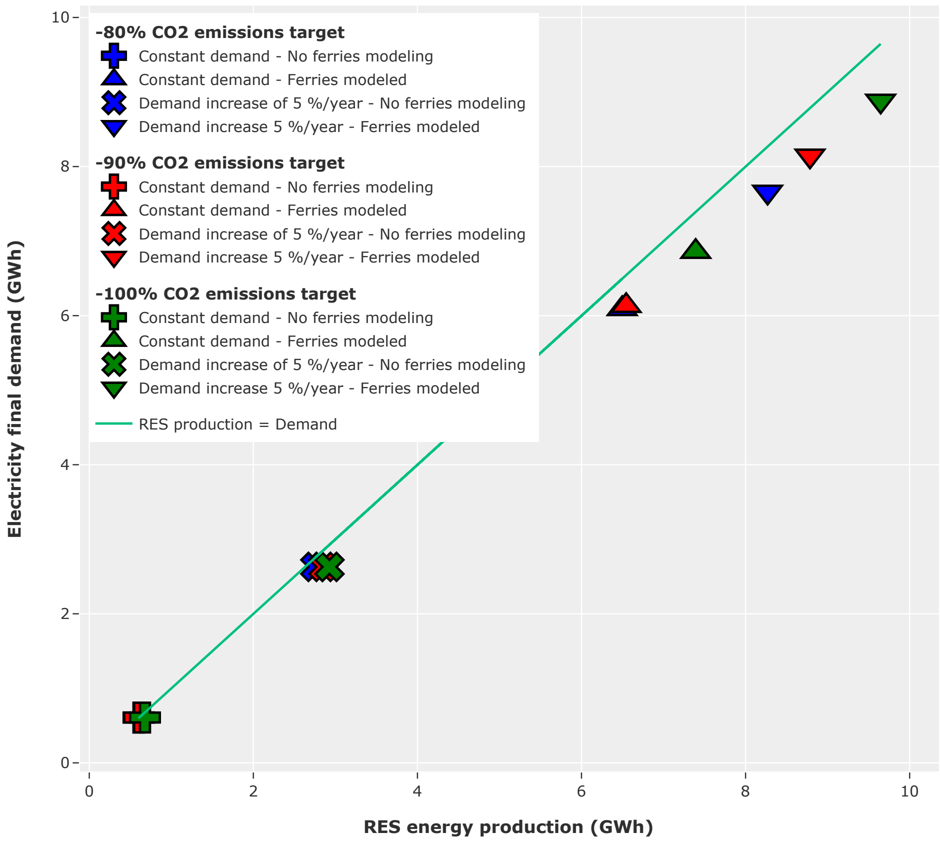


Figure 5.10: Last year renewable energy production and electricity final demand, in function of the CO_2 target and of the demand increments (Levanzo).

According to the results, the renewable power potential of Levanzo is enough for the satisfaction of the electricity demands; also in those scenarios where there is an annual increase of the demand.

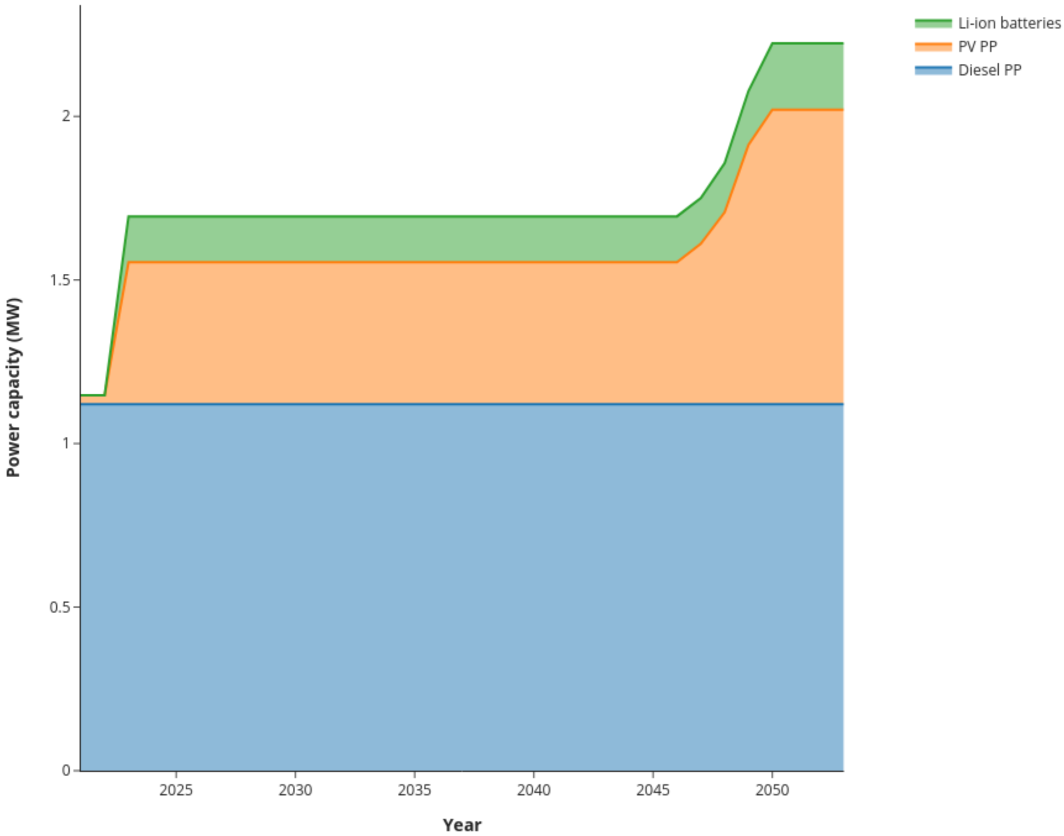


Figure 5.11: Power capacity in Levanzo when the demand is constant and the CO_2 emissions target is zero

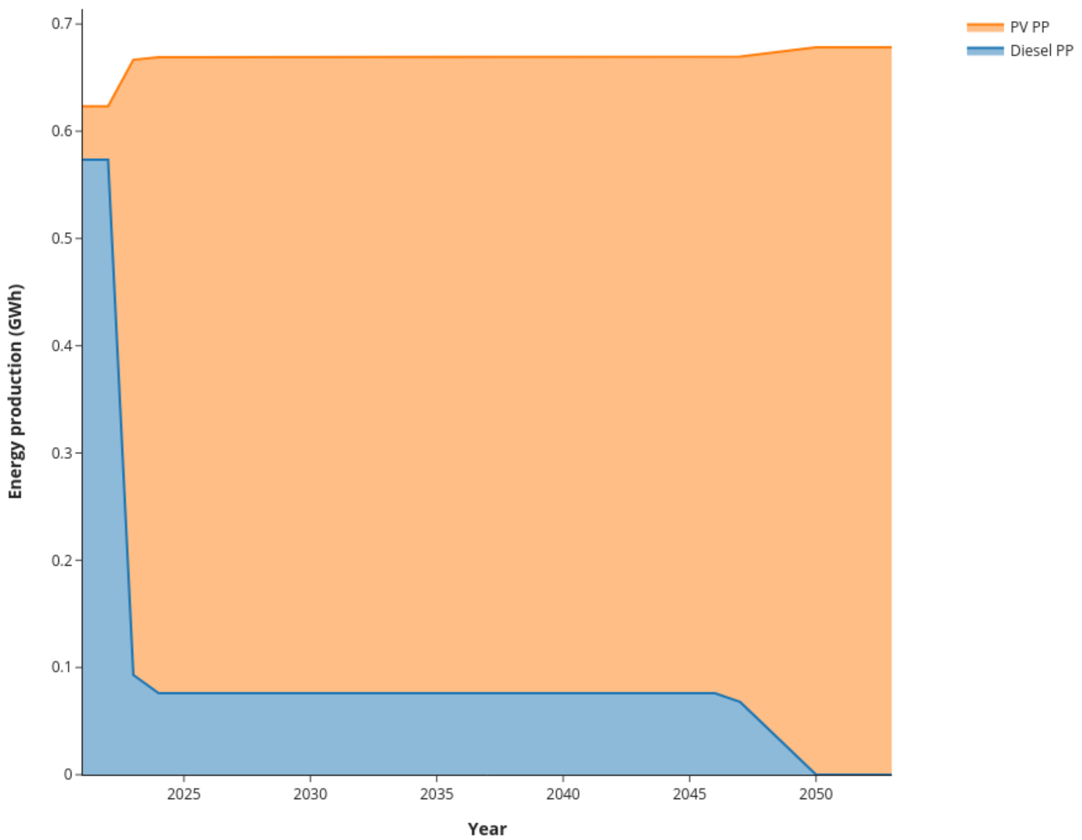


Figure 5.12: Energy production in Levanzo when the demand is constant and the CO_2 emissions target is zero

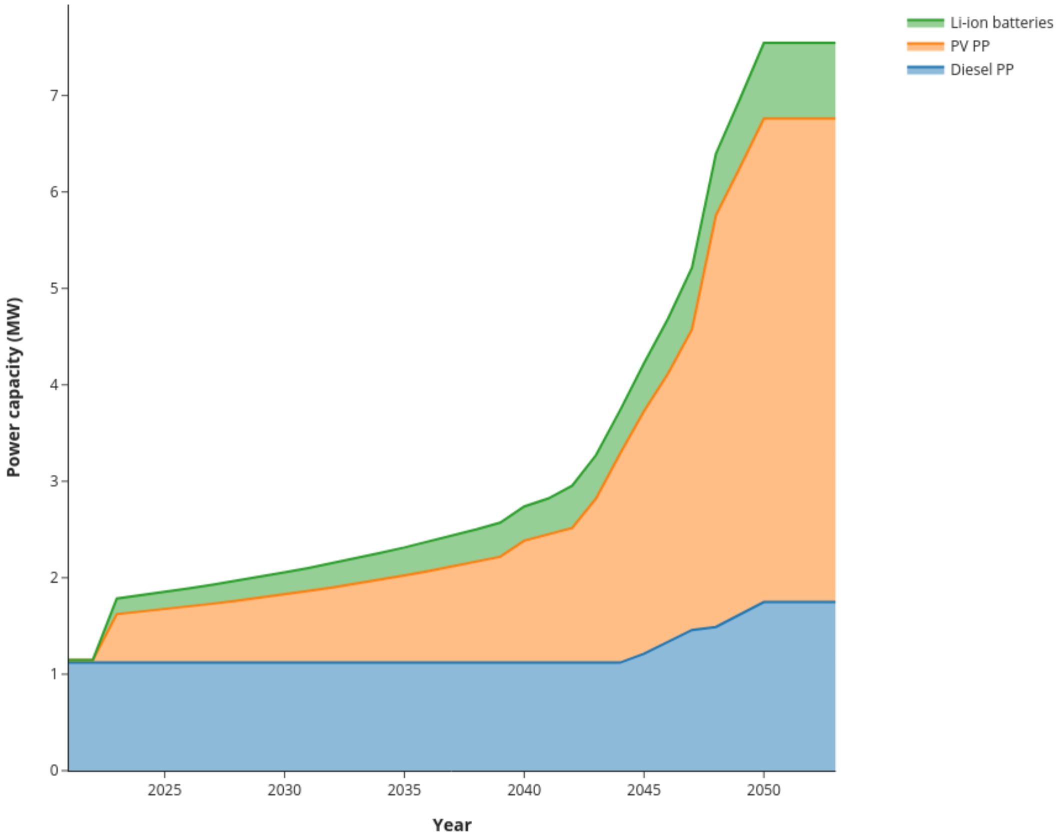


Figure 5.13: Power capacity in Levanzo when the demand annually increases and the CO_2 emissions target is zero

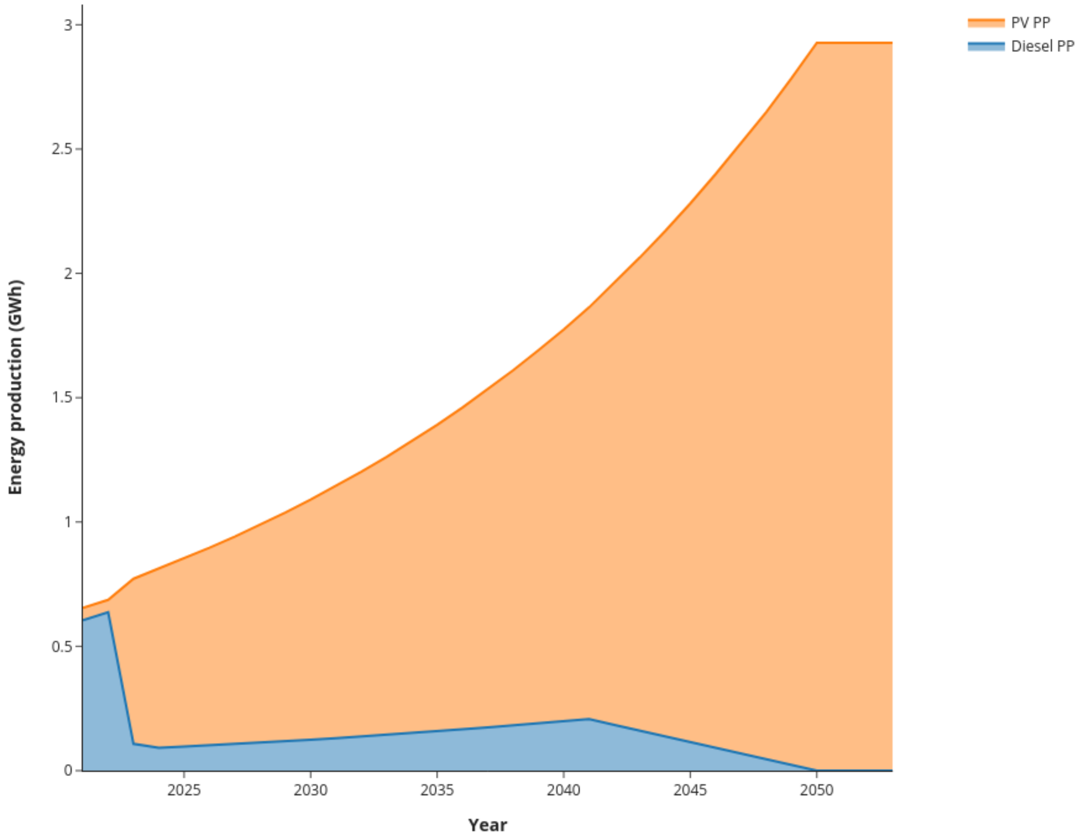


Figure 5.14: Energy production in Levanzo when the demand annually increases and the CO_2 emissions target is zero

5.3 Marettimo

Among the islands, Marettimo is the one with most difficulties in meeting the demands. In fact, when the carbon reduction targets are applied, it seems that the renewable power potential of the island is not enough in order to satisfy the electricity demand. In the figure 5.15 it is possible to see that the carbon-free scenarios require energy storages' capacities over the 3 MWh. In the case of the Li-ion battery, the storage's capacity reaches values up to 3.62 MWh with a rated power of 0.2 MW.

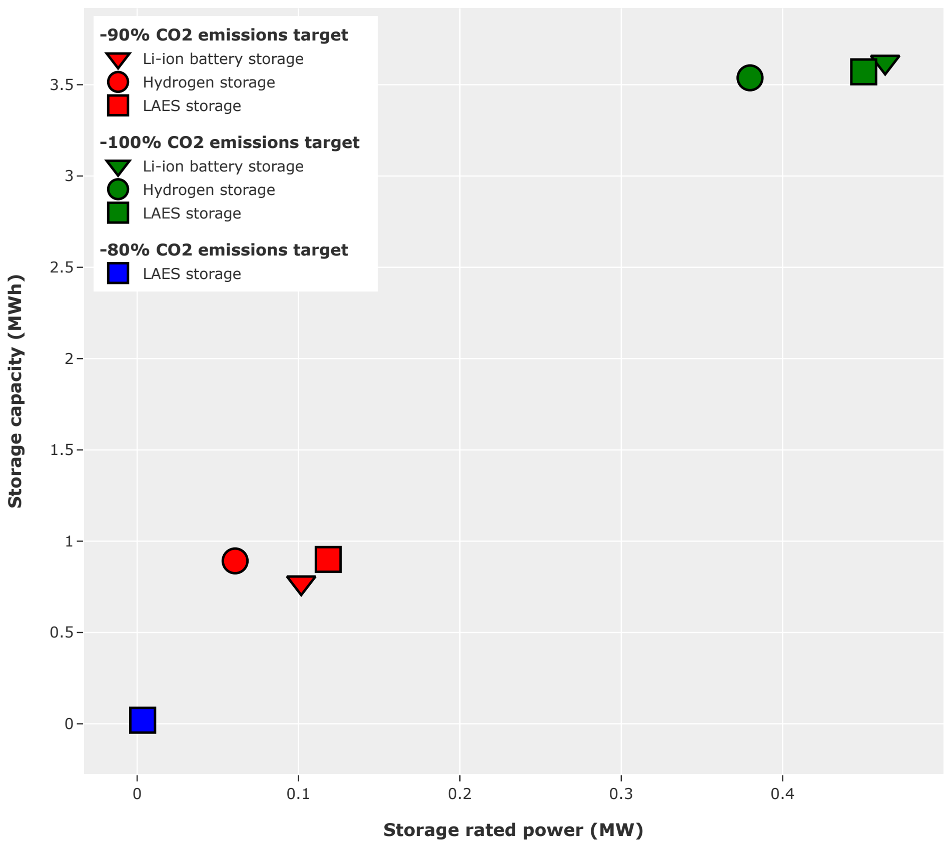


Figure 5.15: Correlation between storage capacity and storage rated power in function of the CO_2 target and of the type of storage (Marettimo)

According to the results plotted in the figure 5.16, the carbon free scenarios reach the maximum renewable power potential of the island (3.545 MW) that has been calculated in the chapter 2. This means that the island could have difficulties to satisfy demand increments, casting doubt on the sustainability of the island to the transition to carbon-free energy systems.

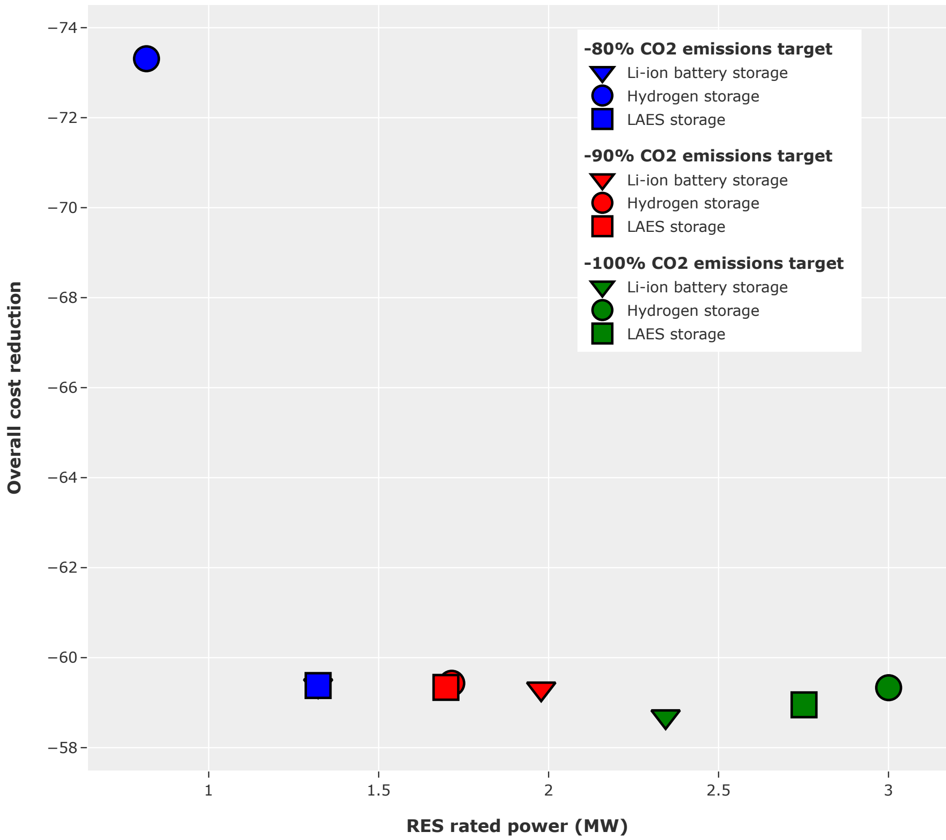


Figure 5.16: Correlation between the rated power of the renewable technologies and the overall cost reduction, in function of the CO_2 target and of the type of storage (Marettimo)

What has been observed before, could be confirmed too by the figure 5.17. In the carbon-free scenarios, in fact, when there is a demand increment, the demand exceeds the energy production of the renewable energy sources (RES). Those scenarios may have converged because of the availability of enough energy in the storage systems, which reached capacities over the 4 GWh. But these are clearly not sustainable scenarios, making it necessary to increment the renewables power potential of the island.

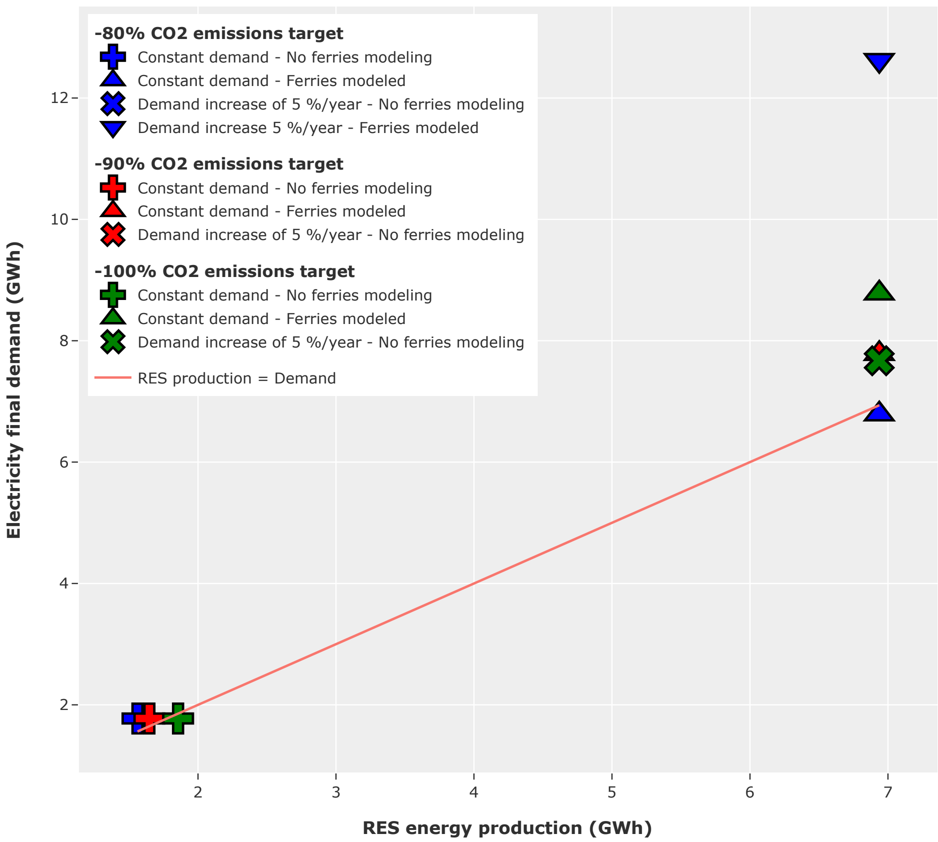


Figure 5.17: Last year renewable energy production and electricity final demand, in function of the CO_2 target and of the demand increments (Marettimo).

In the figures below, the comparison between those scenarios having constant demand and those having an annual demand increase. According to the results explained before, the latter type of scenarios could not be sustained by the island's energy system, despite it could appear to be possible according to the figure 5.20. By looking at the figure 5.21, it is possible to see that there is a peak of energy production between the years 2040 and 2045, which has probably charged the storage, giving to it the possibility to satisfy the demands in the years when the diesel generators cannot be turned on (since 2050). In fact, by looking at the same plots of the other islands, there is not such type of behavior in the energy production curves. It can be concluded that the island of Marettimo could sustain an energy transition to a carbon-free energy system, if the demand of electricity remains constant to 1.8 GWh ca.

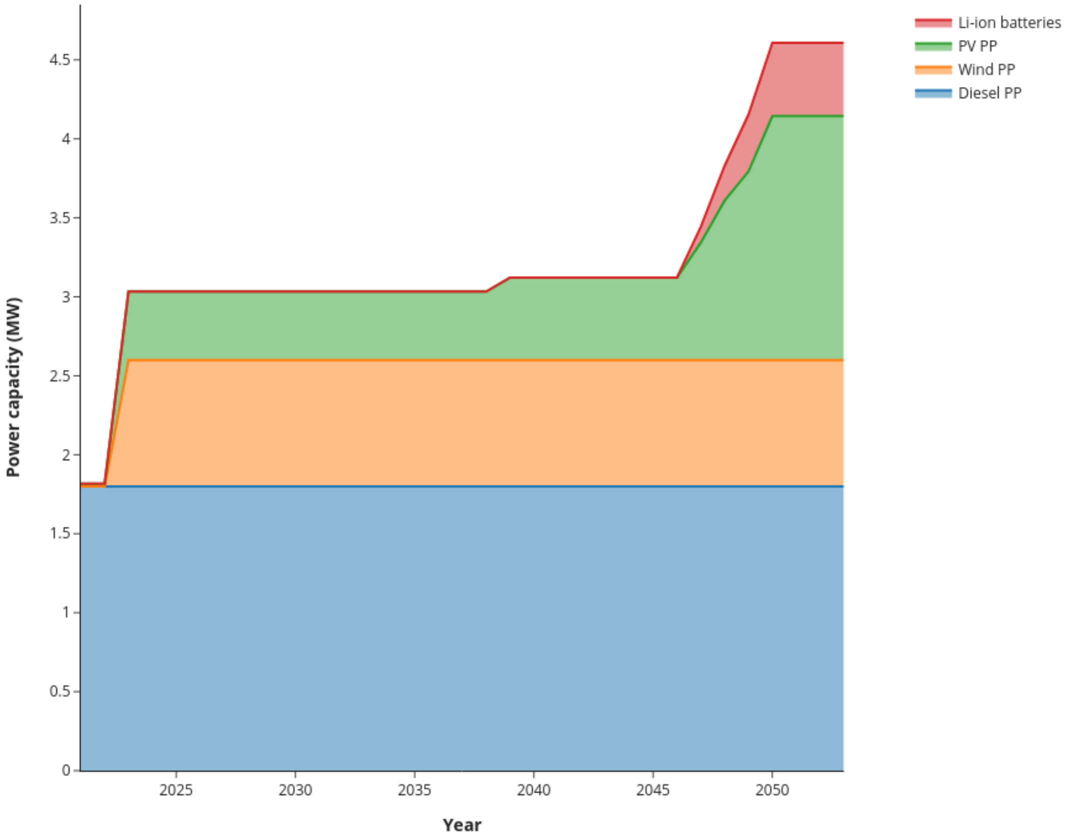


Figure 5.18: Power capacity in Marettimo when the demand is constant and the CO_2 emissions target is zero

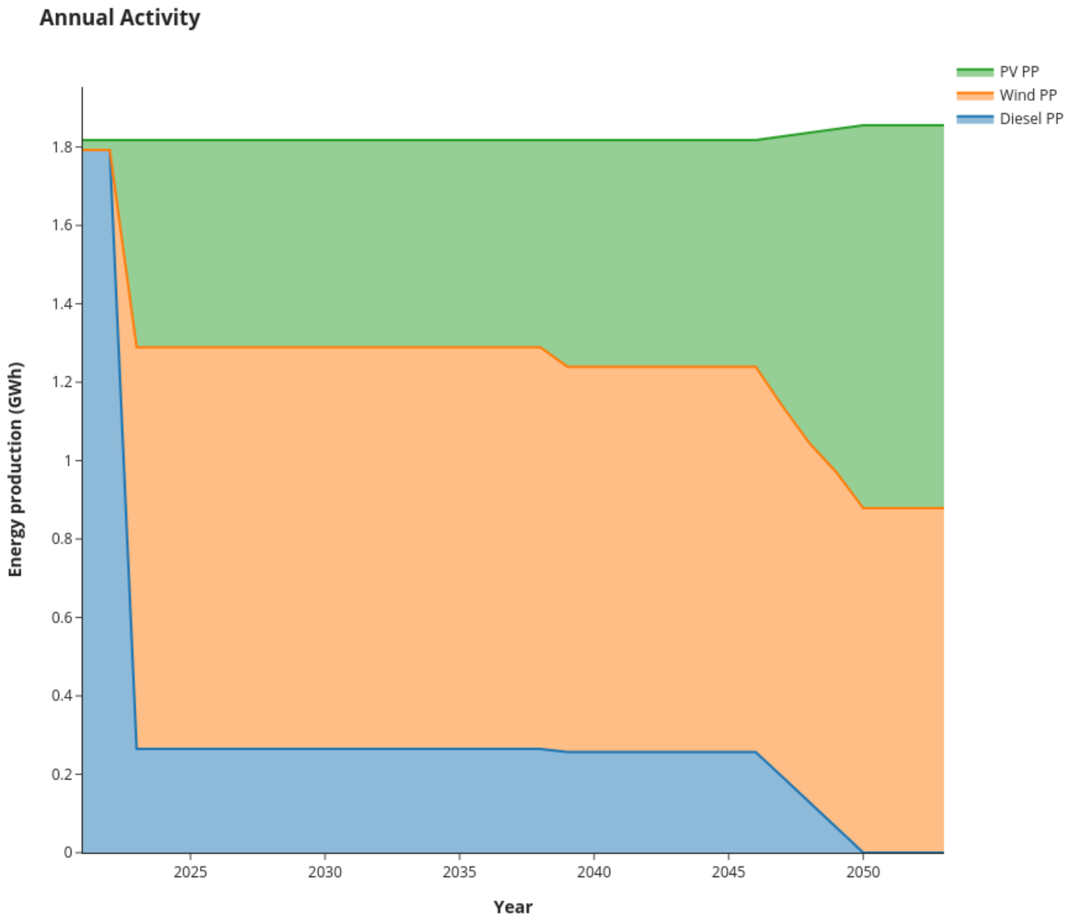


Figure 5.19: Energy production in Marettimo when the demand is constant and the CO_2 emissions target is zero

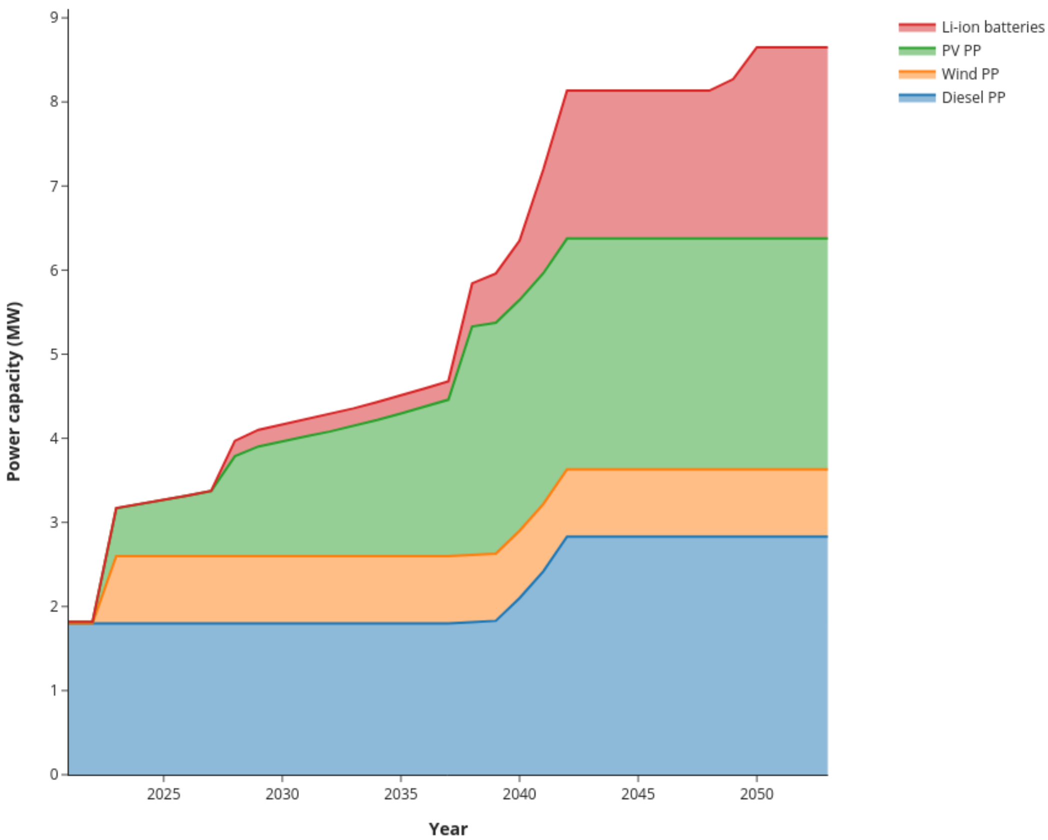


Figure 5.20: Power capacity in Marettimo when the demand annually increases and the CO_2 emissions target is zero

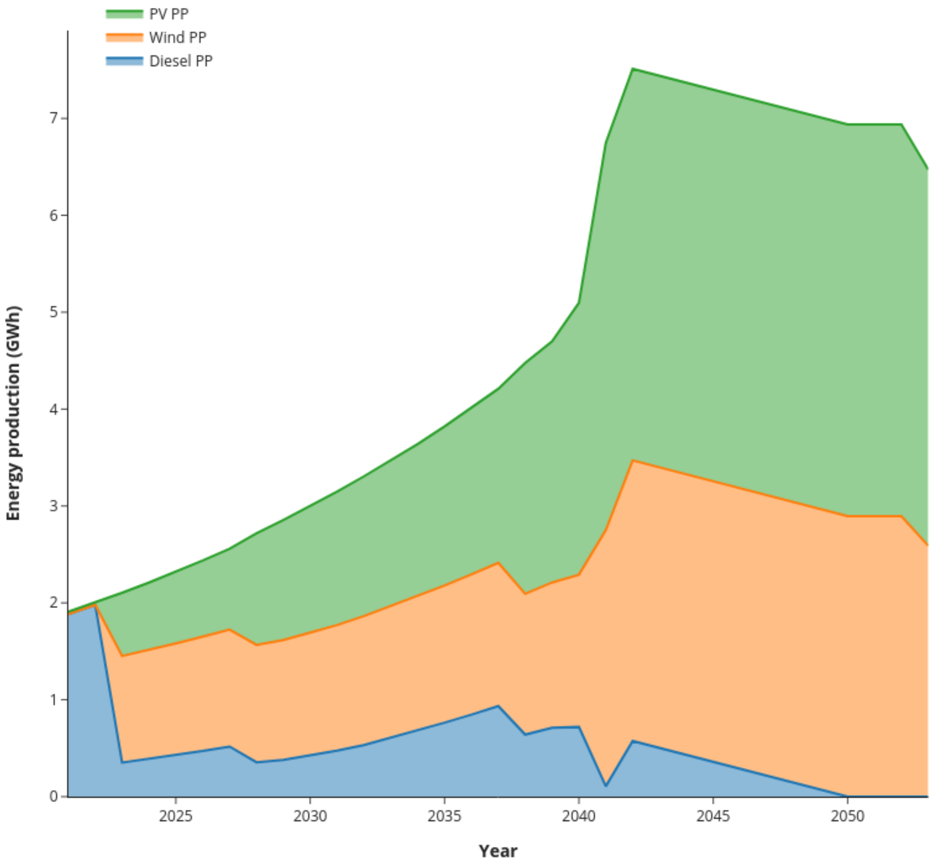


Figure 5.21: Energy production in Marettimo when the demand annually increases and the CO_2 emissions target is zero

Conclusions

The increasing pressure of climate change has prompted nations to take action to counter it. The European initiative "Clean Energy for EU Islands Secretariat" was developed by the European Commission to enable the European Islands to achieve their clean energy transition by pushing a bottom-up approach. The Secretariat promotes a shared process involving policymakers, local stakeholders, technical teams, decision-makers and local communities aiming to decarbonize the islands. These targets can be achieved in different ways: the clean energy transition agenda (CETA) is the most effective. This shared document contains the roadmap to reach the decarbonization of the local energy system within the 2050. The difficulty with this type of approach is that all parties must agree at the scenario planning stage, resulting in multiple meetings and delays. On the other hand, a shared process can assure the realization of the targets posed. The aim of this work was to develop some tools for the creation of multiple scenarios and their visualization to facilitate scenario planning. This was done as part of the study of the energy system of the Aegadian Islands for their CETA. The spatial energy planning of the island areas was carried out using the geographical information tool QGIS. The sizing of renewable energy facilities was done using a different methodology developed for each renewable technology. The application of the normative layers to QGIS was followed by the selection of the areas eligible for the installation of the renewable plants, depending on the norm that restricts them. The selection of the areas was followed by the sizing of the renewable generators. The wind energy potential was evaluated using WaSP, a software for sizing wind turbines and estimating their energy yield. The rooftop photovoltaic systems were sized after the calculation of the solar radiation on the rooftops with the QGIS plugin UMEP, which estimates the solar radiation taking into account shading by buildings and obstacles. Ground PV was instead sized after selecting a few undeveloped areas that could be considered for PV installation. After the dimensioning of the reference energy system of the islands, it was modeled with the modeling framework OSeMOSYS. In this part of the study, two tools have been developed in Python code: the multi-scenarios tool and the visualization tool. With the multi-scenarios tool it was possible to create and simulate multiple scenarios in function of several options, varying demands, renewable power potentials, CO_2 emissions target, turbines technologies, and storage technologies. Together with the multi-scenario tool, it has been developed the visualization tool, which permits the modeler to show the results to the decision-makers in a simple and practical way. The visualization tool is an important aid in visualizing the results, because it allows for easy visualization of all generated scenarios, which previously had to be done manually for each scenario. The tool allows a more effective and productive review process in the discussion phase involving stakeholders in a proactive way. The main limit bonded to the use of the multi-scenario tool is the computational time, which is strongly correlated to the number of the scenarios and to their size. If the objective of the modeler is to compare all the different combinations of the settings, the more options are available and the bigger the simulation would be. But, during the simulations it has been observed that multiple simulation can be run in parallel on the same machine, opening up to the possibility of increasing their combinations and running them in more performing computers. The obtained results demonstrated that the framework of the multi-scenario tool worked properly. It generated around 4500 all different scenarios, combining all the modeling options. Therefore, it was possible to compare the performances of the technologies. It showed that among the storage technologies, Li-ion batteries would perform better in most cases, but at a higher cost. The results also show that in most cases the islands can achieve a reduction in carbon emissions of up to 100% while reducing costs by over 50%.

6.1 Future works

Despite the rise of RES technologies that need to be implemented in the local energy mix, regulatory hurdles are the biggest barrier to full decarbonization. As seen above, this problem is illustrated by the example of the Aegean Islands: strict regulation does not allow the identification of suitable areas for RES exploitation. An improvement could certainly be the relaxation of some laws to reduce the time needed for planning. In addition, the archipelago is a marine protected area that prevents the installation of wave energy converters (WEC) and offshore solar/wind turbines. Relaxing this rule may increase the islands' renewable energy potential and allow them to reduce or eliminate their energy dependence on fossil fuels. However, a careful energy planning must keep in mind the balance between RES exploitation and landscape preservation. This could not only increase the energy potential of the islands, but also reduce the number of renewable energy generators installed on the islands, thereby reducing the visual impact on the beautiful landscape. Program-wise, there could be several improvements. One of the drawbacks of the codes used to create the scenarios and visualize the results is that they are completely uncorrelated. One improvement could be to combine the two programs into a single user-friendly tool. This would be easy to do with the Dash package. Indeed, in Dash there is the possibility to introduce multiple tabs, so it would be possible to integrate scenario modeling into the visualization tool. However, up to now the tool appears not cost-effective showing a high computational cost. A model with 2400 scenarios could take up to fifteen days to converge on a common personal computer. To overcome this issue, multiple sessions were started on the same computer, but in a roundabout way. In the parallel simulations, one model and its inverse were started, which meant that the two simulations could overlap if they were not stopped. Some important improvements would be to facilitate the controlled start of multiple sessions and to improve the CPLEX© settings to increase the performance of the solver. The open source license of this code may allow the introduction of these improvements in future works.

Bibliography

[1] Eurostat. «Energy statistics - an overview». In: (Feb. 2022) (cit. on p. 1).

[2] Eurostat. *Where does our energt come from?* URL: https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html (cit. on p. 1).

[3] Euoactiv. *Widespread support in EU Parliament for 45% renewable energy target*. URL: https://www.euractiv.com/section/energy/news/widespread-support-in-eu-parliament-for-45-renewable-energy-target/ (cit. on p. 1).

[4] Thomas C.D., Cameron A., Green R.E., et al. «Extinction risk from climate change». In: *Nature* 427 (2004), pp. 145–148 (cit. on p. 1).

[5] John T. Abatzoglou, A. Park Williams, et al. «Impact of anthropogenic climate change on wildfire across western US forests». In: *Proceedings of the National Academy of Sciences* 113 (2016) (cit. on p. 1).

[6] Tracy D. Ainsworth, Scott F. Heron, et al. «Climate change disables coral bleaching protection on the Great Barrier Reef». In: *Science* 352 (2016) (cit. on p. 1).

[7] Alexey Mikhaylov, Nikita Moiseev, et al. «GLOBAL CLIMATE CHANGE AND GREENHOUSE EFFECT». In: *ENTREPRENEURSHIP AND SUSTAINABILITY ISSUES* (2020) (cit. on p. 1).

[8] *European Green Deal*. URL: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_it (cit. on p. 1).

[9] *Innovation Fund*. URL: https://eufundingoverview.be/funding/innovation-fund (cit. on p. 2).

[10] European Commission. *Clean Energy for EU Islands* (cit. on p. 2).

[11] *Clean Energy Transition Agenda*. URL: https://clean-energy-islands.ec.europa.eu/assistance/clean-energy-transition-agenda (cit. on p. 2).

[12] Ministro Dell'Ambiente. *Decreto 27 Dicembre 1991*. URL: https://www.mite.gov.it/sites/default/files/archivio/normativa/Egadi_dm-27-12-1991.pdf (cit. on p. 5).

[13] *Direttiva del Consiglio relativa alla conservazione degli habitat naturali e seminaturali e della flora e della fauna selvatiche.* 1992. URL: https://www.msn.unipi.it/wp-content/uploads/2013/03/DIR-CEE-43-1992.pdf (cit. on p. 5).

[14] *Linee guida per l'autorizzazione degli impianti alimentati da fonti rinnovabili.* 2010. URL: https://www.gazzettaufficiale.it/eli/id/2010/09/18/10A11230/sg (cit. on p. 6).

[15] *Decreto presidenziale della Regione Sicilia sulla definizione di aree idonee per l'installazione di generatori eolici.* 2017. URL: http://www.gurs.regione.sicilia.it/Gazzette/g17-44/g17-44.pdf (cit. on p. 6).

[16] *QGIS - The Leading Open Source Desktop GIS.* URL: https://www.qgis.org/en/site/about/index.html (cit. on p. 10).

[17] *Sistema Informativo Territoriale Regionale.* URL: https://www.sitr.regione.sicilia.it/ (cit. on p. 10).

[18] *WAsP.* URL: https://www.wasp.dk/ (cit. on pp. 11, 12).

[19] Lindberg F et al. «Urban Multi-scale Environmental Predictor (UMEP) - An integrated tool for city-based climate services. Environmental Modelling and Software». In: 99 (2018), pp. 70–87 (cit. on pp. 11, 15).

[20] *Getting started with WAsP 9.* URL: https://www.wasp.dk/-/media/Sites/WASP/WAsP-support/Getting-Started-with-WAsP-9.ashx?la=da&hash=81FB2B99DA887C19512836BD90EA2F2173CA3102 (cit. on p. 12).

[21] *Global Wind Atlas Website.* URL: https://globalwindatlas.info/ (cit. on pp. 12, 27, 42).

[22] *Enercon E126 datasheet.* URL: https://www.enercon.de/fileadmin/Redakteur/Medien-Portal/broschueren/EC_Datenblaetter_WEA_en_082019.pdf (cit. on pp. 13, 58).

[23] *Enercon E53 datasheet.* URL: https://www.enercon.de/fileadmin/Redakteur/Medien-Portal/broschueren/EC_Datenblaetter_WEA_en_082019.pdf (cit. on pp. 13, 59).

[24] *Enercon E82 datasheet.* URL: https://www.enercon.de/fileadmin/Redakteur/Medien-Portal/broschueren/EC_Datenblaetter_WEA_en_082019.pdf (cit. on pp. 13, 60).

[25] *Vestas V90 Datasheet.* URL: https://arquivo.pt/wayback/20090706121351/http://www.vestas.com/en/wind-power-solutions/wind-turbines/3.0-mw (cit. on p. 13).

[26] *Bonus B23 Datasheet.* URL: https://en.wind-turbine-models.com/turbines/189-bonus-b23-150-gittermast (cit. on pp. 13, 56, 57).

[27] *WaSP turbine editor*. URL: https://www.wasp.dk/dataandtools/turbine-editor (cit. on p. 13).

[28] *Wind turbine image taken from Wikipedia Commons* (cit. on p. 14).

[29] Lindberg F, Grimmond CSB, Gabey A, Huang B, Kent CW, Sun T, Theeuwes N, and Järvi L. *Urban Multi-scale Environmental Predictor (UMEP) Manual*. University of Reading UK, University of Gothenburg Sweden, SIMS China. 2019. URL: https://umep-docs.readthedocs.io/ (cit. on p. 15).

[30] Lucas Sens, Ulf Neuling, and MartinKaltschmitt. «Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines – Development by 2050». In: (2022) (cit. on p. 15).

[31] M.C. Brito, S. Freitas*, S. Guimaraes, C. Catita, and P. Redweik. «The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data». In: *Renewable Energy* 111 (2017), pp. 85–94 (cit. on p. 16).

[32] Luca Bergamasco and Pietro Asinari. «Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: Application to Piedmont Region (Italy)». In: *Solar Energy* 85 (2011), pp. 1041–1055 (cit. on pp. 16, 17).

[33] *PVGIS website*. URL: https://re.jrc.ec.europa.eu/pvg_tools/en/ (cit. on pp. 17, 38).

[34] Nuria Martín-Chivelet. «Photovoltaic potential and land-use estimation methodology». In: *Energy* 94 (), pp. 233–242 (cit. on pp. 17, 18).

[35] *Marine Traffic Website*. 2021. URL: https://www.marinetraffic.com (cit. on p. 19).

[36] *Liberty Lines timetables of the routes*. 2022. URL: https://www.libertylines.it/orari-tariffe/ (cit. on pp. 19, 22).

[37] *Siremar timetables of the routes*. 2022. URL: https://carontetourist.it/it/siremar/orari (cit. on p. 19).

[38] *Liberty Lines Navy*. 2022. URL: https://www.libertylines.it/compagnia/flotta/ (cit. on p. 20).

[39] *Siremar Navy*. 2022. URL: https://carontetourist.it/it/siremar/la-flotta (cit. on p. 20).

[40] Caterpillar. *Marine Engine Application and Installation Guide*. 2004 (cit. on p. 22).

[41] Copenhagen Centre on Energy Efficiency. *Improving Efficiency*. URL: https://c2e2.unepdtu.org/kms_object/improving-ship-efficiency/ (cit. on p. 22).

[42] Giovanni Riva. «EQUIVALENZA TRA CONSUMI DI COMBUSTIBILE DEGLI IMPIANTI DI RISCALDAMENTO E L'ENERGIA CEDUTA ALLE UTENZE DELLE RETI DI TELERISCALDAMENTO». In: (2016) (cit. on p. 22).

[43] Annie Kortsari, Lambros Mitropoulos, Trine Heinemann, and Henrik Hagbarth Mikkelsen. «E-Ferry Project». In: (2020) (cit. on pp. 22, 82).

[44] Jan Fredrik Hansen and Frank Wendt. «History and State of the Art in Commercial Electric Ship Propulsion, Integrated Power Systems, and Future Trends». In: *Proceedings of the IEEE* 103 (2014), pp. 2229–2242 (cit. on p. 22).

[45] SEA. *Centrale SEA: Produzione*. URL: `https://www.seafavignana.com/produzione/` (cit. on p. 24).

[46] Legambiente. *Isola di Favignana* (cit. on p. 25).

[47] ICEL. *Produzione e Distribuzione di Energia Elettrica a Levanzo*. 2021. URL: `http://www.icelweb.it/?page_id=755` (cit. on p. 32).

[48] Comune di Favignana. *Piano d'azione per l'energia sostenibile e il clima (PAESC)*. 2017 (cit. on p. 39).

[49] Adamo Idrocarburi. *Vendita di carburanti di Adamo Idrocarburi*. 2022 (cit. on p. 40).

[50] *HOMER Software*. URL: `https://www.homerenergy.com/` (cit. on p. 49).

[51] *Open Source Energy Modelling System*. URL: `http://www.osemosys.org/` (cit. on p. 49).

[52] *open energy modelling framework*. URL: `https://oemof.org/` (cit. on p. 49).

[53] Christoph Bohringer and Thomas F. Rutherford. «Combining Top-Down and Bottom-up in Energy Policy Analysis: A Decomposition Approach». In: (2006) (cit. on p. 49).

[54] *GLPK (GNU Linear Programming Kit)*. URL: `https://www.gnu.org/software/glpk/` (cit. on p. 49).

[55] *IBM ILOG CPLEX Optimization Studio*. URL: `https://www.ibm.com/it-it/products/ilog-cplex-optimization-studio` (cit. on p. 49).

[56] *GNU Octave*. URL: `https://octave.org/` (cit. on p. 49).

[57] *Introduction to lp solve*. URL: `http://lpsolve.sourceforge.net/5.5/` (cit. on p. 49).

[58] *Gurobi optimization*. URL: `https://www.gurobi.com/` (cit. on p. 49).

[59] A.H. Land and A.G. Doig. «An Automatic Method of Solving Discrete Programming Problems». In: (1960) (cit. on p. 50).

[60] *What CPLEX can do.* URL: https://www.ibm.com/docs/en/icos/20.1.0?topic=cplex-what-does-do (cit. on p. 50).

[61] Mark Howells et al. *OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development.* 2011, pp. 5850–5870 (cit. on p. 50).

[62] Kelly Benton. «A life cycle assessment of a diesel generator set». In: (2016) (cit. on p. 55).

[63] *Renewables ninja website.* URL: https://www.renewables.ninja/ (cit. on p. 60).

[64] Salahuddin Qazi. «Chapter 2 - Fundamentals of Standalone Photovoltaic Systems». In: (2017) (cit. on p. 61).

[65] Andrea Vecchi, Yongliang Li, Yulong Ding, Pierluigi Mancarella, and Adriano Sciacovelli. «Liquid air energy storage (LAES): A review on technology state-of-the-art, integration pathways and future perspectives». In: *Advances in Applied Energy* 3 (2021) (cit. on p. 61).

[66] Solomos Georgiou, Nilay Shah, and Christos N. Markides. «A thermo-economic analysis and comparison of pumped-thermal and liquid-air electricity storage systems». In: *Applied Energy* 226 (2018), pp. 1119–1133 (cit. on pp. 61, 66).

[67] B Kennedy, D Patterson, and S Camilleri. «Use of lithium-ion batteries in electric vehicles». In: *Journal of Power Sources* 90 (2000), pp. 156–162 (cit. on p. 62).

[68] Hector Beltran, Pablo Ayuso, and Emilio Perez. *Lifetime Expectancy of Li-Ion Batteries used for Residential Solar Storage.* 2019 (cit. on p. 62).

[69] Kendall Mongird, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, and Vincent Sprenkle. «2020 Grid Energy Storage Technology Cost and Performance Assessment». In: (2020) (cit. on pp. 62, 66).

[70] MAHYTEC. *Compressed hydrogen storage.* URL: https://www.mahytec.com/en/compressed-hydrogen-storage/ (cit. on p. 62).

[71] Lucas Sens, Ulf Neuling, and Martin Kaltschmitt. «Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines - Development by 2050». In: *Renewable Energy* 185 (2022), pp. 525–537 (cit. on p. 66).

[72] O. O'Callaghan and P. Donnellan. «Liquid air energy storage systems: A review». In: *Renewable and Sustainable Energy Reviews* 146 (2021) (cit. on p. 66).

[73] Riccardo Novo, Francesco Demetrio Minuto, Giovanni Bracco, Giuliana Mattiazzo, Romano Borchiellinni, and Andrea Lanzini. «Supporting Decarbonization Strategies of Local Energy Systems by De-Risking Investments in Renewables: A Case Study on Pantelleria Island». In: *Energies* 15 (), p. 1103 (cit. on p. 67).

[74] *Combustion of Fuels - Carbon Dioxide Emission*. URL: `https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html` (cit. on p. 69).

[75] *Overview of Dash and Dash Apps*. URL: `https://plotly.com/dash/` (cit. on p. 85).

[76] *Support Vector Machine (SVM) Explorer*. URL: `https://github.com/plotly/dash-svm` (cit. on p. 85).