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Improving the land use sector representation in open–source bottom-up energy system optimization models: The TEMOA-Pantelleria case study

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Abstract

In the context of the fight against climate change, energy system optimization models are becoming increasingly useful for this purpose. These models enable us to represent and analyse environmentally impactful sectors, such as the energy and agricultural ones. Currently, numerous sector-specific models are available for in-depth impact assessment. However, these models frequently lack a holistic perspective, neglecting to account for the interconnections between the sector under analysis and other related sectors, e.g. water and land use. In response to these issues, a recent approach called the Water Energy Food (WEF) Nexus has gained growing relevance. This approach emphasizes the significance of adopting a comprehensive perspective in managing and optimizing the intricate interconnections among water, energy, and food systems. In the framework of the Nexus, Integrated Assessment Models (IAMs) link multiple sectors and consider the synergies between them, understanding and analysing the potential consequences of different scenarios. In this context, islands, especially isolated ones, can serve as unique Nexus laboratories due to their limited natural resources and smaller spatial scale. In this thesis, to investigate possible trade-offs and synergies between the energy and the land use sectors, a model of the latter has been added to an energy system optimization model and applied to a well-defined case study. The versatile, open-source energy system optimisation model, TEMOA (developed in Python), has been selected, for which an instance was already developed for the Pantelleria Island in Italy. Crop yields from FAOSTAT (the best European statistics site by FAO) and ISTAT (Italy's primary statistics source) have been considered, together with several factors for crop modelling (energy usage for fertilization, machinery, and irrigation). As for the land,

data on elevation, slope, irradiance, wind productivity, and the distance from the electrical grid were collected for each spatial parcel. Advanced clustering methods were tested and eventually used to incorporate the land use data into the model. To represent the land use sector within the TEMOA framework, new parameters such as Land Use Intensity, land area, and crop fuel consumption have been added to the model. Finally, after the implementation of the land-use sector. The model was able to optimise the use of soil choosing between different crops and RES to be installed on the spatial domain under investigation. The model was checked to be able to choose the technology that mostly reduces the economic output, expressed as the total cost of the energy-land system.

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1 Introduction

1.1 Climate change and European mitigation strategies

In the contemporary global landscape, the challenges posed by climate change have swelled into an unequivocal and defining issue, demanding our attention, concerted efforts, and innovative solutions. Climate change has transcended being a mere scientific hypothesis, becoming a pervasive reality that impacts every facet of our lives, from our environment to our economy, and from social dynamics to international relations. As appreciable in Figure 1,several factors are proof of the environment change in act: the increasing frequency and intensity of temperature changes, the relentless march of rising sea levels (+15%), and the shifts in ecosystems and biodiversity stand as stark reminders of the urgency to take decisive action,. Now more than ever, humanity faces the imperative to address the profound consequences of climate change [1]. As governments worldwide have placed significant emphasis on addressing climate change, as evident through milestones such as the 1998 Kyoto Protocol [2] and the 2015 Paris Agreement [3], Europe has emerged as a pivotal actor in the global struggle against climate change. The European Union (EU), with its rich history of pioneering environmental policies, has taken the lead in shaping comprehensive strategies to mitigate the adverse effects of climate change [4].

The *European Green Deal*, a transformative and far-reaching policy framework, represents a cornerstone of the EU's commitment to contrast climate change. The Green Deal outlines a holistic approach to make the EU climate-neutral by 2050, underpinned by the goal of net-zero greenhouse gas emissions. This ambitious target aligns with the Paris Agreement and signifies a resolute commitment to substantially diminish the EU's environmental impact [5].

Additionally, the *Fit for 55* packages introduced by the European Commission, further underscores Europe's commitment to climate action. It is a multifaceted plan aimed at achieving a 55% reduction in greenhouse gas emissions by 2030, compared to 1990 levels [6]. This initiative reflects the EU's dedication to implementing concrete measures and policies to meet its climate targets.

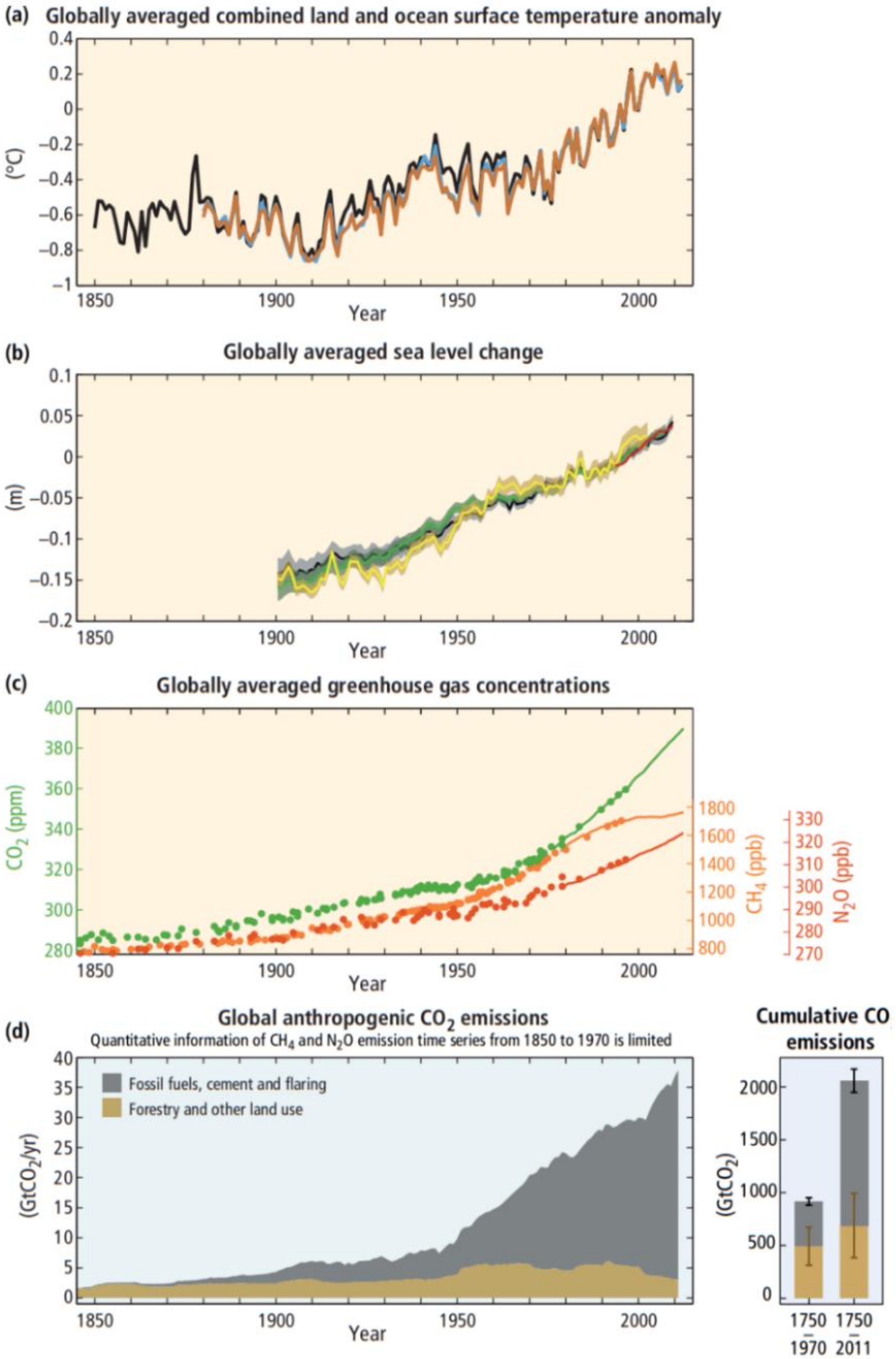


Figure 1 - In order: a) Global averaged surface temperature anomaly through the years b) Global averaged sea level change through the years c) Global averaged greenhouse gas concentrations through the years d) Global anthropogenic CO2 emissions through the years.[1].

European measures to combat climate change involve a mix of national and international policies, including the adoption of renewable energy sources, increased energy efficiency, and incentives for low-carbon technologies. The European Union's emissions trading system (EU ETS) plays a pivotal role in incentivizing industries to lower their greenhouse gas emissions. The European Emissions Trading System (EU ETS) is the world's largest greenhouse gas emissions trading system, created by the European Union. It allocates emission allowances to companies, requiring those exceeding their allowances to purchase emission credits, while companies emitting below their allowances can sell their credits [7].

The EU ETS has two primary and intentional goals:

- The efficient reduction of greenhouse gas emissions, finding a negotiated balance between cost and environmental benefits.
- The encouragement of corporate investment in low-carbon technologies draws insights from economic and political economy literature [7].

Europe is also actively investing in clean technologies and fostering research and development of sustainable solutions, as confirmed by the European Taxonomy for sustainable investments [8]. These efforts aim not only to reduce domestic emissions but also to export global solutions, assisting other nations in their climate change mitigation endeavours [9].

In summary, Europe has assumed a leadership role in the global battle against climate change by taking ambitious measures, such as the *Green Deal*, the *commitment to net zero by 2050*, and the comprehensive *Fit for 55* packages. Europe's participation in the *Intergovernmental Panel on Climate Change* (IPCC), adherence to the Paris Agreement, and robust mitigation policies demonstrate its unwavering commitment to addressing this critical challenge.

The regulations and international agreements provide the framework for action against climate change, but it is within the energy sector that we can identify the main actor responsible for carbon emissions[10]. Indeed, as appreciable by Figure 2, energy-related emissions occupy the largest share.

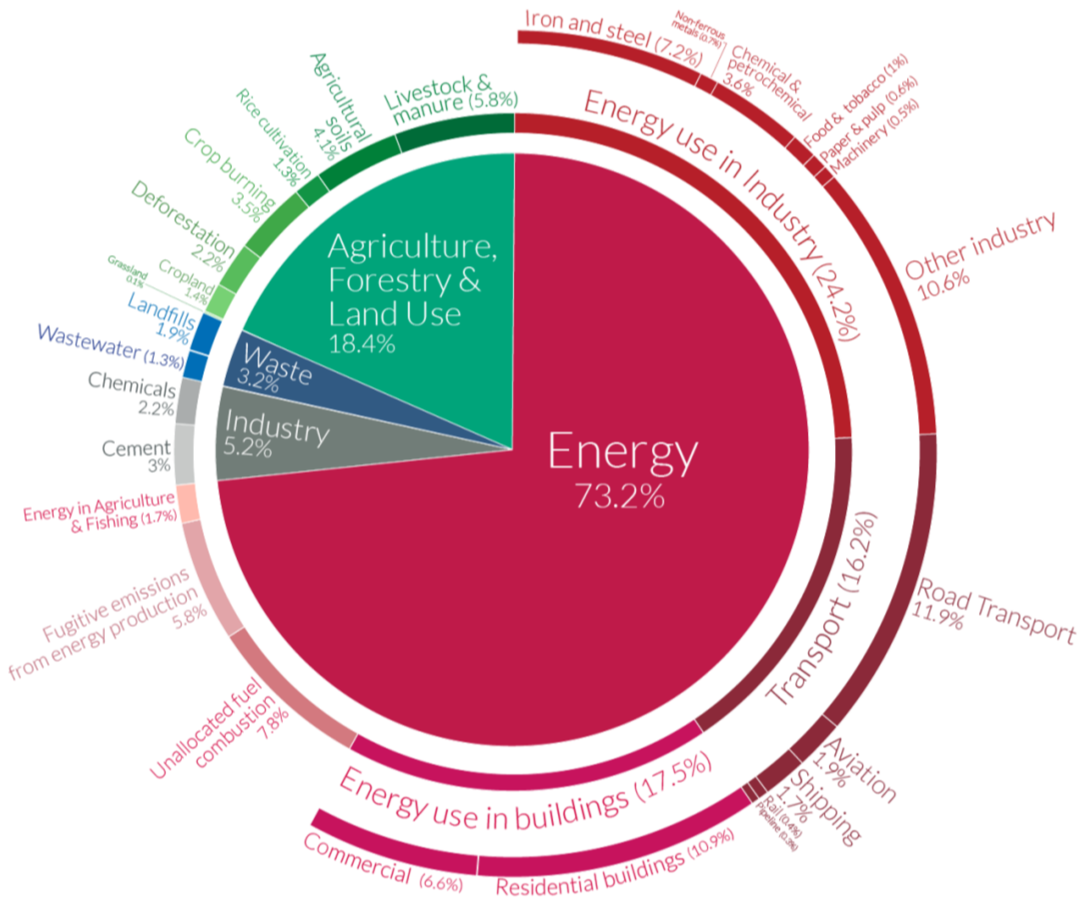


Figure 2 - Global greenhouse gas emissions by sector [10]

Throughout history, the use of fossil fuels for energy production has been a fundamental pillar of the global energy supply. However, this practice has resulted in a substantial increase in CO2 emissions into the atmosphere, Figure 3.

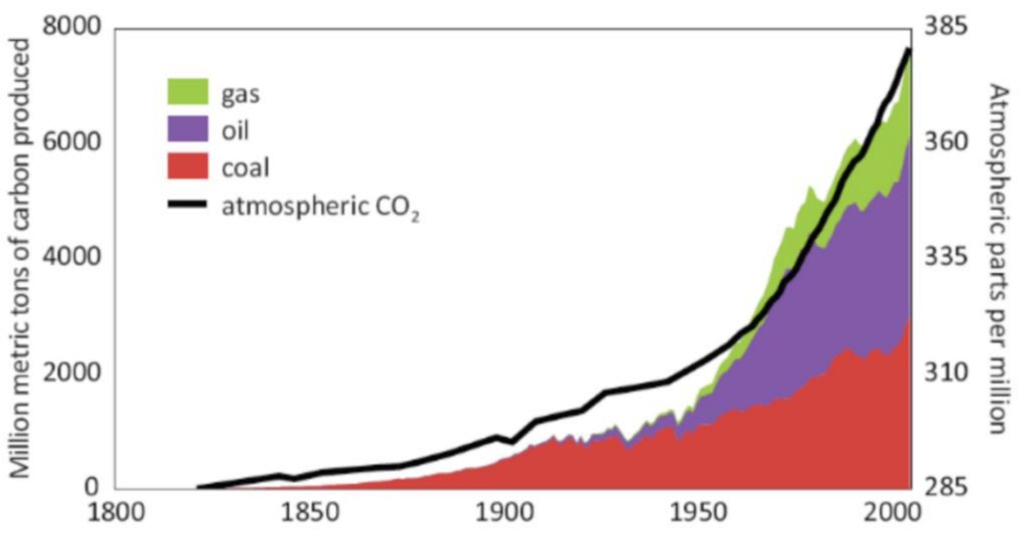


Figure 3 – CO_2 emissions from fossil fuels and its atmospheric concentration [11]

Renewable energy resources offer a promising solution. Solar, wind, hydroelectric, and other renewable energy sources have been extensively studied and tested as low-impact environmental alternatives. The transition to cleaner energy sources has become a key objective for reducing greenhouse gas emissions and mitigating the effects of climate change [12].

Expanding renewable energy capacity is pivotal for the European Union to meet its decarbonization goals, and a fundamental aspect of this endeavour will be the identification and allocation of adequate land resources [13].

1.1.1 Land-use sector contribution to the climate change

Other than the energy sector, two of the key players are the agricultural and land use sectors. These sectors, including crop, livestock production, forestry, and associated land use changes, contribute significantly to greenhouse gas (GHG) emissions [14]. According to the Intergovernmental Panel on Climate Change (IPCC), they are responsible for a substantial fraction of anthropogenic emissions, accounting for up to 30% [15]. Agriculture, indeed, plays a significant role in both contributing to and suffering the consequences of climate change [16]. Emissions originating from agricultural activities currently account for 12% of global greenhouse gas (GHG) emissions, equivalent to approximately 7.1 billion tons of CO2 equivalent (Gt CO2-eq). The imminent rise of a growing and more affluent global population is projected to amplify the worldwide demand for agricultural products by 50% before mid-century [16]. This surge in demand poses a risk of exceeding international climate targets, underscoring the necessity of integrating agriculture into any climate change stabilization strategy that aims to achieve net-zero GHG emissions [17].

Differently from other sectors, in the agricultural sector, CO2 is not the primary pollutant emitted [18]. Instead, the predominance of greenhouse gas (GHG) emissions in agriculture is due to methane, contributing to 54% followed by nitrous oxide at 28%, and carbon dioxide at 18% (as illustrated in Figure 4(C)) [18]. It is noteworthy that both methane and nitrous oxide are powerful GHGs, possessing a global warming potential of approximately 28 and 265 times greater than that of carbon dioxide, respectively, over a 100-year timescale. Consequently, achieving net-zero emissions in agriculture necessitates not only a net-zero for carbon dioxide (CO2) emissions but also for methane (CH4) and nitrous oxide (N2O) emissions [18].

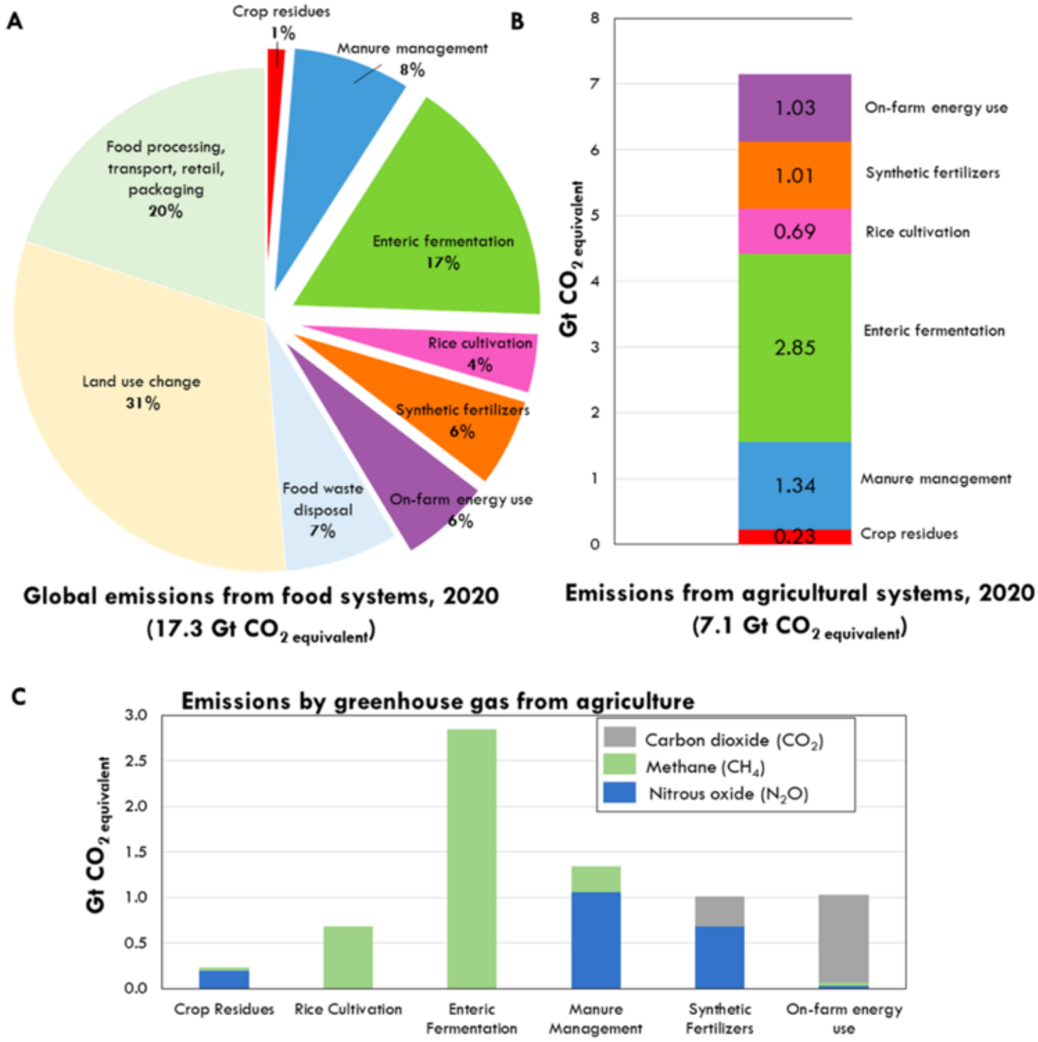


Figure 4 – Greenhouse gas emission from agriculture A) share of greenhouse gas emission by sector in 2020. B) GHG emissions from agricultural sectors in 2020. C) GHG emission from agriculture sectors for Methane, Carbon dioxide and nitrous oxide. [18]

Starting from the year 2000, there has been a rapid expansion of cropland, enlarging the global agricultural area by 9%. This expansion has been primarily driven by agricultural growth in Africa and South America [16]. Nonetheless, significant yield gaps, representing the disparity between actual on-farm yields and the potential yields achievable with effective management practices that minimize yield losses, continue to be a persistent challenge in developing countries. Notably, enhancements in the fertilizer industry, irrigation methods, and other agricultural technologies have contributed to improved land and energy efficiency within the agricultural sector[16].

Land use is not solely tied to the agricultural sector but also encompasses the energy and industrial sectors. To decarbonize industrial sectors that require a significant amount of energy for their processes, such as the chemical industry, the use of biomass, in conjunction with carbon capture and storage (CCS) or carbon capture and utilization (CCU), appears to be a viable solution today. Each path to achieving net-zero emissions in these sectors may involve trade-offs in terms of environmental resources, including land use, water consumption, and the accessibility of sustainable biomass [19].

The main issue is that replacing fossil fuels with biomass or hydrogen requires a significantly high amount of land and water [19].

In some regions of the world, we are already facing a situation of land scarcity and water scarcity [20].

P. Gabrielli et al [19] developed an index, translated in a visualization tool, to forecast possible land and water scarcity. Figure 5 represents the scarcity factor worldwide. "*A scarcity factor greater than 1 implies that more water or land is used than is sustainably supported by the environment. For example, land scarcity is observed when anthropogenic activities entail deforestation (note that this can be observed in countries with large surface areas), and water scarcity can be observed when more water is used than is regenerated by hydrological basins after accounting for environmental flows (as is already the case in the MENA region, India, and China).*"[19]

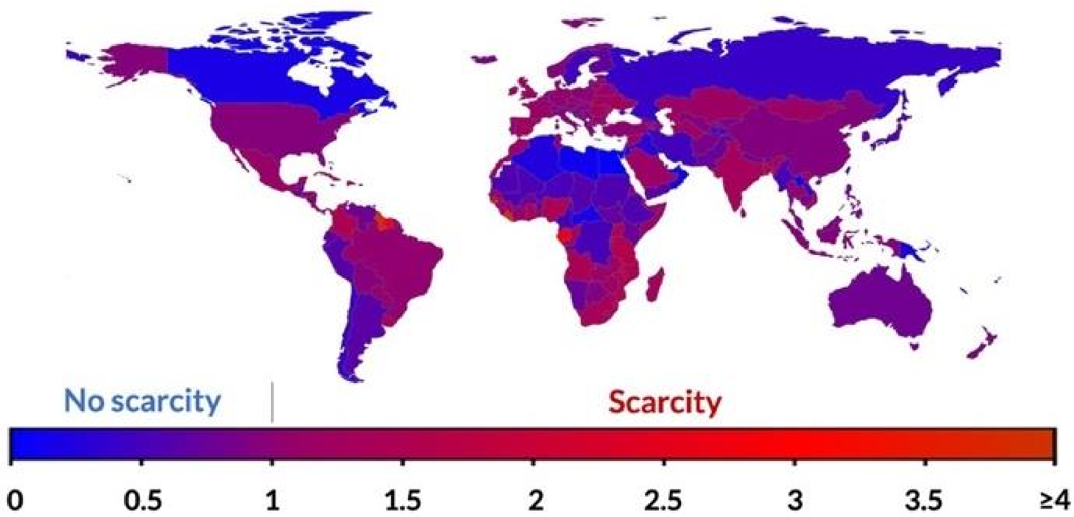


Figure 5 - World map of the scarcity factor [19]

It is therefore of fundamental importance to understand how to optimize the use of land and water to achieve greater production from a smaller space with improved water use efficiency.

While it is crucial to comprehend how to optimize land and water use for enhanced production and water efficiency on a fundamental level, tackling this challenge globally could potentially lead to the omission of crucial details. Specifically, land use is intricately connected to the morphology and characteristics of the territory.

To test this hypothesis regarding the influence of a detailed microscale data collection phase prior to modelling, the selected case studies should focus on small spatial extents. Once the validity of this theory is validated by numerous studies, it will be possible to extend it to a larger scale.

Considering the above, the choice of Pantelleria Island as the study area was influenced by the wealth of available data concerning the island, as well as its confined and easily adaptable geographical features. These qualities collectively establish it as an excellent candidate for the intended study. A detailed explanation of rational behind the choice is provided in Section 1.1.2

1.1.2 Islands as a lab for energy transition

In the context of European policies and actions to contrast climate change, since the early 1990s, the islands have been pivotal in shaping sustainable development strategies [21]. Serving as vital assets for European nations, islands offer significant contributions in sectors like tourism, ecological diversity, cultural heritage, and historical significance.

Nonetheless, these regions are exceptionally susceptible to the repercussions of climate change. Extreme climatic phenomena, including heatwaves, prolonged droughts, tidal surges, and rising sea levels, manifest with increased frequency and severity in these territories compared to mainland regions [22].

Furthermore, geographical isolation results in the islands facing increased transportation expenses, a predominantly fossil fuel-dependent energy infrastructure, bigger water shortages, and constrained economic diversification [21].

For the past three decades, the European Union and regional governmental bodies have put significant effort in transforming the isolation challenge into a leverage point, spearheading innovative sustainable transition initiatives.

The first collaboration between the EU islands traces back to 1993 [21]. The Western Isles, Shetland, Portuguese Islands, and Canary Islands, together with the Island Commission of the CPMR (Conference of Peripheral Maritime Regions), founded the European Islands Energy and Environment Network (ISLENET). Its primary objective was to form an interconnected EU island network with aspirations to diminish energy reliance, amplify the availability of trustworthy and economical energy solutions, increase the energy security, curtail GHG emissions, and mitigate the implications of climate change.

In 2007, the EU introduced several plans to address the problems of the islands. These plans focused on using renewable energy and supporting local sustainable energy projects [23]. Around 2009, the ISLEPACT project was launched to promote sustainable energy plans on these islands, creating the Pact of Island (PoI) [24]. By 2015, the PoI joined forces with the Covenant of Mayors, as guided by the European Union. The main goal of this pact was to develop and put into action Island Sustainable Energy Action Plans (ISEAPs) [24], aiming to reduce CO2 emissions by at least 20% by 2020. Following this, the SMILEGOV project, supported by the EU, was started "to improve the implementation of sustainable energy plans on European islands through better multi-level governance" [25]. This project aimed to achieve the goals of PoI by promoting collaboration between national, regional, and local governments. One of the main results of SMILEGOV [25] was the Smart Islands Strategy (SIS). This strategy suggested various actions, including partnerships between EU islands and plans from EU organizations, businesses, and the public. An important point in the SIS is recognizing the potential of islands as test locations for projects that can later be expanded to larger areas. Pantelleria is one of the major examples of this last goal embracing several projects about sustainability.

In 2017, the Clean Energy for EU Islands (CE4EUI) project was introduced as a component of the 'Clean energy for all Europeans' package. The goal of CE4EUI is to establish a lasting structure that enables EU islands to produce their own affordable, sustainable energy [26]. The expected outcomes of the CE4EUI project include:

- Lower energy costs and boost renewable energy (RE) production.
- Build energy storage solutions and create demand response systems.
- Enhance energy security.
- Reduce pollution in air, water, and land.
- Create new job opportunities.

The CE4EUI team is dedicated to helping EU islands with their clean energy transitions. They offer support in planning for cleaner energy, setting decarbonization goals, and executing individual projects. This support includes both technical and financial help, as well as access to a collaborative online platform.

Starting in 2018, the FEDARENE effort (specifically, the European Federation of Agencies and Regions for Energy and Environment) introduced a new island-focused division [21]. This division bridges European Institutions and Member States, ensuring the technical and financial backing for island energy transformations.

The EU's increasing focus on its islands is understandable given their significant value and their strategic role. Testing pilot projects on islands, with their simpler systems, serves as a foundation for broader transition initiatives. Islands can indeed be seen as a scaled-down representation of larger national projects and thus serve as a testing ground for future national projects.

In 2014, the island of Pantelleria joined the Covenant of Mayors, marking the beginning of its journey towards energy transition [27]. Later, within the scope of the CE4EUI project, Pantelleria was chosen in 2019 as a leading island for energy transition. Following this, an Energy Transition Agenda was established in 2020, aiming for complete decarbonization by 2050 [27].

1.2 Energy system modelling

Energy system modelling and scenario analysis are instrumental in addressing climate change and developing innovative adaptation solutions, particularly in anticipating the long-term evolution of the energy mix.

Research conducted on these subjects is increasingly becoming a point of reference for policymakers. This ensures that energy policies are supported by rigorous, impartial, and verifiable assessments of their efficacy in achieving the desired outcomes [28].

Energy system models are used to represent energy systems through models. Therefore, it is necessary to first clarify what energy systems are and how they are structured. Per IPCC, an Energy System is defined as " A system that comprises all components related to the production, conversion, delivery and use of energy " [29].

In Figure 6, we can observe a broad representation of an exemplary Reference Energy System (RES). This diagram illustrates the energy flow, starting from primary resources and concluding with final consumption. A RES is composed of various sectors, each further subdivided into subsectors [30].

The sectors that characterize every energy system are:

- *Primary energy*: this sector is composed of all the resources.
- *Conversion*: In this sector, the resources are converted into final energy or new resources.
- *Transportation and distribution*: In this sector, the resources or the final energy is transported and distributed to the consumer.
- *Final energy consumption*: Here the resources and the final energy are used, this sector can also be called the demand sector.

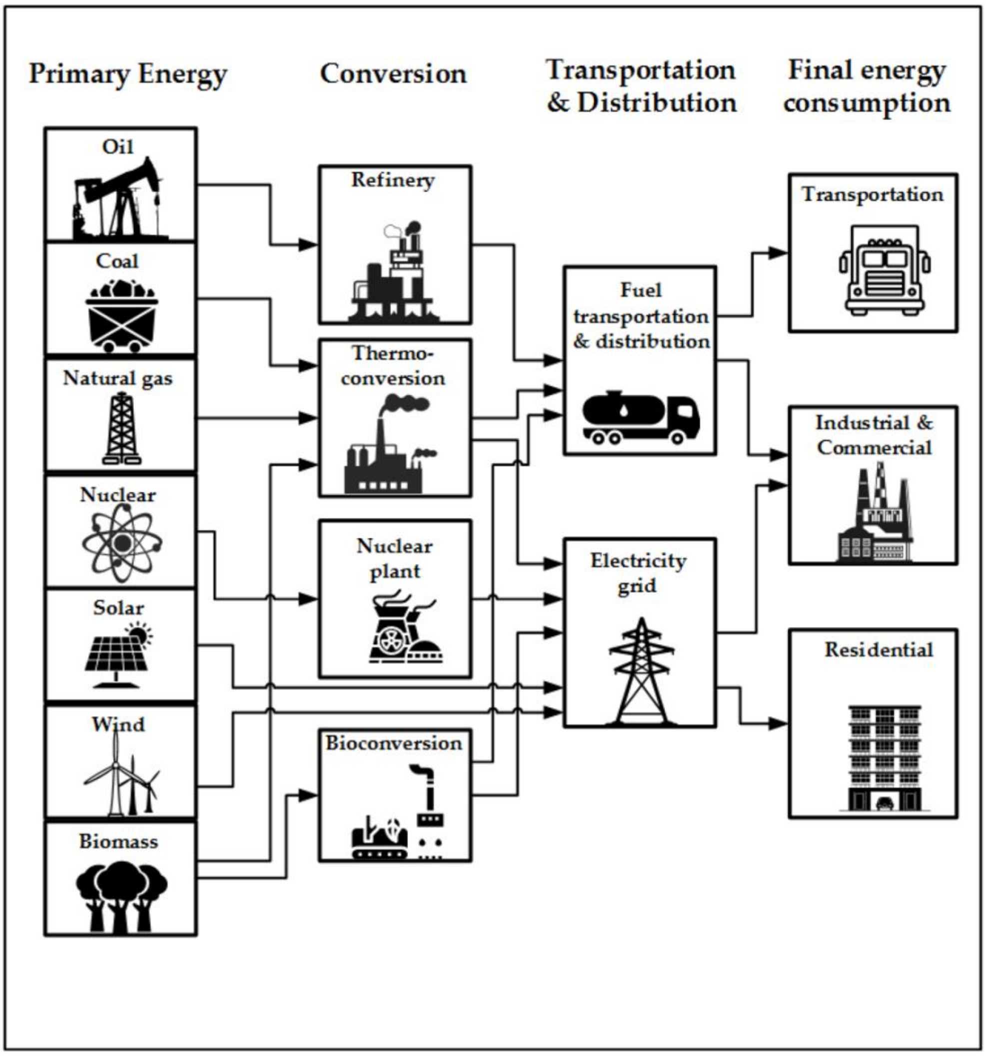


Figure 6 - Energy system showing the flow of energy from primary energy supply to final energy consumption [30]

Energy system models are mathematical representations that mimic the characteristics of energy systems to facilitate their study and analysis [31].

Typically, the objective of RES (Reference Energy System) modelling is to depict one or more energy system scenarios to make predictions, and these models can be either deterministic or stochastic [30].

Energy system modelling proves to be an invaluable resource for policymakers as it can furnish pertinent insights into various aspects, including the economic and environmental aspects of the system under examination.

1.2.1 Bottom-up energy system optimisation models

There are numerous energy system models, and they can be categorized in various ways but there are two major approaches: the top-down macroeconomic approach and the bottom-up engineering approach [32].

The economic approach revolves around constructing top-down models that encompass the entire economy. These models emphasize the capacity to substitute different production factors to optimize societal well-being, with less emphasis on technical specifics. The interaction between energy and other production factors for economic growth is captured through production functions, and the potential for alterations in fuel mixes is described by substitution elasticities. Another crucial parameter related to responses to energy policy is autonomous energy efficiency improvement, which allows for production improvements based on assumed technological advancements [33].

Conversely, the engineering approach involves the development of bottom-up models, providing in-depth descriptions of the technological aspects of the energy system and its potential evolution. These models often take energy demand as an exogenous input and focus on analysing how to efficiently fulfil this given energy demand.

Bottom-up model complexity can range from the optimization of a single component through an entire sector to a whole national energy system.

Spatially, they can focus on a single point representative of a broader region, or they can simulate several regions through a multi-node approach, as appreciable in Figure 7.

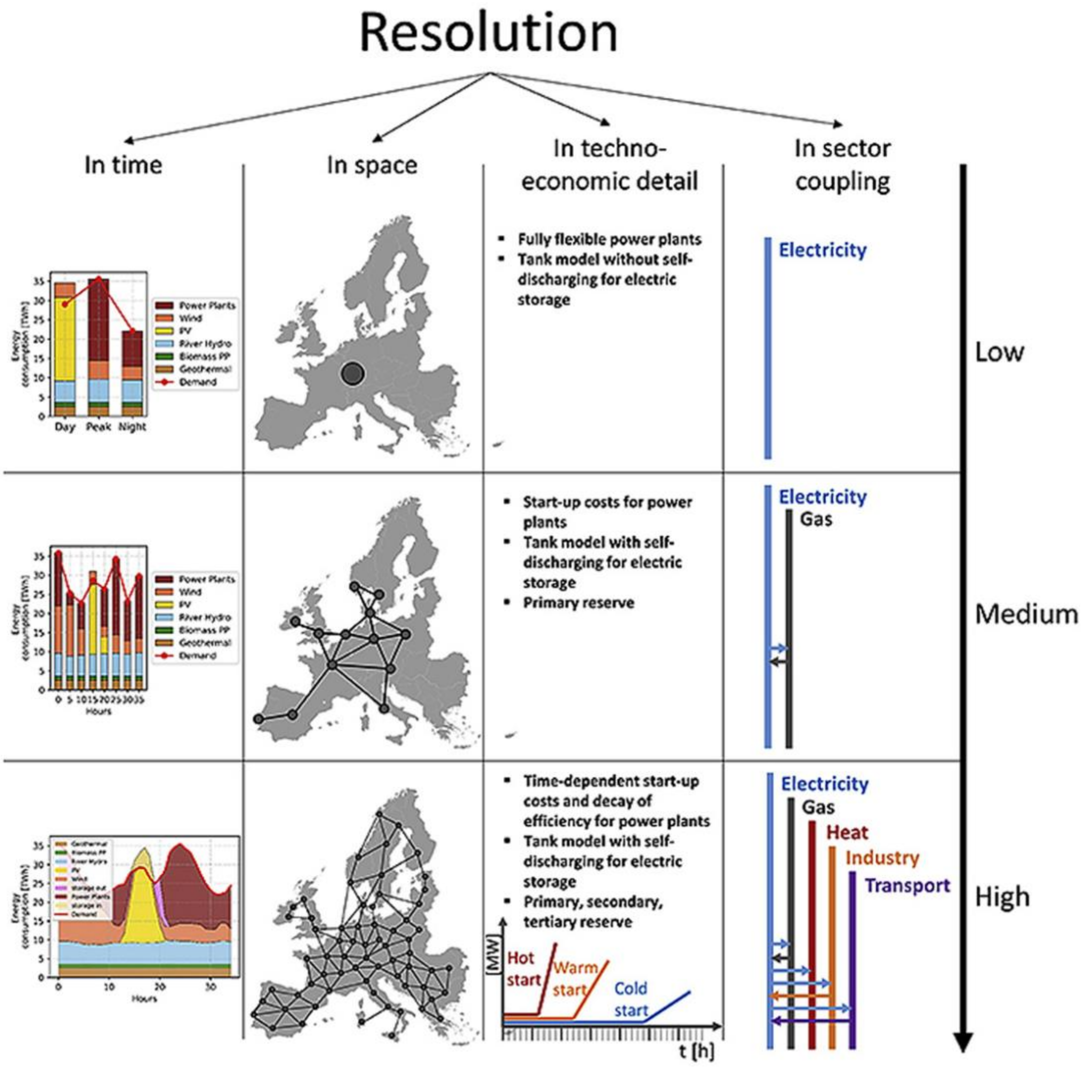


Figure 7 - Possible resolutions of bottom-up energy system model [34]

The family of bottom-up models encompasses three distinct methodologies [35]:

- *Accounting Models*: These maintain an equilibrium of fluxes across various commodities and technologies and are inherently static in nature.
- *Simulation Models*: Given specific data inputs, these models forecast system responses without necessarily identifying the most optimal configuration.
- *Optimization Models*: These are designed to identify the best possible configuration for all decision variables. Typically, the objective function is to minimize the cost of technologies used to meet demand.

Simulation and optimization methodologies derive both from accounting models and share primary drivers like GDP growth, energy prices, and policy objectives. However, optimization models primarily focus on achieving an ideal configuration, whereas simulation models aim to compare multiple scenarios.

Bottom-up Energy System Optimization Models (ESOMs) are predominantly employed due to their distinct optimization criteria defined by their objective function. This precision helps reduce uncertainties arising from the perspective of the modeller. Additionally, ESOMs possess the capability to model and delve into the primary determinants shaping upcoming energy choices and investment inclinations.

ESOMs employ linear programming (LP) algorithms to optimize the overall energy supply and demand costs within the system. The components of the LP formulation consist of:

- *Decision variables*: Derived as outcomes from the optimization model, these encompass new capacity augmentations, cumulative installed capacity, and the operational levels of individual technologies.
- *Objective function*: A guiding criterion, to be either minimized or maximized.
- *Constraints*: Formulated as equations or inequalities that connect with the decision variables, delineating the feasible solution space.

In the creation of an ESOM, it is essential to choose an appropriate time horizon and temporal framework, with milestone years serving as representative intervals. The outcomes are computed for each of these designated milestone years.

As previously highlighted, within the ESOMs, the objective function is driven by costs and can be expressed as (1).

$$min\ [GDR\ *\ (\sum_{r,t,p}(Invest\ cost_{r,t,p} + Fixed\ cost_{r,t,p} + Var.cost_{r,t,p}))] \tag{1}$$

Where GDR is the global discount rate, r stands for region, t for technology and p for time period.

1.2.2 TEMOA

Within the different ESOMs, significant attention is directed towards the creation of open-source modelling tools, driven by the following features:

- A linear structure inherent in the database.
- A simplified version of the optimization problem.
- Capability to effectively model expansive systems while maintaining high performance.
- Unrestricted access to open-source versions of commercial solvers. Notably, the two most prevalent open-source ESOMs are OSeMOSYS and TEMOA [36].

For this thesis project, the case study model has been constructed utilizing the TEMOA framework, primarily for the following reasons:

- Its credibility has been validated through a comparative analysis against the well-established TIMES model [36].
- The framework facilitates the use of solvers designed to handle substantial-scale models, as exemplified by Gurobi.
- The utilization of Python, along with its associated software packages and libraries (as depicted in Figure 8).
- TEMOA presents itself as a comprehensive, multi-regional, and intricately detailed technological model.

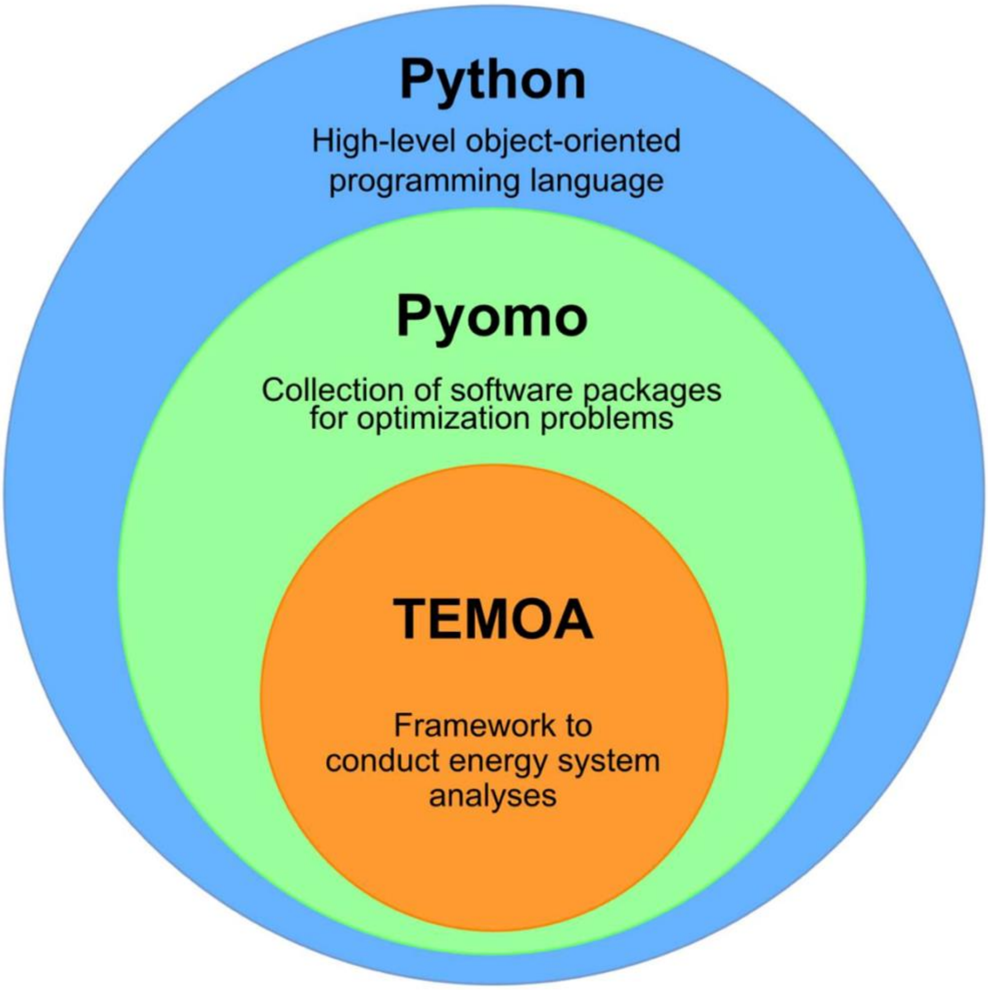


Figure 8 - TEMOA context [37]

It is necessary to document the characteristics of the reference energy system within an SQL spreadsheet, which is subsequently converted into SQLite format to serve as TEMOA's input file. Before initiating the TEMOA model, an automated algorithm populates the SQLite database [38], thereby circumventing the need for annual data entry to project constraints. The model's resolution requires the invocation of an external open-source solver (Gurobi). Additionally, the TEMOA framework comprises a collection of Python-based files enabling users to both construct and execute model instances.

1.3 Nexus approach

To obtain a comprehensive perspective and encompass multiple sectors, in addition to the energy one, it is necessary to employ a different type of approach than the traditional one (where sectors are separately modelled and optimized). This new approach is referred as the nexus.

Nexus approaches play a crucial role in advancing sustainability by identifying both beneficial synergies and adverse side-effects. These approaches foster increased resource efficiency, reduced pollutant and waste production, and the development of more coherent policies [39].

Figure 9 represents how the nexus approach highlights the interconnections between sectors.

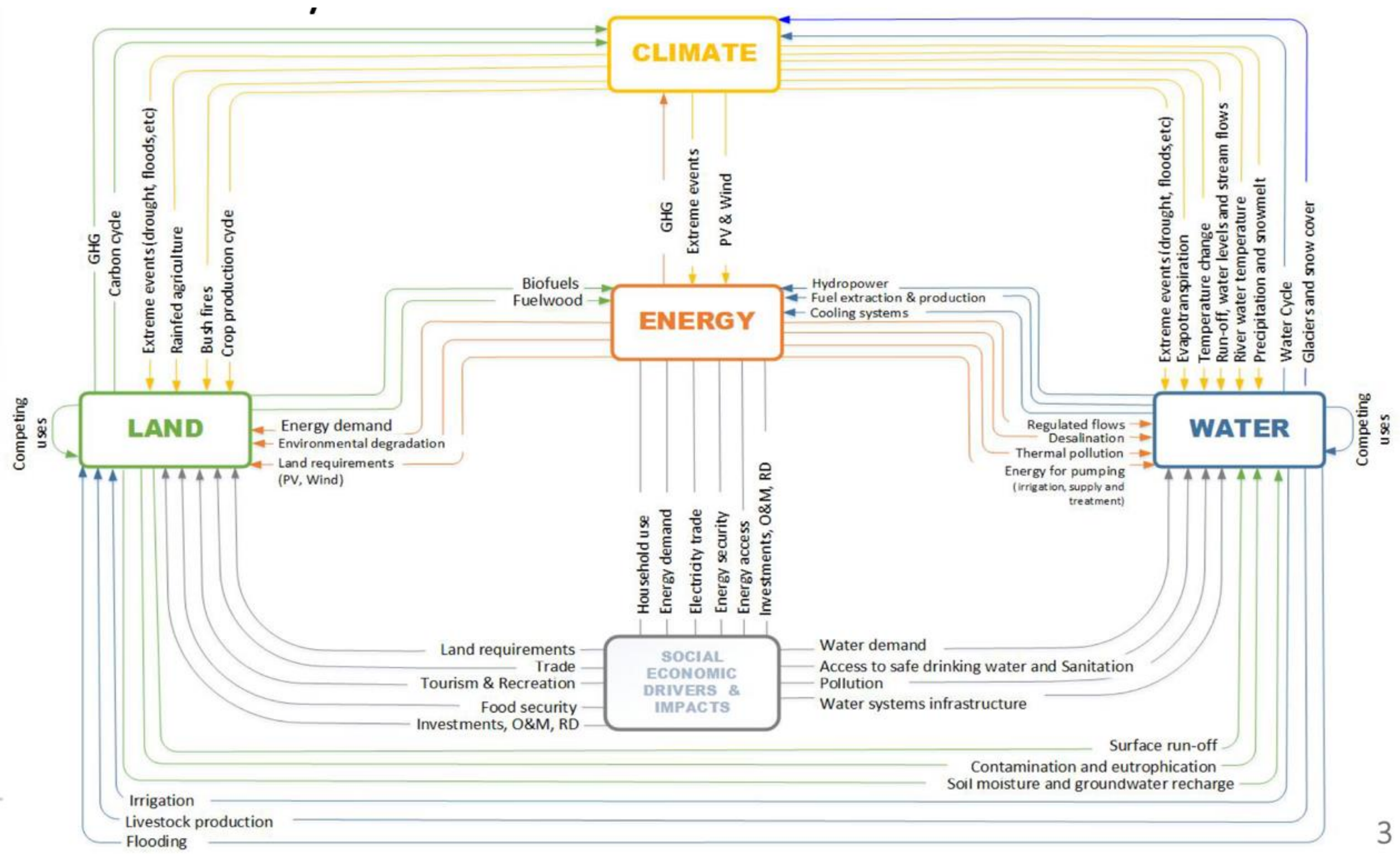


Figure 9 - Representation of nexus sectors and their connections [40]

Nexus approaches are adept at recognizing synergistic effects and co-benefits that might otherwise go unnoticed within intricate production systems and supply chains. They also aid in the identification and mitigation of negative trade-offs. For instance, in arid regions, farmers often face trade-offs when selecting from various crop types with distinct water and energy requirements [39].

Nexus approaches can identify synergistic effects and co-benefits that might otherwise be missed in traditional optimization [41]. For example, multi-sectoral systems analysis reveals that in London implementing urine separation technology (UST) that requires less water than conventional methods could lead to a 10% reduction in water needs [22]. Also, as mentioned in the Italian Adaptation and Mitigation Plan to Climate Change, integrated governance of water and land resources for agriculture can provide up to 30% savings in freshwater consumption [42]. A. Daccache et al. [43] indicate that switching from gravity-fed to pressurized irrigation increases carbon emissions by 135% [43]. Transitioning from rain-fed to irrigated agriculture, which enhances land productivity, would increase both water demand and carbon emissions by 168% and 270%, respectively [43].

This approach is highly valuable in assisting and guiding policymakers and politicians in decision-making. However, it is not without drawbacks. Specifically, nexus approaches tend to incur higher costs compared to silo approaches, but quantifying the additional requirements in terms of expertise, time, coordination, and financial resources remains elusive. Nexus approaches demand expertise across all relevant sectors rather than focusing on a single sector. Moreover, they necessitate the coordination of experts from different sectors. For instance, research into the food–energy–water nexus mandates expertise in food, energy, and water, along with the coordination of experts from these fields [41]. To achieve a common overarching goal, experts must comprehend each other's work. Consequently, conducting nexus research requires more time and financial resources.

1.3.1 Land use in optimization models

Several models already present the land use sector as a single optimized one [44] or as part of an integrated process [45].

To date, according to Melania Michetti et al.[46], macroeconomic models for WEFE nexus assessment can be divided into three main categories: Partial Equilibrium Models (PEM), Integrated Assessment Models (IAM), and Computable General Equilibrium Models (CGE). In Table 1, a review of the well-established modelling framework is shown.

Table 1 - Major optimization models and their characteristics

Model	Type	Spatial resolution	Strength	Weakness
GTAP	CGE	Global (10 regions)	Useful to assess economic impact of trade policies	Limited on energy and environment
TIMES	PEM	Global	Specialized in energy and environmental sector	Limited in sectors other than the energy
MAgPIE	PEM	Global	Very detailed land- use sector analysis	Does not account other sectors than land-use
MESSAGEix-GLOBIOM	IAM	Global (11 regions)	Integrates a wide range of sectors	High computational resource consumption

Computable General equilibrium model

Computable General Equilibrium (CGE) models, functioning as macroeconomic tools, blend economic theory with empirical data to study the repercussions of structural modifications and external shocks on economic systems. They not only facilitate the assessment of different policies aimed at mitigating such impacts but also emulate the mechanics of a real-world economy through a series of structural equations. These equations elucidate the rational behaviour of economic agents and, consequently, the endogenous dynamics of the system [47].

The process of estimating the economic impact involves a comparative analysis of the economy's state before and after the introduction of the policy or economic shock. As the economy adapts to a new equilibrium following such changes, CGE models play a crucial role in unveiling the intricacies of this adjustment, guided by the economic relationships specified in the system of equations [48].

Integrated into CGE models is a comprehensive representation of the entire economy, accounting for intricate interactions and cascading effects among its various segments. Furthermore, these models include the supply side, providing the capability to accommodate price movements. Notably, CGE models are firmly grounded in economic theory, establishing a robust foundation for their analytical framework [49].

Partial equilibrium models

In Partial Equilibrium models (PEMs), production and consumption respond to price variations, adjusting to achieve equilibrium between demand and supply for specific commodities within a sector. These models, typically bottom-up approaches, offer a detailed specification of the studied sector, enabling a thorough analysis of its markets. Their detailed specification and simple market structure make these models particularly attractive for integration with other optimization or equilibrium approaches [50].

They enable relatively rapid and transparent analysis of a broad spectrum of commercial policy issues. Despite the limitations, valuable insights can be gained within time and data constraints, offering practical advantages over more complex analyses. In certain circumstances, justifying the allocation of scarce resources to intricate models with marginal extensions may be challenging. Additionally, introducing general equilibrium constraints to relevant market equations can be impossible in some econometric exercises [51].

Advantages of the model include its simplicity in computational implementation and application to real data. It is highly applicable at a disaggregate level, providing a contrast to the limitations of CGE models. The model directly generates results on various policy-relevant variables, including revenue and trade volume.

On the downside, the model requires knowledge of key parameters (elasticities), and its outcomes are sensitive to the values chosen for these parameters. Additionally, it fails to account for potential interactions among segments of the larger economy. There is a concern that the assumptions underlying the partial equilibrium specification may not always be satisfied [52].

Integrated assessment model

Integrated Assessment Models (IAMs) explore how human economic activities affect Earth's natural systems, including climate change, energy, and land use. These models focus on economic growth dynamics while considering the complex interplay between greenhouse gas emissions and climate systems. IAMs provide valuable insights into economic policies for mitigating or adapting to global warming, emphasizing the integration of scientific and socio-economic aspects related to climate change. This interdisciplinary approach relies on specific assumptions about economic factors, population dynamics, technological change, land use management, fossil fuel emissions, and atmospheric and ocean concentration dynamics.

IAMs compare a standard economic growth framework with a climate/environmental one, internalizing externalities like greenhouse gas emissions that impact economic productivity. Within this framework, three main groups are distinguished: policy-optimization models, policy-evaluation models, and policy-guidance models. The first group assesses potential outcomes through various "what-if" exercises to determine optimal policies. Policy-evaluation models, or simulation models, scrutinize the consequences of specific policies in hypothetical scenarios. Policy-guidance models focus on identifying policies that can meet predefined constraints, adding a subjective dimension to the analysis [46].

IAMs have their strength in the possibility to study multiple sectors and their interaction by linking multiple models together using the output of one model as the input of the connected model and vice versa.

On the other hand, these models require substantial computational resources and a large amount of data. Typically, IAMs can be intricate and may necessitate collaborative efforts for validation.

Here below, a review of the main optimization models of the different categories described (CGE, PEM, and IAM) is provided, analysing how these models, if applicable, implement the land-use sector and a nexus approach.

After analysing the models listed in Table 1, as detailed in Appendix A, it is clear that there have been notable advances in global assessment techniques and model development in the area of LULUCF. However, there is still work to be done to further improve the process. There are several methodological challenges that need to be addressed to improve the accuracy of the LULUCF assessment process:

- *Global Analysis and Spatial Considerations*: Understanding land-use systems globally is crucial for various reasons. The impacts of LULUCF often extend globally, and activities in one region can affect outcomes beyond its borders, environmentally or economically [50].
- *Depicting Land Diversity and Product Variability*: A crucial aspect of global land use assessment is representing land diversity accurately. From a modelling perspective, this is a complex task, especially for economically focused models that may overlook variations in land quality. Most models do not consider soil composition as a parameter, which can impact model choices, leading to the installation of crops on unsuitable terrain [50].

- *Challenges with Data Availability*: One primary obstacle to progress in this field is the availability of data. A comprehensive understanding of LULUCF relies on accessible data, influencing the spatial breakdown of land-use categories, socio-economic statistics, and types of land use [50].

1.4 Aim of the work

In the previous section, an overview of the main modelling framework for the modelling of land use and the energy sectors is discussed. In that list, some of the selected models are capable of model one sector only (whether it is land or energy, like TIMES and MAgPIE) while others can model both (MESSAGEix-GLOBIOM or GTAP-AEZ do).

In the context of energy model analysis, is now becoming increasingly more important to account for the "land use" sector [53]. This necessity is essential because the omission of "land use" in an energy scenario could lead to misleading conclusions. Energy scenarios, that may appear feasible without accounting for land use consumption, could be unworkable due to a lack of adequate space for the installation of necessary energy technologies [54]. This aspect becomes increasingly significant with the growing use of renewable energies (RES) [55]. RES-based technologies on average require larger land areas compared to traditional fossil fuel-based technologies [54]. To illustrate, at a European level, the land requirements to meet wind and photovoltaic solar capacity targets are substantial. In France, Germany, and Italy, where approximately 50% of the EU's renewable energy installations are anticipated, achieving the renewable capacity objectives for 2040 would necessitate an additional 23,000 to 35,000 square kilometres of additional land, equivalent in size to Belgium [56].

Consequently, the integration of the "land use" sector into energy optimisation models becomes crucial for accurately assessing the feasibility and sustainability of such energy transitions.

The analysis of land assumes an increasingly meaningful role in geographical contexts with limited available space, such as islands, often characterized by a lack of connection to the national grid and an energy supply based on fossil fuels. Moreover, as already discussed, there exist trade-offs and synergies between the energy and the land field. Since these effects influence the results of ESOM, they need to be accounted for inside them.

Therefore, it has been decided to integrate this sector into the energy optimization model TEMOA Pantelleria. The main reasons for this choice are as follows:

- None of the models examined implements the "land use" sector in a complete and detailed manner directly within the energy model. This type of integration allows for greater computational efficiency and simplicity, avoiding the need to use external models integrated or linked to the energy optimization model.
- The inclusion of the "land use" sector is done comprehensively and accurately, treating this sector on par with other energy sectors, rather than as a separate single technology or commodity.
- The TEMOA model was selected because it is a "bottom-up" model that provides a highly detailed description of the technologies involved. This technical modelling precision aligns with the intention to examine how the land use sector technologies respond to policies, going beyond just economic aspects, although economic considerations are also considered, as TEMOA is an economic model.

The integration of the "land use" sector in TEMOA-Pantelleria represents a significant advancement in modelling future energy strategies, offering a more comprehensive and detailed view of the impact of policies and technologies on the landscape.

2 Case study: The Pantelleria Island

2.1 Geographic and morphologic framework

The Island of Pantelleria, located in the middle of the Mediterranean Sea at around 70 km from the Tunisia and 100 km from the Sicilian coasts, is the biggest island among the ones around Sicily. It has a surface of 83 square kilometres, a maximum height of 836 m above the sea at the peak of the 'Montagna grande' (big mountain) and a cost length of 78 km.

Pantelleria is a volcanic Island; only 28% of the volcanic is above the sea, while the remaining 72% is submerged down to a depth of around 1200m.

The formation of the island started around 330000 years ago and one of the main volcanic events occurred 45000 years ago when the island was fully covered by a thick layer ranging from 5 to 20 meters of ignimbrite rock[57].

Today, the volcanic activity in the emerging part of the island is characterized by second-type activities such as fumaroles and hydrothermal hot water springs present throughout the island, for this reason, Pantelleria Island can be considered as an open-air thermal spa [58].

The volcanic activity across the years has produced different types of rocks with different properties; there are acidic vulcanite rocks (rich in silica) and basic vulcanite rocks (poor in silica). The acid vulcanite rocks are mainly trachyte and rhyolites with a high presence of sodium and potassium in their composition, due to this composition these rocks are also called "pantellerite" [58]. In Figure 10 a representation of the types of rock present in the Island of Pantelleria is provided.

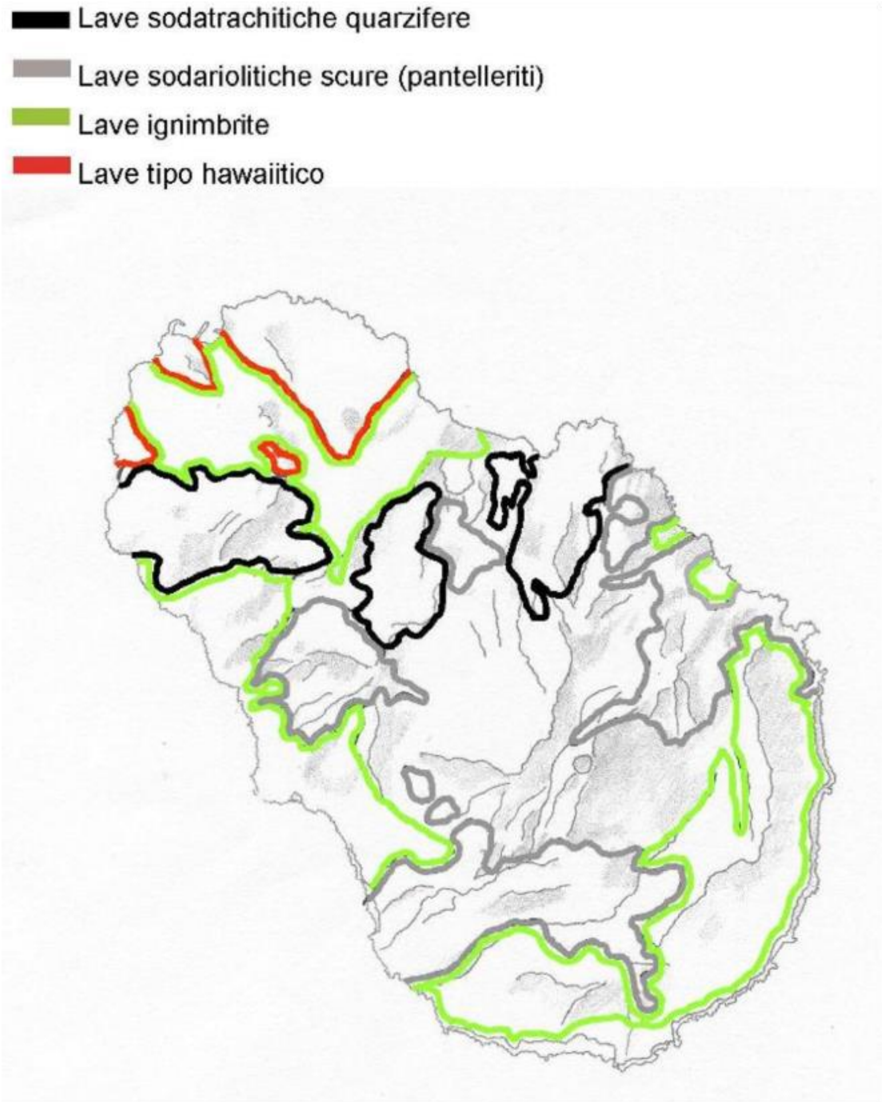


Figure 10 - Rock types on Pantelleria Island [58]

The weather in Pantelleria is very diversified due to the presence of a mountain, several hills and many small valleys protected from the wind.

Mean temperatures range from 11°C to 18°C during the cold season and from 21°C to 30°C during the hot season. The temperature typically doesn't go higher than 34 °C or lower than 8°C, ensuring appreciable weather throughout the year [59].

The wind on the island is constant all over the year: the windiest period goes from the 31st of October to the 28th of April and the mean wind speed is 21 km/h, the quietest period of the year goes from the 28th of April to the 31st of October with a mean wind speed of 17,67 km/h [59].

The constant speed of the wind which can reach speeds up to 45 km/h forced inhabitants to adapt agriculture to protect the plants from it.

The soils, which derive entirely from volcanic rocks, are sandy in texture, well-drained and often with rocky outcrops. The ground is poor in organic substances due to the high summer temperatures, poor in nitrogen, phosphorous and calcium, but very rich in potassium.

2.2 Social and political framework

The island has a population of 7300 inhabitants, but in the summer, due to tourism, the island can host around 30000 people [60]

“Pantelleria centro” is the main town, with around 5000 residents, where is placed the town hall and the hospital. The rest of the population lives mainly in two other villages: Khamma-Tracino and Scauri, populated by 1,200 people each [61].

The entire territory is Administratively part of the Municipality of Pantelleria, under the Free Municipal Consortium of Trapani (Sicily).

In July 2016, the "Island of Pantelleria" National Park was officially created. As depicted in Figure 12, the park is divided into three distinct zones, each possessing noteworthy natural, landscape, agricultural, historical, and cultural significance [62]:

- *The first zone* is characterized by a lack of or minimal human intervention.
- *The second zone* is marked by a limited degree of human activity.
- *The third zone* exhibits a high level of human influence.

The primary objective behind the establishment of the Pantelleria National Park is to preserve the island's precious natural resources and promote sustainable development.

Are very popular all over the island the so-called ‘muretti a secco’ (dry wall in English), Figure 11, these types of walls are built with blocks of stone suitably arranged and assembled, without the use of binders or mortars of any kind. These walls are from the 2018 UNESCO Heritage and are used to divide the land properties, terraces and to protect plants from wind [63].

Figure 11 - Terraces with dry walls in Pantelleria Island [64]

Even though the entire island has officially gained the status of a national park, represented in Figure 12, which prevents the construction of new energy production facilities that could alter the landscape, there is still the possibility of redeveloping and utilizing previously anthropized areas by introducing new systems for sustainable electricity generation [65].

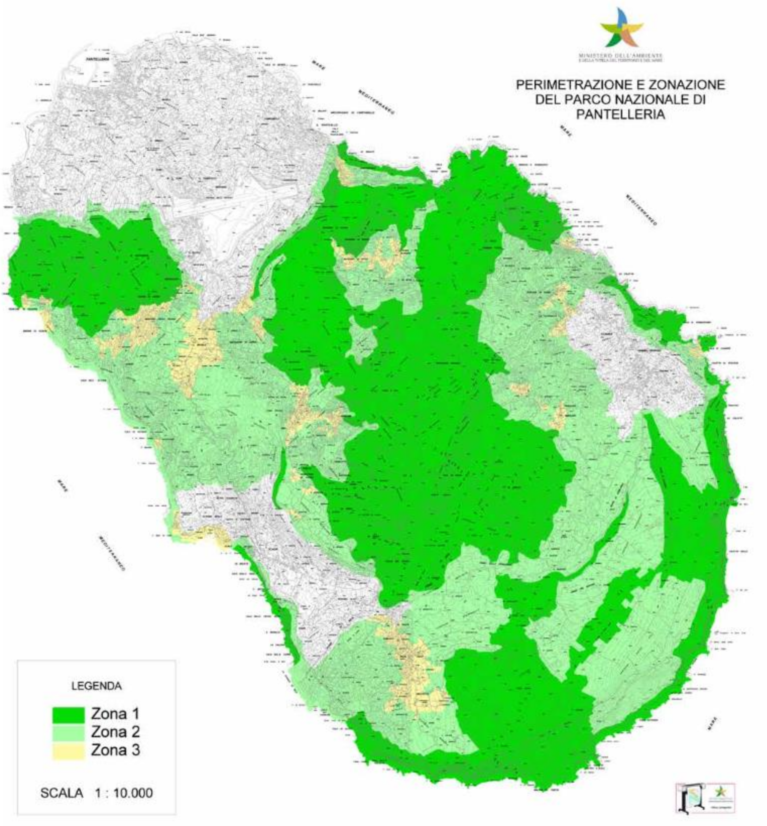


Figure 12 - Pantelleria's national park [66]

2.3 Economic framework

Pantelleria's economy thrives on three pillars: viticulture, caper farming, and tourism. In the following two paragraphs, the agriculture sector and the tourism sector will be described.

2.3.1 Agriculture

The agricultural sector in Pantelleria, bolstered by caper farming and wine production, has flourished despite the challenges posed by the island's rocky, sloped and dry terrain [58]. Over the ages, farmers have ingeniously adapted to the environment, implementing measures to shield crops from fierce winds and optimize water usage. Such resilience has earned Pantelleria's agriculture the title of 'heroic' [67]. A testament to this tenacity is the transformation of the island's rugged landscape into approximately 5700 hectares of arable land, achieved by crafting terraced plots and constructing dry-stone walls using stones cleared from the fields [68].

Viticulture holds a special place in Pantelleria's economy. The island's vineyards, completely non-irrigated, benefit from the unique “alberello” planting style and practices like weeding, which involves surface tilling of the soil. In 2016, UNESCO recognized the centuries-old tradition of cultivating the Zibibbo grape in the “alberello style” as a world heritage practice (as shown in Figure 4). The alberello method, shown in Figure 13 involves planting vines in shallow basins about 20 cm deep, which not only shield the grape clusters from wind but also help in rainwater retention, ensuring soil moisture. Weeding serves dual purposes: it eliminates competing weeds and prevents soil compaction, which could increase evapotranspiration and deplete soil moisture; it also enhances air circulation facilitating rapid drying of the topsoil. This process disrupts the upward movement of water, ensuring that moisture is retained in the deeper layers [67].

Figure 13 – Vite ad alberello, a typical plant of Pantelleria.[69]

The most renowned product of Pantelleria viticulture is the so called 'Passito di Pantelleria'. Despite the current importance of the wine industry, vine cultivation has dropped from around 7,000 [ha] in 1940 to around 1,000 [ha] in the 2000s [67].

The island's arid terrain is a haven for caper cultivation, which earned the IPG certification in 1996. The Pantelleria PGI caper has a globular, sub-spherical shape, occasionally long and conical, with a green colour tending towards mustard. It has a strong and distinctive smell, and the taste is aromatic and typically salty. The percentage of sea salt in the packaging does not exceed 25% of the caper's weight [70].

2.3.2 Tourism

Tourism is the primary economic driver for Pantelleria. Thanks to its spectacular natural landscapes, the beautiful sea, and the centenary culture the island began attracting tourists in the 1970s, and its popularity has soared since. Today, especially during the summer months, the island welcomes around 90.000 visitors annually. Over the past decade, this number has remained relatively consistent, with only minor fluctuations year on year [71], [72] as highlighted in Figure 14.

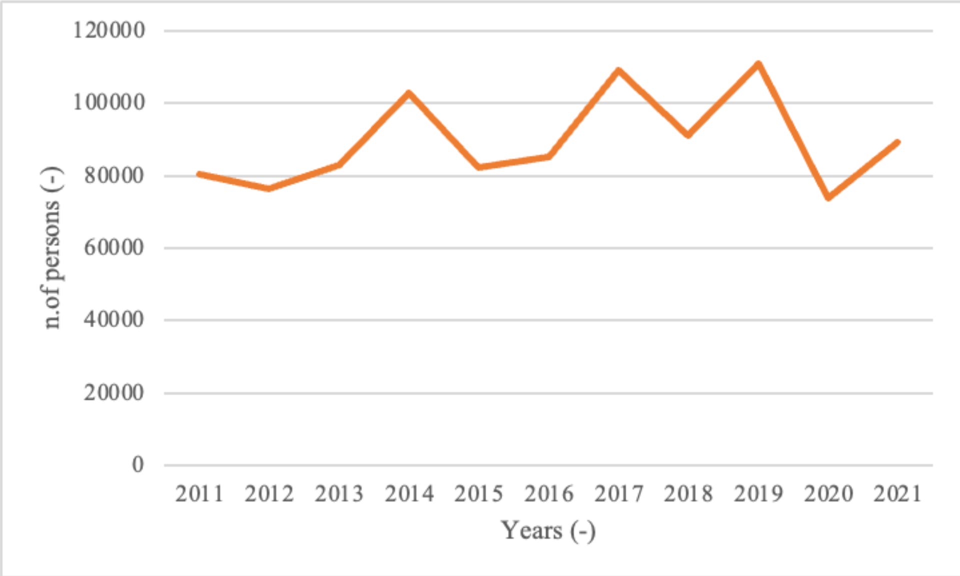


Figure 14 - Yearly tourist presences in Pantelleria island from 2010 to 2021 [71]

The tourism industry significantly influences the island's energy and water usage, as well as its CO_2 emissions. Yet, transitioning to sustainable practices could enhance the sector by ensuring more consistent energy and water supplies.

3 Reference energy system

As previously mentioned, the Reference Energy System (RES) serves as a conceptual representation of all the processes involved in energy conversion, transmission, and consumption from primary sources to the demand sector. Modelling the RES using a bottom-up Energy System Optimization Model (ESOM) requires detailed techno-economic characterization of supply-side, conversion and demand-side sectors. In the TEMOA framework, the energy system is modelled as a network that transforms input energy commodities (e.g., oil or renewable potential) into end-use services (e.g., cooking, heating, or transport) utilizing intermediate commodities (e.g., electricity) and specific conversion (e.g., power plants) or utilization technologies (e.g., cookers, space heaters, vehicles). These technologies are defined based on technical, economic, and environmental attributes (e.g., efficiency, costs, emission rates) [73]. Commodities and technologies specified in energy system models are site-specific, varying depending on the area of study and the chosen base year.

Small parts of the RES, due to the lack of data and challenges related to modelling new technologies specific to the island, rely on data from the mainland (TEMOA-Italy [74])

3.1 Pantelleria energy system

The Pantelleria energy system was initially modelled for the base year of 2013 (as depicted in Figure 15). In 2013, the upstream sector (represented in green) consisted of diesel, gasoline, LPG, and a small number of solar resources. Primary fossil fuels were imported by shipping from the mainland at high transportation costs. Gasoline was solely utilized in the transport sector, LPG met cooking demands, and diesel was used for both transportation and electricity generation. Like many Mediterranean islands, the power sector in Pantelleria was not connected to the mainland and relied on fossil fuels [67].

The Pantelleria power sector in 2013 (highlighted in yellow in Figure 15) included a diesel power plant and a few distributed photovoltaic facilities. The diesel plant, owned by S.M.E.D.E S.p.A. and comprising six diesel units and two gas turbines, adapted for diesel use, had a total installed capacity of 22 MW. The photovoltaic capacity amounted to approximately 140 kW [55].

The distribution grid (depicted in violet in Figure 15) served various demand-side sectors, which included buildings (comprising residential, commercial, and agricultural properties), transportation, and water production.

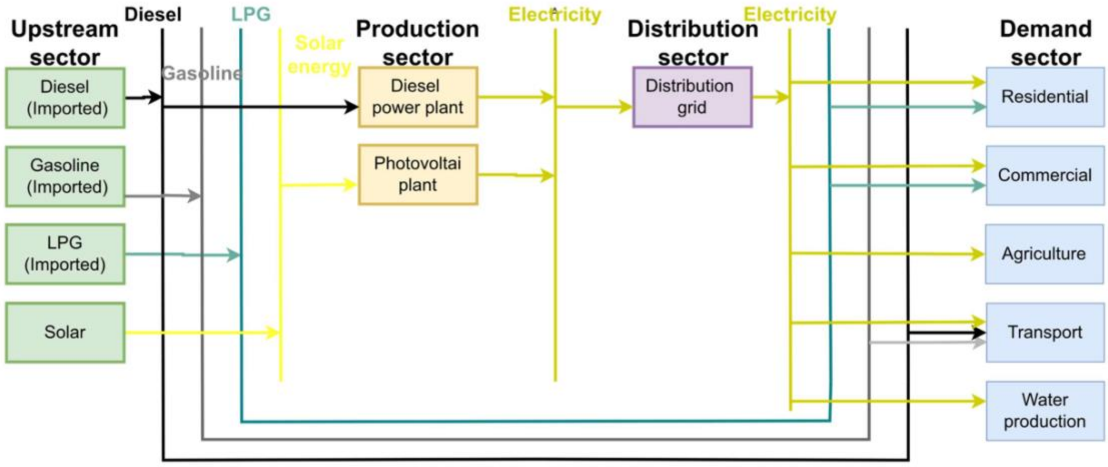


Figure 15 – Pantelleria electricity sector representation [67]

3.1.1 Renewable source potential

One of the focuses of this work is to assess the production potential of renewable energy sources, specifically photovoltaic and onshore wind technologies, without delving into the economic and technical aspects of PV plants. These aspects are already integrated into the TEMOA-Pantelleria database. The analysis is limited to these two technologies due to their significant role in both regional and national energy scenarios and their high land use intensity compared to other energy sources like hydro, biomass, or gas. A brief recap of the other energy sources is, however, provided in this chapter to give the reader a more comprehensive view of the renewable energy potential of the island.

Solar

Pantelleria has an average solar irradiance in the optimal plane of around 2000 kWh/m^2 [75].

Wind

The island, thanks to its location at the heart of the Sicilian Channel, benefits from consistently strong winds prevailing northwest at approximately 7 m/s, measured at a height of 25 meters above sea level [76].

Figure 16 shows the annual average wind speed at 50m.

Figure 16 - Map of the average wind speed on Pantelleria [77]

Geothermal

Since the island of Pantelleria is the emerged part of an active underwater volcano, there is the possibility of harnessing geothermal heat to generate electricity [75]. A project was proposed for the construction of a medium-enthalpy electricity generation plant with an indicative capacity of 2.5 MW at a site located in the Serraglio district, about 14 km from the town centre of Pantelleria, in the central-southern part of the island. This project could have covered almost 50% of the island's electricity demand [78].

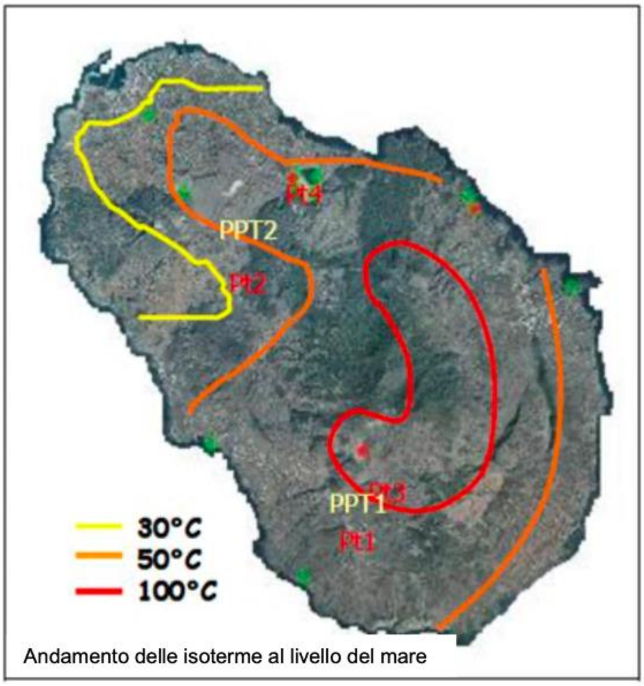


Figure 17 - Isothermal lines on the sea level [75]

However, to date, the project has never been seriously considered.

Wave

Pantelleria, along with the western region of Sardinia, stands out as one of the most energy-rich locations in the Mediterranean Sea. The average annual incident energy flux in the northwest part of the island is estimated at around 7 kW/m as represented in Figure 18, referring to the unit length of the wavefront [79].

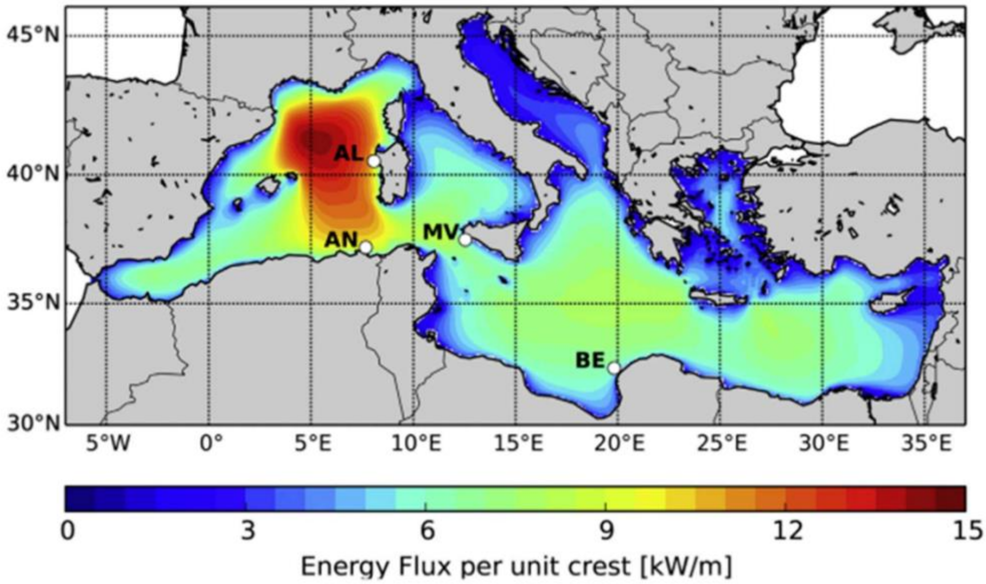


Figure 18 – Mean wave energy flux from 1979 to 2013 [79]

Biomass

Pantelleria's biomass potential stems from organic residues sourced from forestry, agriculture, and the organic fraction of municipal solid waste (OFMSW) [75]. Agricultural waste is estimated to comprise around 950 tons/year from viticulture and approximately 400 tons/year from oil production. While the island's forest residues total about 6000 tons/year, only 15% is deemed usable due to recovery challenges. Additionally, the island generates close to 1100 tons/year of organic municipal solid waste. Al this type of organic matter can be exploited to produce energy through biomass energy converter [75].

3.2 TEMOA Pantelleria modelling

The Reference Energy System (RES) for the island of Pantelleria has an already existing modelling instance developed by the MATHEP group at the Politecnico di Torino. For a detailed description of the model (TEMOA-Pantelleria), please refer to [67] .

In this section, an overview of the main components of the RES will be provided to offer a comprehensive understanding of the context in which the land-use sector will be developed. As shown in Figure 19, the Reference Energy System consists of the following parts:

- Upstream sector
- Intermediate commodities
- Power sector
- Demand side sector
- Demand side services

Figure 19 – Reference energy system of Pantelleria [67]

3.2.1 Upstream and power sector

The upstream and the power sectors together structure the supply side of the RES. Within the supply side, primary energy resources are converted into energy vectors through various technologies, and these energy vectors serve as input commodities for the demand-side sectors.

Upstream sector

The upstream sector is composed of fossil fuels and renewable resources. Since Pantelleria imports fossil fuels from the mainland rather than extracting them locally, they are entirely modelled as imported resources, representing an external input to the energy system. Fictitious technologies are used to model the import of fossil fuels giving them a price (Table 2)and constrains.

Table 2 - Fuel importation price for Pantelleria Island [67]

Fuel category	**Fuel**	**Pantelleria importation price [M€/MWh]**
Oil products	Diesel	1.21E-04
	Gasoline	1.21E-04
	LPG	1.21E-04

The capacity of renewable energy sources has been modelled through technologies designed to represent them. These technologies are defined with a cost, it is also possible to set constraints in the base year and for future scenarios.

Power sector

Since the heat is produced from the demand side technologies absorbing electricity the power sector, in this model, produces only electricity.

The electricity is produced by two technologies in the base year: the diesel plant (producing almost the overall electricity needed by the island) and the solar photovoltaic panels.

Table 3 summarizes the characterization parameter of the two technologies and their values in the base year.

Table 3 - Power sector technologies characterization [67]

Technology description	Input commodity	Output commodity	Efficiency	Installed power [MW]	Fixed operation and maintenance cost [M€/MWh]	Variable operation and maintenance cost [M€/MWh]
Diesel plant	Diesel	Electricity	3.9E-1	22	22	1.8E-6
Solar plant	Solar	Electricity	1.00	1.4E-1	3.1E-2	5E-5

3.2.2 Demand side

The demand side has been divided into the following Sectors:

- Agriculture
- Commercial
- Residential
- Transport
- Water production

3.2.2.1 Residential

In 2013 the residential sector consumed 15 GWh of energy [78] .

In this sector mostly Electricity was used. The LPG is only used for cooking. In Table 4 all the residential technologies are represented together with all their parameters.

Table 4 - Residential technologies characterization [67]

Energy service	Technology	Input commodity share f_{tech} [%]	Input commodity	Final Energy $E^{f}_{tech,eu,f}$ [MWh]	Efficiency [%]	Useful energy E^{u} [MWh]
Demand-side technologies by Residential energy services						
Space heating <1919	Resistance	84	Electricity	284	90%	255.6
	Electricity heat pump	16		54	200%	108
Space heating 19/45	Resistance	84	Electricity	361	90%	324.9
	Electricity heat pump	16		69	200%	138
Space heating 46/61	Resistance	84	Electricity	258	90%	232.2
	Electricity heat pump	16		49	200%	98
Space heating 62/71	Resistance	84	Electricity	129	90%	116.1
	Electricity heat pump	16		24.6	200%	49.2
Space heating 72/81	Resistance	84	Electricity	116	90%	104.4
	Electricity heat pump	16		22	200%	44
Space heating 82/91	Resistance	84	Electricity	38.7	90%	34.83
	Electricity heat pump	16		7.4	200%	14.8
Space heating 92/2001	Resistance	84	Electricity	26	90%	23.4
	Electricity heat pump	16		5	200%	10
Space heating 2002/13	Resistance	84	Electricity	77.4	90%	69.7
	Electricity heat pump	16		14.7	200%	29.4
Space cooling	Centralized heat pump	54	Electricity	127.5	360%	459
	Room heat pump	4		9.4	360%	33.8
	Electric chiller rooftop	42		99.2	372%	369
Water Heating	Electric heater	100	Electricity	3543	91%	3224.1
Refrigerator	Refrigerator	78	Electricity	1474	100%	1474
	Freezer	22	Electricity	415.7	100%	415.7
Cooking	LPG cooker	100	LPG	3527.7	50%	1763.8
	El cooker	100	Electricity	472.4	80%	377.9
Electric Stoves	Electric Equipment	100	Electricity	1299	100%	1299
Washing	Electric Equipment	100	Electricity	1181	100%	1181
Lighting	Incandescent	75	Electricity	620	13%	77.5
	Fluorescent	20		165.3	62%	102.5
	Halogen	5		41.3	21%	8.7
	LED	0		0	71%	0
Other	Electric Equipment	100	Electricity	826.7	100%	826.7

3.2.2.2 Commercial

The commercial sector is very similar to the residential one. It consumes almost all electricity except the cooking service that uses LPG [78].

The commercial sector consumes around 13 GWh of energy at the base year and its technologies are listed in Table 5 [78].

Table 5 - Commercial technologies characterization [67]

Demand-side technologies by commercial energy services						
Energy service	*Technology*	*Input commodity share [%]*	*Input commodity*	*Final Energy $E^{f}_{tech,eu,f}$ [MWh]*	*Efficiency [%]*	*Useful energy E^{u} [MWh]*
Space heating	Resistance	25	Electricity	1444.5	0.90	1300.1
	Electricity heat pump	75		4333.5	2.00	8667.1
Space cooling	Centralized heat pump	55	Electricity	953.4	3.60	3432.2
	Room heat pump	11		190.7	3.60	686.4
	Electric chiller rooftop	34		589.4	3.72	2192.4
Water Heating	Electric heater	100	Electricity	1155.6	0.91	1051.6
Refrigeration	Refrigerator	100	Electricity	231.1	1.00	231.1
Cooking	LPG cooker	100	LPG	1004.9	0.50	502.4
Electric office equipment	Electric Equipment	100	Electricity	577.8	1.00	577.8
Lighting	Incandescent	75	Electricity	1560.1	1.17	1825.3
	Fluorescent	20		416.0	5.63	2342.2
	Halogen	5		104.0	1.60	166.4
	LED	0		0.0		0.0

3.2.2.3 Transport

The transport sector is divided into aviation, navigation, road, and bunkers. These vehicles consume three types of fuels: Motor gasoline, diesel and aviation gasoline. In Table 6 the energy consumption of the transportation sector is divided for each category and for each fuel [78].

Table 6 - Fuel consumption by transport category [67]

Energy consumption by fuel E_{af} [MWh]			
Transport category	*Motor gasoline*	*Diesel*	*Aviation gasoline*
Aviation			24120
Road	18474	17366	
Domestic navigation		317	
Bunkers		792	

In Table 7 all the consumption of each technology are reported.Table 7 - Transport technology characterization [67]

Demand-side transports technologies by transportation modes.					
Transport modes		*Technology*	f_{tech} *[%]*	*input commodity*	*final energy* $E^{f}_{tech,tm,f}$ *[MWh]*
Road	Cars	Diesel car	1	diesel	16497.3
		Gasoline car	1	gasoline	14040.2
	2 wheels	Moped diesel	0.32	diesel	277.8
		Motorcycle diesel	0.68	diesel	590.4
		Moped gasoline	0.32	gasoline	236.5
		Motorcycle gasoline	0.68	gasoline	502.5
	Trucks	Trucks gasoline	1	gasoline	3694.8
Navigation	Domestic Navigation	Domestic navigation	1	diesel	316.7
	Bunkers	Bunkers	1	diesel	791.7
Air	Domestic	Domestic aviation	1	aviation gasoline	24120

3.2.2.4 Water

In the water production sector, electricity is the only energy vector employed. The energy consumption for desalination technologies in the base year amounted to approximately 11,260 MWh [78].

At the base year, two different technologies produce electricity by desalination and their characteristics are reported in Table 8.

Table 8 - Desalination technologies characterization [67]

Demand-side technologies by commercial energy services						
Energy service	*Technology*	*Input commodity share [%]*	*Input commodity*	*Final Energy* $E^{f}_{tech,eu,f}$ *[MWh]*	*Conversion coefficient* $coff_{DES}$ *[m³/MWh]*	*Water production demand* D_{DES} *[m³]*
Desalination	EDR	27.5	Electricity	696.3	3.03E-04	2.11E+05
	MC	72.5		10564	5.26E-05	5.56E+05

3.2.2.5 Agriculture

Within the reference energy system, the agricultural sector was initially modelled in the base year as a direct consumer of primary energy carriers, without intermediate technologies linking demand and supply.

However, in subsequent chapters, this sector, that is represented in the TEMOA-Pantelleria model only as a single technology (with upstream as input and demand commodity as output), will be expanded to include various technologies reproducing crops, that will consume energy for both production and irrigation.

4 Land-Use reference system

In this chapter, it will be finally explained how the land-use sector has been modelled within the energy optimization model Temoa-Pantelleria. Starting with an exploration of how the land-use sector significantly differs from reference energy end water systems, this chapter will elucidate the practical modelling of this sector. Subsequently, it will be described the data collection process and the transformation of gathered data to enable its incorporation into the model.

4.1 Major differences with the existing reference systems

In general, both energy and water can be represented as a system that converts input commodities (upstream sector) into end-use services (demand sector) through flows and intermediate commodities and technologies as represented in Figure 20. For example, in the reference energy system, the input commodities are energy ones such as imported fossil fuels, that finally generate demand commodities (can be hot water, heating) passing through a series of processes. In the same way, for the reference water system, incoming commodities will be salt water or water imported from the peninsula and as demand commodities fresh water for domestic or commercial use. Optimization mainly characterizes the flows and the choice of intermediate commodities.

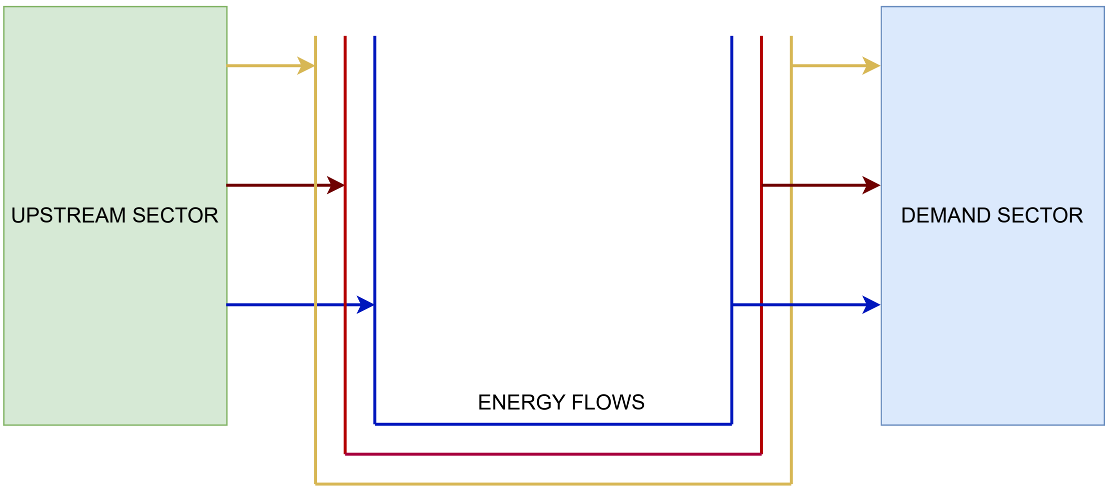


Figure 20 - Scheme of reference energy system

Differently from water and energy, land is not a commodity that is exchanged between process, starting from an initial upstream phase, and ending up in satisfying a demand. Rather, Land can be seen as a natural element (a finite resource) that is occupied by a certain process (a power plant or a crop that occupy soil). For this reason, land cannot be modelled as a process, and a new method for inserting this element is ESOM is necessary.

In particular, land has two primary roles that can be linked to model interpretable amounts. Primary, land limit capacity development of both renewable installation and crop production. Therefore, land is a constraint. Second, land has some technical attributes (related to its quality and its position) that can alter the producibility of the technologies installed on it. Therefore, for each technology, there is a spatial extent (or a land) that guarantees certain characteristics.

In this context, the role of ESOM is double. It has both to find a solution considering spatial limitations, but also suggesting the optimal way to allocate land. Especially in a context of limited resources.

In summary, concerning the land use sector, there is no longer an optimization of flows but rather of space.

We move from an optimisation of flows to a spatial optimisation while maintaining a model structure congruent with the reference energy system and linking the land use sector to the previously mentioned sectors.

The area of the island of Pantelleria is optimized by the model by choosing the best technology to install on an economic basis. Since the objective function to be minimized is an economic function, the technology that most effectively reduces the system's costs, or at least the technology with the best ratio of quantity produced to energy utilized, will be selected.

To serve this purpose, the way crop and energy technologies are modelled considering spatial attributes is explained. Then, it will be shown how the model has been modified to account for spatial variability of crop and power producibility and how the problem has been constrained to account for land limitations.

4.2 Land modelling

In ESOM, Land has a double utility. It can be intended as a natural resource that limits development by imposing constraints on the occupiable area, but also as an element that can guarantee certain soil conditions. These conditions, both in terms of energy availability and soil characteristics, allow the installation of certain technology at a certain potential. Here, the aim is to explain how land can be modelled and how land-specific technology (such as crops) can be characterized.

In particular, the available land area of the island has been incorporated into the model as a space that can be consumed by crops or energy resources that, once installed, will occupy the available space through a parameter called Land Use Intensity (LUI). This new parameter represents the amount of soil that a technology will occupy to its capacity. Therefore, for the crops, the LUI will be measured in m^2/ton and represent how much space is occupied by a ton of crop product. For what concerns the RES the LUI is measured in m^2/MW and represents how much space is needed to install 1 MW of that technology. The LUI change between different technologies but also between different soils. A detailed explanation of this parameter and the rationale behind its inclusion in the model are provided in Section 5.1.

The amount of space occupied by each crop will vary depending on the type of terrain in which it is installed, for example, it will be more challenging to cultivate on higher-altitude or steeper terrain.

Regarding the implementation of the land area, the following parameters characterizing each particle of terrain on the island are required:

- Altitude
- Slope
- Type of land
- Irradiance
- Wind producibility
- Distance from the grid

Altitude and inclination are the primary factors that affect crop yield. Altitude influences the climate, with greater climate variability and moisture variations at higher altitudes. Meanwhile, increased inclination alters the exposure of crops to sunlight and the soil's water retention capacity. The energy demand will be higher for energy production on steep or high-altitude terrain, as machinery will require more fuel to operate under challenging conditions.

Type of land is useful to determine which parts of the territory are not suitable for the installation of some technologies and which, on the other hand, already host existing technologies.

Irradiance and wind producibility are crucial characteristics as they impact the feasibility of installing photovoltaic or wind power systems.

Distance from the electrical grid influences the choice of installing an electricity generation system, as installations farther from the grid require higher connection costs and are, therefore, less cost-effective.

4.3 Technology modelling

Currently, in Pantelleria Island, only two types of crops are cultivated: vines and capers. Other crops will be still considered within this study because limiting it to only two would excessively limit the crop technological scope of the analysis. Furthermore, data available for cultivations on Pantelleria are extremely limited.

Regarding renewable energy resources, there are no large installations on the island, only a few rooftop photovoltaic panel installations; and a small 32 kW of micro-eolic installation [80]. In this case as well, to create the most comprehensive model possible, the possibility of installing both wind and photovoltaic power generation systems is considered.

Crops and renewable resources within the model are represented as technologies that occupy the land (commodities) on which they are installed with a certain Land Use Intensity. Each crop will be characterized by the following factors:

- Crop yield
- Energy consumption for cultivation
    - Machinery
    - Fertilizers
- Energy consumption for irrigation
- Economic output

Crop yield, measured in [ton/m^2], indicates how much land is needed for a crop to grow, it varies both by crop type and the characteristics of the terrain in which it is cultivated.

Energy consumption represents the energy exploited by agricultural machinery during all stages of crop cultivation, including the energy consumption for the production and use of fertilizers. Energy consumption is calculated in [MWh/ton] and includes both the use of electricity and diesel for agricultural machinery.

Energy consumption for irrigation, measured in [MWh/m^3], is identified by the energy costs of water pumping and is directly proportional to the water required by each crop. This factor relies solely on electricity. Not all crops modelled were treated as irrigated, but for each type of crop, two technologies were developed: one for irrigated and one for non-irrigated crops. For non-irrigated crops, the energy consumption for irrigation was not included.

Economic output, measured in [€/ton], represents the economic return of each crop, it corresponds to the price at which each crop is sold on the market, and it has a negative value in the cost variable parameter because it lowers the total cost of the system.

Each renewable resource, on the other hand, will be characterized by:

- Capacity factor
- Investment costs
- Fixed costs
- Energy land consumption

Capacity factor is the ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full-power operation during the same period.

Investment costs, in [€/MWh], represent the costs incurred for the manufacturing and installation of the facility.

Fixed costs [€/MW] are the costs incurred during the lifetime of the facility, such as maintenance costs.

Energy land consumption in [MW/m^2] is the equivalent of crop yield and indicates how much space each MW of facility occupies. In this case, differently from the crop yield, energy land consumption is independent of the land in which the facility is installed. Indeed, 1 MW of PV will always occupy the same amount of space.

4.4 Data gathering

Before the implementation of the TEMOA model, a complete data collection is necessary. All the values of the previously listed parameter that will later be implemented in the model are essential. The data collection was divided into two parts: crop and RES data and soil characteristic data.

4.4.1 Crop and RES data collection

The first step has been to select some crops that would be considered representative of the agriculture sector.

To select the crops to model and to calculate their crop yield, Jupyter Notebook [81] is used.

Jupyter Notebook is an interactive application that combines elements of text, code, and visualizations in a single document. It enables users to write and execute code directly in the browser, making data analysis, mathematical modelling, chart creation, and process documentation easy. This tool supports multiple programming languages, including Python, R, and Julia. However, for this thesis, Python was used as the programming language [81].

The 10 main types of crops produced in Sicily were selected to be modelled.

This decision has been led by two criteria:

1. In Pantelleria Island only two crops (grapes and capers) are primarily cultivated, therefore other crops are needed.
2. The similarity of the Sicilian soil to that of Pantelleria.

Data was collected from the ISTAT database (Italian National Institute of Statistics [82]), which provides both regional and national crop data. Then, to verify and validate the collected data, data available on the FAOSTAT website (Food and Agriculture Organization Corporate Statistical Database[83]) was used. The FAOSTAT data are widely employed in the models described in Chapter 1.3.1 and are considered reliable.

For the data validation, the values of the total production and of the crop yield were compared. It was not possible to use the regional scale, as FAOSTAT data is only available at the national level, so the latter was used.

Since the ISTAT website did not directly provide the crop yield data, it was calculated by dividing the harvested production (in quintals) by the total cultivated area (in hectares). The crop yield calculated at (2) was used both for data validation and for data implementation in the model.

$$crop\ yield = \frac{harvested\ area\ [quintals]}{total\ cultivated\ area\ [ha]} \tag{2}$$

After obtaining the values of total production and crop yield for both websites, the validation of ISTAT data was initiated. Specifically, the percentage deviation was calculated for each type of crop, both for crop yield and total production.

$$Tot.prod._{\%\,\mathrm{dev}} = \frac{\left|Tot.prod._{ISTAT,i} - Tot.prod._{FAOSTAT,i}\right|}{Tot.prod._{FAOSTAT}} \tag{3}$$

$$Crop\ yield_{\%\,\mathrm{dev}} = \frac{\left|crop\ yield_{ISTAT,i} - crop\ yield_{FAOSTAT,i}\right|}{crop\ yield_{FAOSTAT,i}} \tag{4}$$

As evident from Table 9, the percentage deviations are not high, and for some crops, the ISTAT and FAOSTAT data appear to be extremely similar.

Table 9 - Crop yield and total production percentage deviation between ISTAT data and FAOSTAT data

Crop	**Crop yield percentage difference [%]**	**Total production percentage difference [%]**
Grape	9,64	13,14
Wheat	0,71	0,77
Maize (corn)	0,70	1,25
Tomatoes	10,54	16,68
Sugar beet	1,32	0,00
Apple	2,55	0,59
Olives	1,04	2,44
Orange	2,62	2,75
Rice	0,03	0,33
Potatoes	7,47	23,6

Therefore, the ISTAT data can be considered validated, production and harvested area data specific to the Sicilian region was downloaded to calculate the crop yield using (2).

Initially, 10 crops were selected for the study; however, due to some issues related to the implementation of these crops in the TEMOA model, the selection was reduced to just 5 (as detailed in Chapter 5.1). The chosen crops are as follows:

- Grape
- Orange
- Tomato
- Lemon
- Potato

The crop yield for these selected crops is provided in Table 10.

Table 10 - Crop yield for each crop irrigated and not irrigated

Crop yield	Grape	Orange	Tomatoe	Lemon	Potatoe
Non-irrigated [kg/m^2]	0,82	1,82	1,71	1,59	1,55
Irrigated [kg/m^2]	1,06	2,36	2,22	2,07	2,00

The energy consumption of each crop was gathered from the study [84]. Table 11 contains all the energy costs associated with the use of diesel for each crop.

Table 11 - Energy consumption by each crop for each sector

Crop	Seeds [ton/MWh]	Fertilizer [ton/MWh]	Pesticides [ton/MWh]	Machinery [ton/MWh]
Grape	0	6,96	8,84	3,89
Orange	0	2,03	8,21	2,09
Tomatoes	21,54	11,30	59,10	12,90
Lemon	0	1,87	13,16	1,41
Potatoes	12,67	6,65	34,76	7,59

As evident from Table 11, only tomatoes and potatoes have energy costs for planting because they are annual crops and need to be replanted each year.

The columns "Fertilizer" and "Pesticides" represent the energy costs linked to the production of these substances. These costs are indirect, but they will still be treated as direct costs. The application on the crop of fertilizer and pesticides is included in the "machinery" column (referred to as diesel in the study [84]). The latter column encompasses all costs related to the use of machinery for cultivation [85].

The energy consumption values listed in Table 11 for each crop will be summed, representing the aggregate energy consumption for both fuel and fertilizer (FF) within the model.

For the irrigated crops another component will be added to the total energy consumption. The irrigation energy consumption was derived from the study [84] and it was validated with two other studies [86] and [87].

In Table 12 is possible to see the values for the selected crops.

Table 12 - Irrigation energy consumption by each crop

Crop	Grape	Orange	Tomatoes	Lemon	Potatoes
Irrigation [ton/MWh]	46,02	5,57	9,58	8,67	7,37

The irrigation energy (IRR) will represent another factor besides the Fuel and Fertilizer inside the model.

The renewable resources modelled were solar photovoltaics and wind power.

As mentioned above, the following parameters were used to integrate these technologies into the model and characterise them: capacity factor, investment costs, fixed costs, and energy land consumption.

The capacity factor is strictly dependent on the characteristics of the terrain on which the technology is installed, and its description and calculation are explained in more detail in chapter 5.1.

4.4.2 Land data collection

For the land data collection was used a tool called QGIS.

QGIS, Quantum GIS, an open-source Geographic Information System, born in May 2002. The primary goal was to make GIS software accessible to anyone with a personal computer, in contrast to the traditionally expensive proprietary solutions.

The software is designed to be a user-friendly GIS system that encompasses essential functions and features. While its initial objective was to serve as a GIS data viewer, QGIS has evolved into a comprehensive tool used for daily GIS data visualization, data capture, advanced GIS analysis, and the creation of sophisticated maps, atlases, and reports [88].

Furthermore, QGIS supports a wide range of data formats from raster to vector data, and the architecture allows for easy integration of additional formats through plugins.

QGIS is distributed under the GNU General Public License (GPL). This open-source approach empowers users to inspect and modify the source code, ensuring that QGIS remains a freely accessible and customizable GIS program [88].

Before the collection of the land data the Pantelleria island administrative boundaries were downloaded using the Quick Open Street Map tool [89]. It is a free tool in Qgis. In Figure 21 is possible to see the Pantelleria boundaries map.

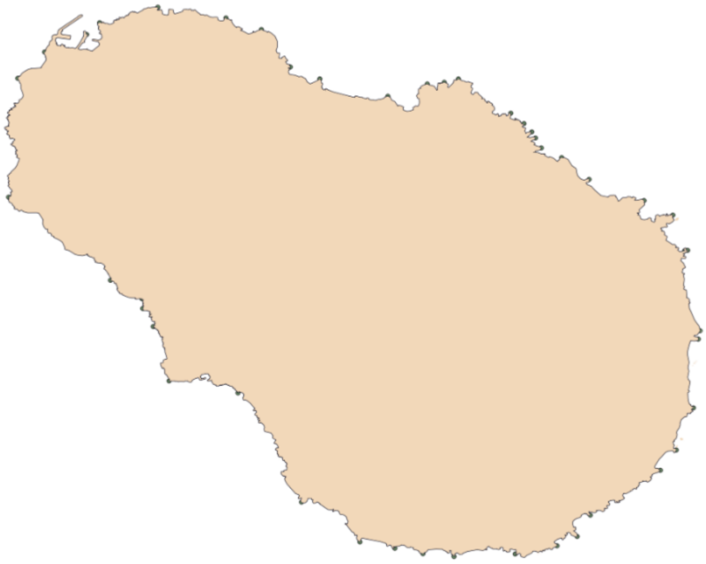


Figure 21 - Pantelleria boundaries by Open Street Map tool [89]

The altitude profile of the island was found in [90]. This site provides a very detailed Digital Elevation Model (DEM) of Italy with a 10 m-cell size grid in GeoTIFF format. In the Tiny Italy site, Figure 22, is possible to download only a portion of the country elevation model. For Pantelleria, since the island stands alone in the middle of the Mediterranean Sea, there was a dedicated square.

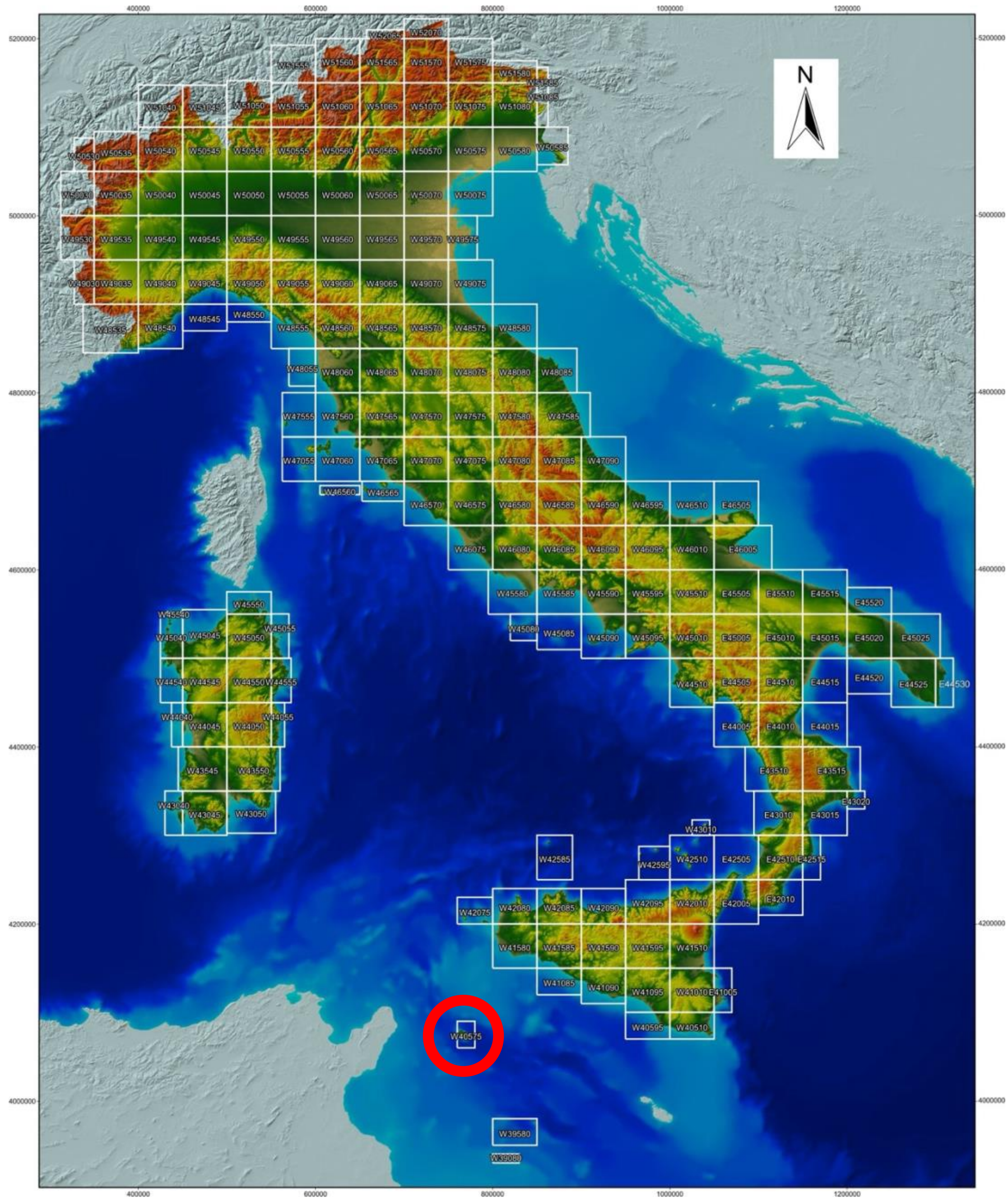


Figure 22 - Tiny Italy digital elevation model of Italy [90]

Once downloaded it was possible to add the elevation raster layer to the Pantelleria Qgis file and the results is showed in Figure 23.

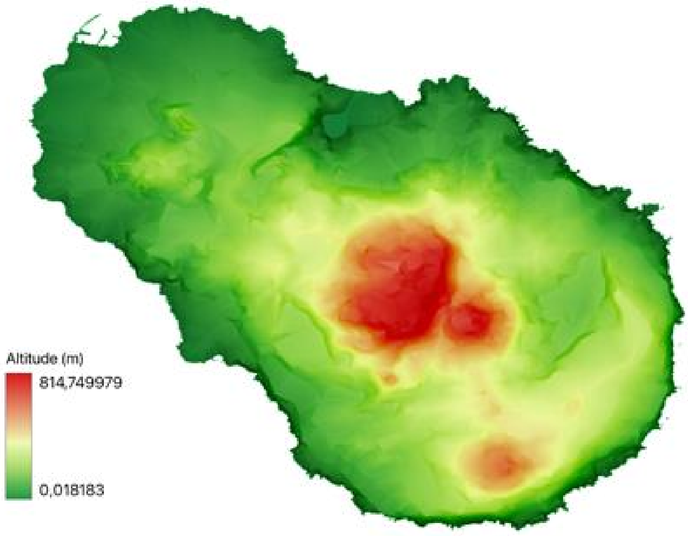


Figure 23 - Altitude raster map of Pantelleria

The slope of the island was calculated in QGIS thanks to the raster analysis function that permits the calculation of the slope starting from the digital elevation raster map of the island.
To analyse the altitude and slope of each particle of the island the two rasters needed to be converted into vectors. To do so it was used an algorithm called "Raster pixels to points", that converts a raster layer to a vector layer, by creating point features for each individual pixel's centre in the raster layer.

For the representation of the land type, Corine Land Cover 18 was used. The Corine Land Cover (CLC) [91] is a European system for land classification that provides detailed information on land cover and land use in Europe.
Its implementation involves a hierarchical classification of different types of land cover, divided into categories such as forests, urban areas, agricultural land, and water bodies, each one characterized by a number. This allows for a comprehensive and detailed understanding of the distribution of land cover in a specific area. The Figure 24 represents the corinne land cover map of Pantelleria with the associated number of each land type.

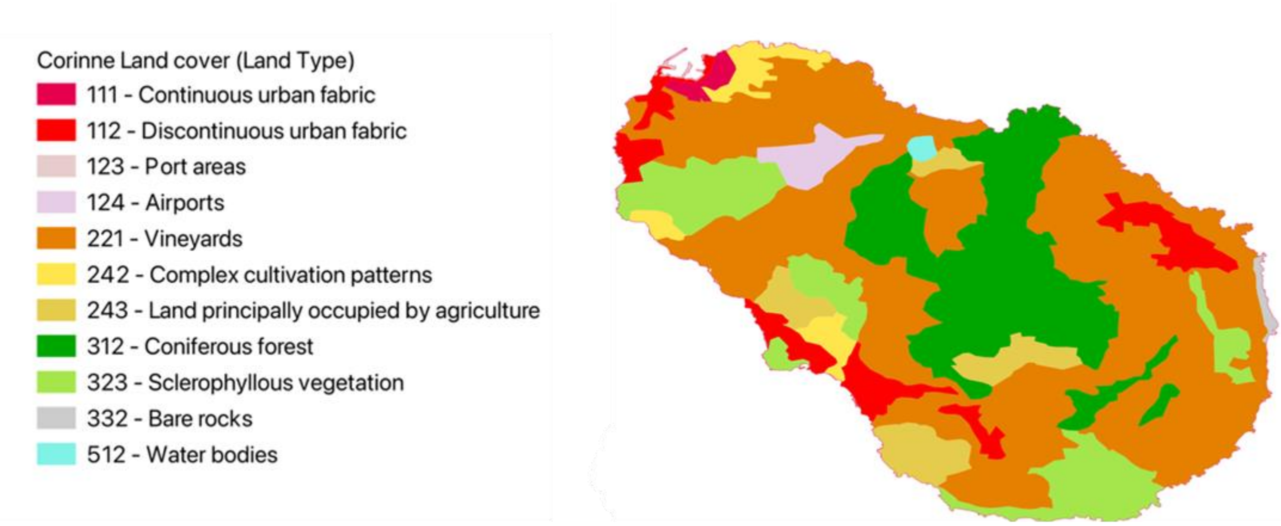


Figure 24 - Corinne land cover of Pantelleria Island [91]

The Global Horizontal Irradiation (GHI) is calculated using r.sun [92] based on the previously described DEM. "r.sun" is an irradiance model that computes direct (beam), diffuse, and reflected solar irradiation raster maps for given day, latitude, surface and atmospheric conditions. Figure 25 illustrates the annual global horizontal irradiation in Wh/m^2.

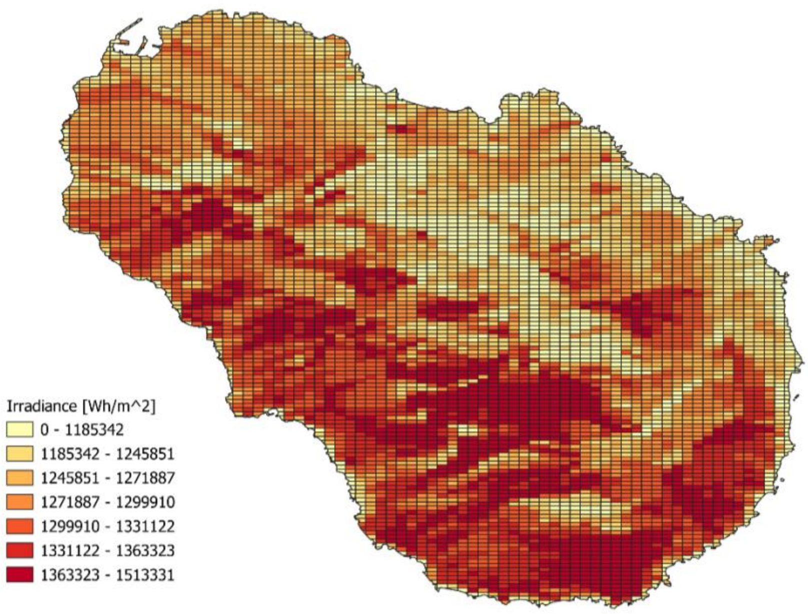


Figure 25 - Annual global irradiance on Pantelleria [92]

Since both irradiance and altitude are derived from a 10 m * 10 m DEM, the island has been divided with a grid where each cell has dimensions of 10x10 m and represents a value of irradiance, altitude, and slope in their respective layers.

Regarding wind productivity, it was extrapolated using the AEOLIAN web tool [93]. This software provides two types of data: the average annual wind

speed at various heights (50, 75, 100, 125, and 150 m above sea level) and wind productivity in MWh/MW at different heights (50, 75, and 100 m above sea level).
The map of annual specific productivity represents the average annual productivity of a wind turbine related to its rated power. This quantity (expressed in MWh/MWyear or simply hours/year) can be interpreted as the number of equivalent annual hours of operation of the wind turbine at its full rated power [94].

The calculation of productivity depends on wind speed, but its calculation is not limited to this factor. It is carried out using two curves:

- The wind speed distribution curve refers to the hub height of the wind turbine.
- The power curve of the wind turbine of interest is also typically expressed as a function of wind speed at the hub height [94].

In Figure 26 the wind average speed and producibility are shown. It’s observable how the largest share of average windspeed values is in the range of 8 m/s. Moreover, it’s also appreciable how by a proper selection of wind turbine there is no direct proportion between windspeed and producibility, since also the lower speed can be exploited by the right turbines.

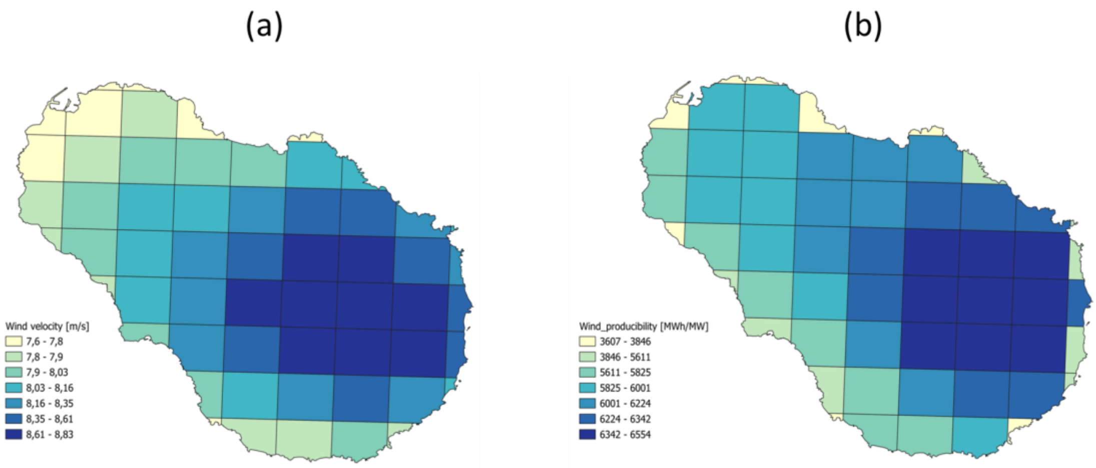


Figure 26 - Wind mean velocity (a) and producibility (b) for the Pantelleria Island.

The resolution of these maps, as easily noticeable from the grid in Figure 26, is with each cell having a size of 1 x 1 km. However, the data has been represented on a finer grid with a resolution equal to that used for solar irradiance, and the result is observable in Figure 27.

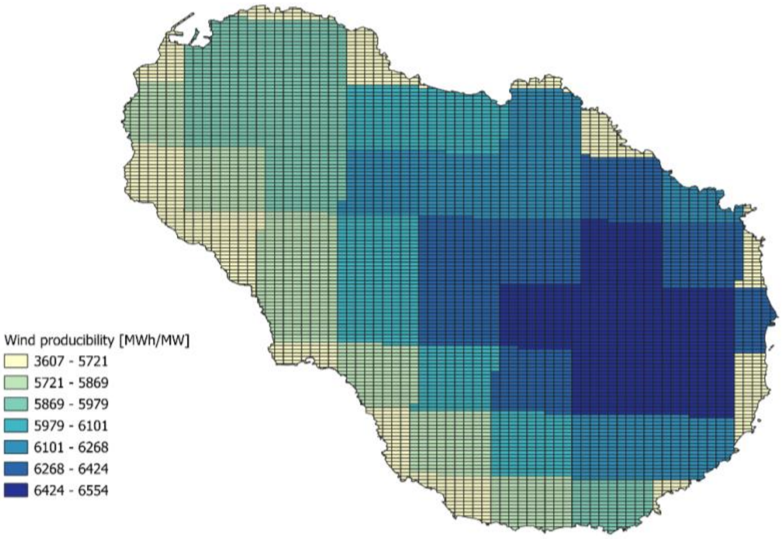
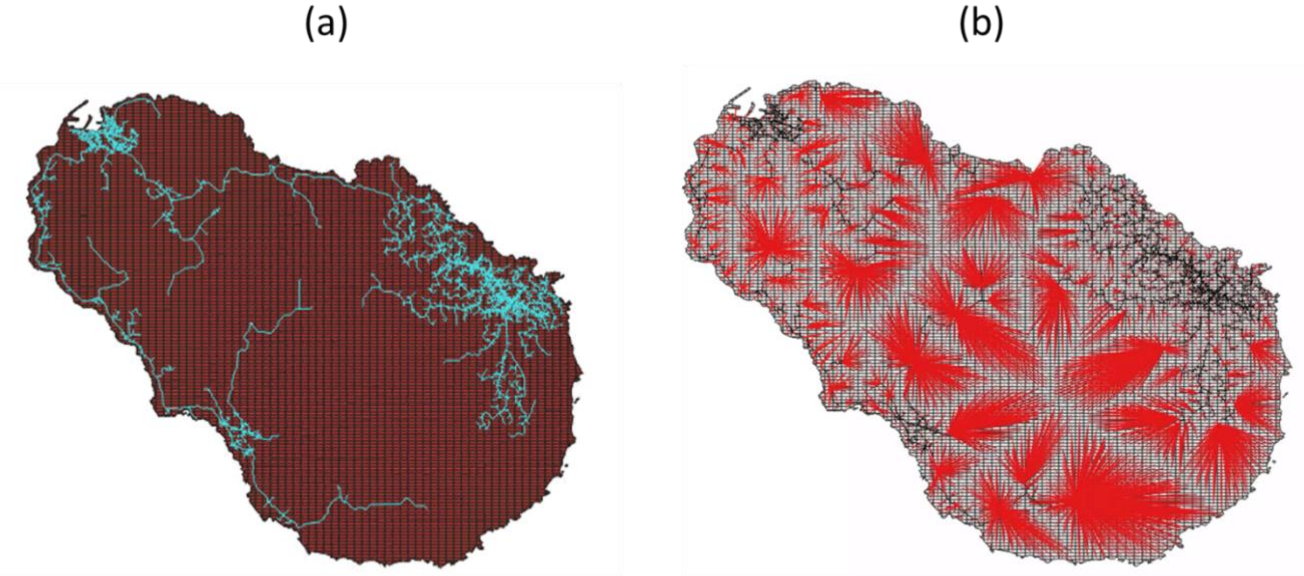


Figure 27 - wind producibility @100m map of Pantelleria with a finer grid

To determine the distance from the electricity distribution grid, the "Distance to Nearest Hub" tool in QGIS was utilized. After obtaining and integrating the Pantelleria electricity grid profile [95] into the QGIS environment, as depicted in

Figure 28 (a) , this tool was employed to calculate the distance of each grid



cell from the nearest point on the electricity grid, as illustrated in

Figure *28* (b).

Figure 28 - Electricity distribution grid map of Pantelleria (a) and Distance of each cell (red lines) from the electricity distribution grid (b) [95]

After integrating all the layers in QGIS, the data from each layer were merged into a unified table. This table comprises rows representing all the particles and columns containing the features of each layer, along with the coordinates of each cell.

Considering that the Wind Producibility layer has a lower resolution (1 km x 1 km instead of 10 m x 10 m), the productivity value in each cell of the wind layer was extrapolated to all the cells (10 m x 10 m) within that layer. Refer to Figure 27 for visualization.

Upon equalizing the resolution of all layers, their values were merged into a single table using QGIS's "Join Attributes by Location" tool. This tool assesses the spatial positions of particle values within each layer and consolidates them into a unified table.

4.5 Data transformation

The table, constructed at the end of Chapter 4.4, containing the values of each layer for every grid cell, is too large, exceeding 10,000 rows, for implementing the land characteristics into the TEMOA software, it is not feasible to input such many values for each attribute (such as Altitude, slope, etc.).

At this point, it is crucial to anticipate that the land characterization was conducted through specific attributes, such as Altitude, slope, and CLC for crops, while for renewable energies (RES), factors like Irradiance, wind producibility, CLC, and distance from the grid were considered. However, these factors will not be directly implemented in the software. Instead, they will be used to influence the attributes characterizing the technologies that will be implemented in the software, including crop yield and energy efficiency for crops, and the capacity factor for renewable energies.

This is justified by the need to have, as input for the next technological aggregation step, a reduced set of data to reduce the computational effort.

The land characteristics have been grouped into classes. This decision was made to ensure compatibility of the land characteristics with the integration into the TEMOA model.

To group land characteristics into classes, clustering is utilized.

According to the Webster dictionary [96], cluster analysis is defined as "a statistical classification technique for discovering whether the individuals of a population fall into different groups by making quantitative comparisons of multiple characteristics."

The [97] provides a more operational definition of clustering: "Given a representation of n objects, find K groups based on a measure of similarity such that the similarities between objects in the same group are high while the similarities between objects in different groups are low".

Currently, there are numerous types of clustering algorithms, which can be, according to [98], divided into hierarchical or partitional algorithms. Hierarchical algorithms discover clusters successively by building upon previously established clusters, while partitional algorithms identify all clusters simultaneously. Hierarchical algorithms can follow an agglomerative (bottom-up) or divisive (top-down) approach. Agglomerative algorithms initiate with each element as a distinct cluster and progressively combine them into larger clusters. Divisive algorithms start with the entire set and progressively partition it into smaller clusters [98].

The main algorithms in this context are hierarchical clustering, k-means and k-medoids algorithms, DBSCAN algorithms [99], and SNN algorithms [100].

Among the various algorithms proposed for clustering particles, two of the most widely used methods have been chosen: the k-means algorithm and hierarchical Clustering (Agglomerative).

4.5.1 K-mean

The k-mean method is the most famous and used between the clustering method [101].

According to Jyoti Yadav et al.[102] “K-mean is an unsupervised, non-deterministic, numerical, iterative method of clustering. In k-mean each cluster is represented by the mean value of objects in the cluster”.

In the k-mean method a set of n objects is organized into k clusters to minimize intercluster similarity and maximize intracluster similarity. Similarity is evaluated based on the mean value of objects within a cluster.

The steps to perform the k-mean algorithm are:

1. Set the desired number of clusters, k.
2. Randomly allocate a centroid to each of the k clusters.
3. Compute the distance of all data points to each of the k centroids.
4. Assign data points to the closest centroid.
5. Repeat steps 2, 3, and 4 until convergence is achieved.

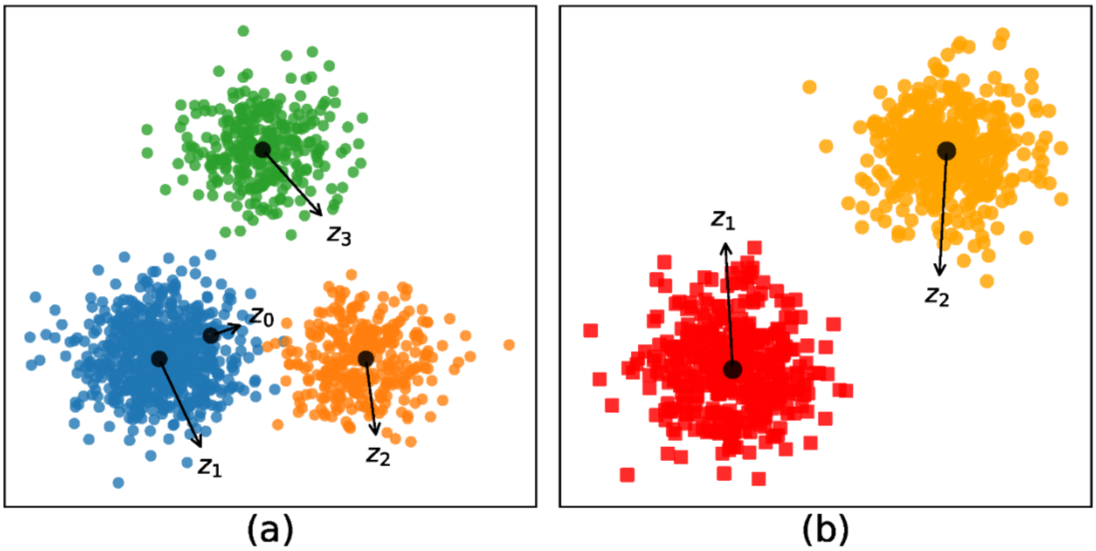


Figure 29 - k-mean cluster with distance from the centroid (z) [103]

To measure the "distance" of each point to the centroid is used, usually and in our case, the Euclidean distance.

The Euclidean distance is calculated as (5):

$$d(i,j) = \sqrt{(\sum_{i=0}^{n}(x_i - y_i)^2)} \qquad (5)$$

Where:

$i = x_i$ and $j = y_i$ are two n-dimensional data objects.

4.5.2 Hierarchical

Hierarchical clustering involves constructing a binary merge tree, beginning with the data elements stored at the leaves (interpreted as singleton sets) and proceeding to merge pairs of the "closest" subsets (stored at nodes) until reaching the root of the tree, which contains all the elements of X. The distance between any two subsets of X, known as the linkage distance, is denoted by Δ(X_i, X_j). This technique is also referred to as agglomerative hierarchical clustering because it starts from the leaves storing singletons (the x_i) and iteratively merges subsets until reaching the root [104].

The visual representation of the binary merge tree described above is called dendrogram, see Figure 30.

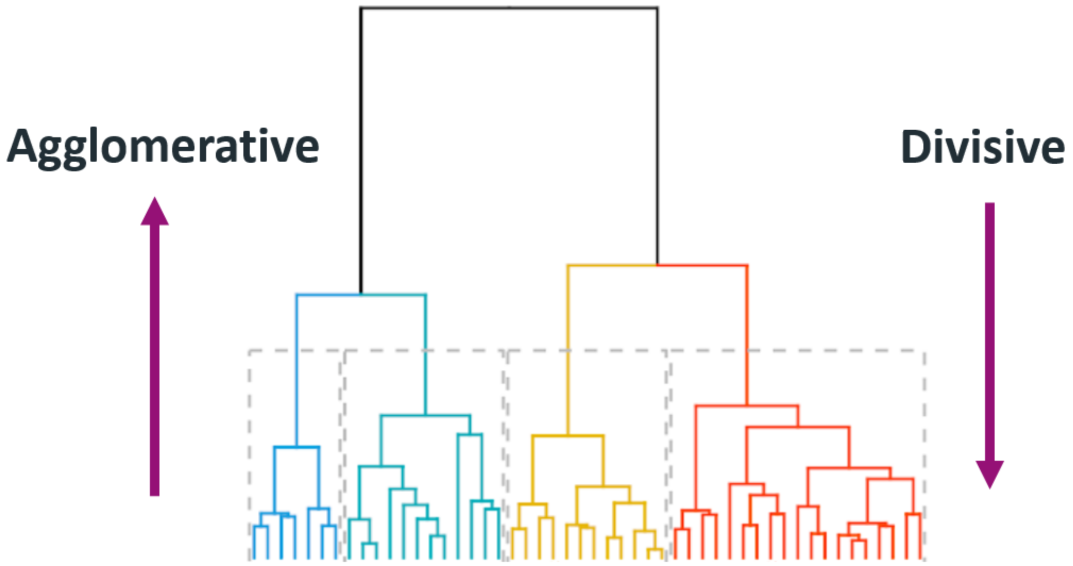


Figure 30 - dendrogram produced from hierarchical clustering [105]

The steps to perform hierarchical clustering to N data are:

1. Designating each data point as an individual cluster, resulting in N clusters, each containing a single data point.
2. Identify the closest (most similar) pair of clusters and merge them into a single cluster, reducing the total number of clusters to N-1. This merging process can be accomplished using different similarity measures.
3. Identify and merge the two closest clusters, reducing the number of clusters to N-2.
4. Repeat steps 2 and 3 until all observations are consolidated into a single cluster with a size of N [106].

A representation of the steps is proposed in Figure 31.

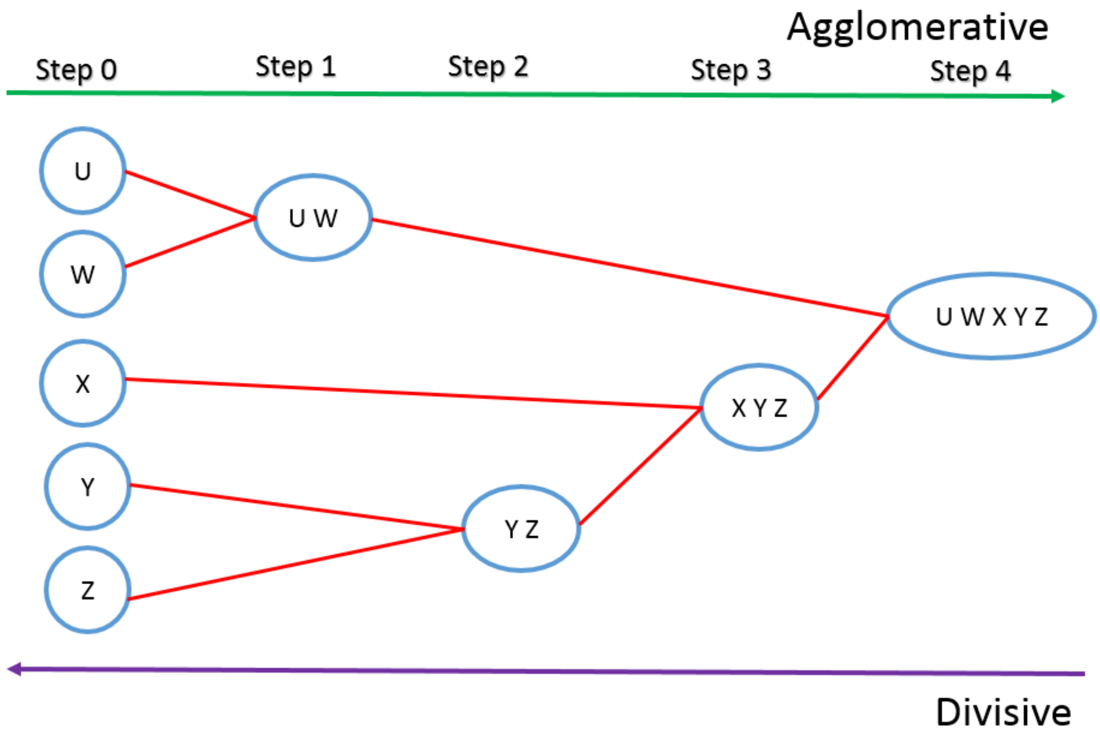


Figure 31 - Steps to build the cluster, hierarchical agglomerative clustering [105]

To find the closest/most similar element to group there are different approaches the most common are:

- Euclidean Distance
- Manhattan Distance
- Minkowski Distance

The major advantage of hierarchical clustering lies in the utilization of the dendrogram. In fact, the use of the dendrogram offers two significant benefits:

- There is no requirement to pre-specify the number of clusters. Instead, the dendrogram can be cut at the appropriate level to obtain the desired number of clusters.
- Data can be easily summarized and organized into a hierarchy using dendrograms. Dendrograms simplify the examination and interpretation of clusters [107].

Silhouette score

To calculate the optimal number of clusters for the k-means method, the silhouette score was used.

The Silhouette Score is a metric to evaluate the effectiveness of clustering outcomes by offering a quantitative measure of the clarity and distinctiveness of clusters. This score quantifies the degree to which a data point aligns with its assigned cluster and how different it is from other clusters. It assesses the cohesion and separation of data points within clusters, aiding in the determination of whether clusters are well-defined and internally homogeneous [108].

The silhouette score is numerical measure within the range of -1 to 1.

- A score of 1 indicates well-separated and clearly distinguished clusters.

- A score of 0 suggests indifference among clusters, indicating that the distance between them is not significant.

- A score of -1 implies that clusters are incorrectly assigned.

It is calculated as (6)

$$Score = \frac{\sum_{i=1}^{n}(\frac{\max(a_i, b_i)}{b_i - a_i})}{n} \tag{6}$$

Where:

- a_i is the average distance from data point i to all other data points within the same cluster (intra-cluster distance)
- b_i is the average distance from data point i to all data points in the nearest cluster (inter-cluster distance) [108]
- n is the number of clusters

In Figure 32 the distances used in the calculation of the silhouette score are represented.

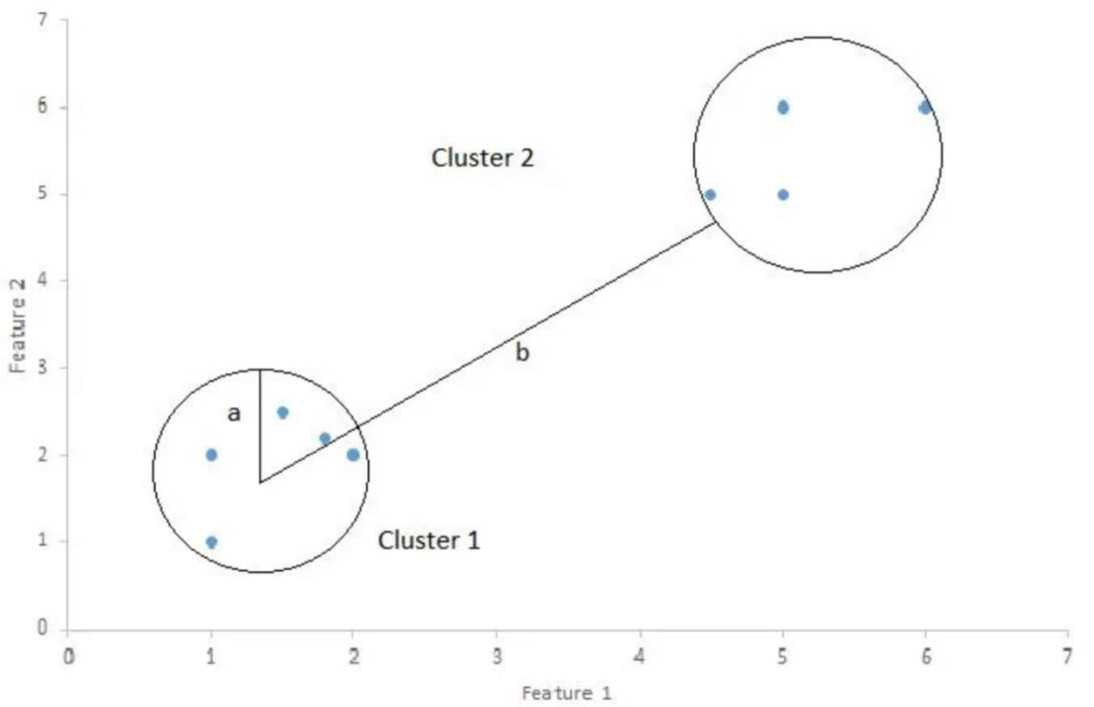


Figure 32 - Representation of the distances used in the silhouette score calculation [108]

4.5.3 Clustering

Similarly, to the crop yield calculation process described in Chapter 4.4.1, for this section, the Jupyter Notebook tool was used to perform data clustering.

Given the lack knowledge about the optimal number of clusters to divide the particles into, several clustering attempts were made, which will be detailed in this section.

In all the attempts, the following factors were considered as distinguishing attributes of the particles:

- Annual solar irradiance
- Wind producibility at 100m above sea level
- Altitude
- Geographic coordinates
- Slope
- Distance from the power grid

The K-means clustering method was applied, and through the analysis of the silhouette score for various cluster configurations a particularly low silhouette score was observed regardless of the number of clusters, as clearly depicted in Figure 33.

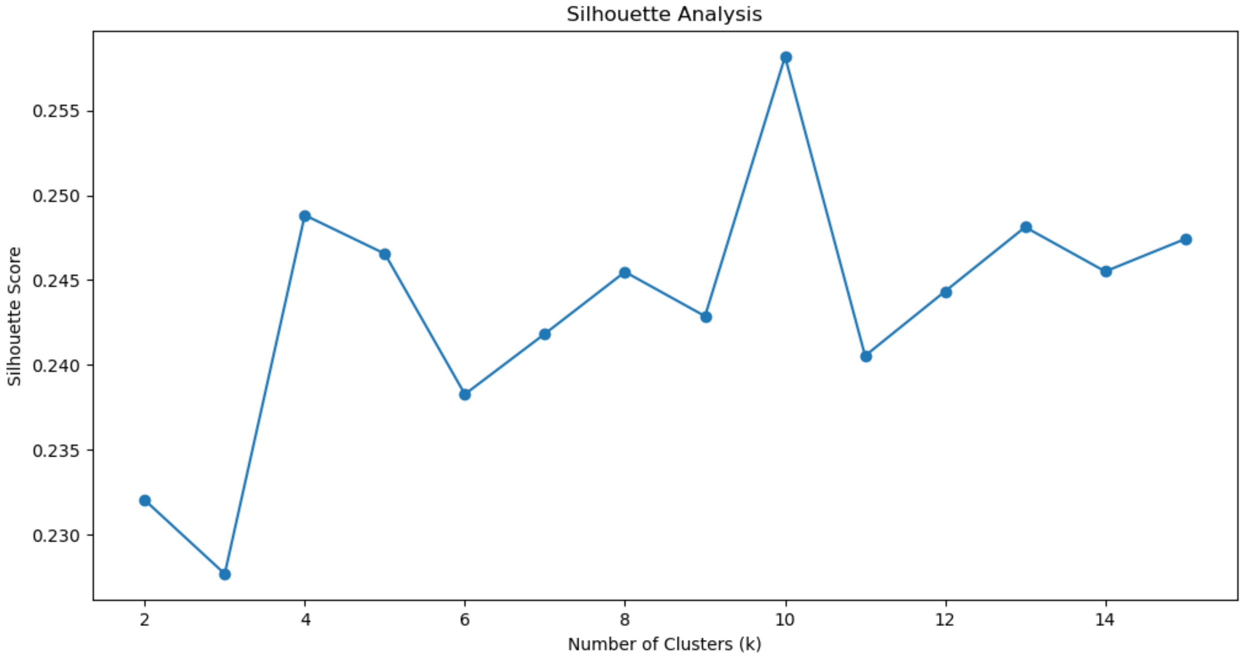


Figure 33 - Silhouette score of the k-mean clustering

As appreciable by Figure 33, the optimal number of clusters turned out to be 10, with a silhouette score of 0.258.

On the other hand, by implementing the hierarchical algorithm, a significantly higher silhouette score of 0.654 was achieved for a cluster number of three.

In Figure 34 and Figure 35, a graph illustrating the silhouette score and the dendrogram can be observed.

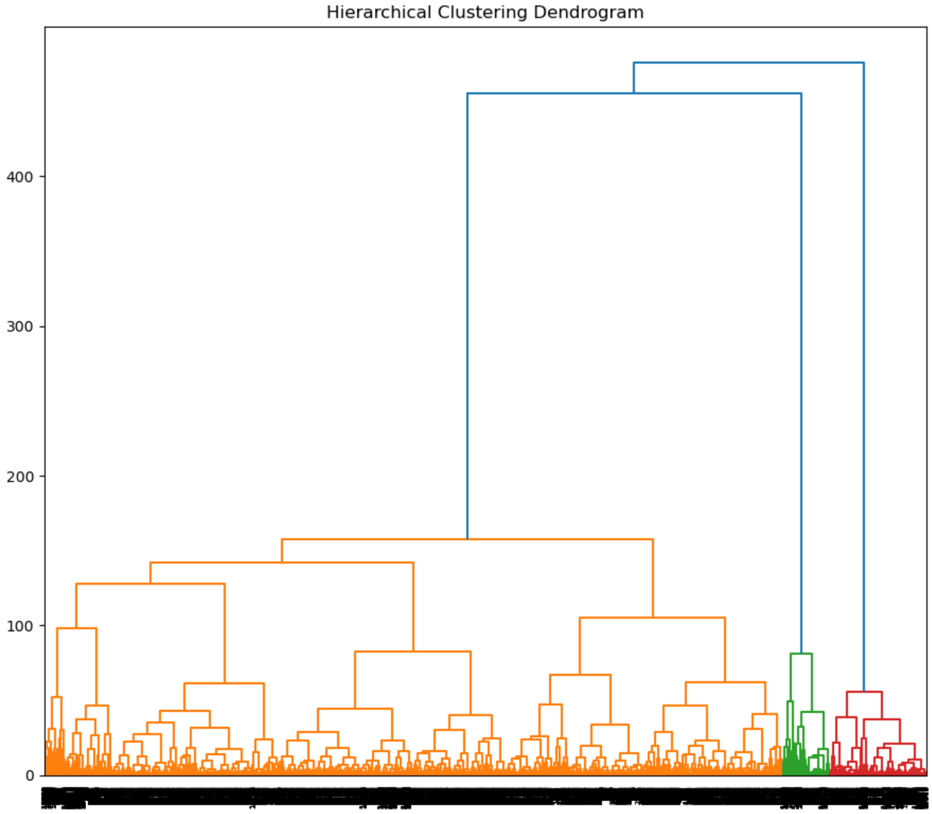


Figure 34 - Dendrogram of the hierarchical clustering

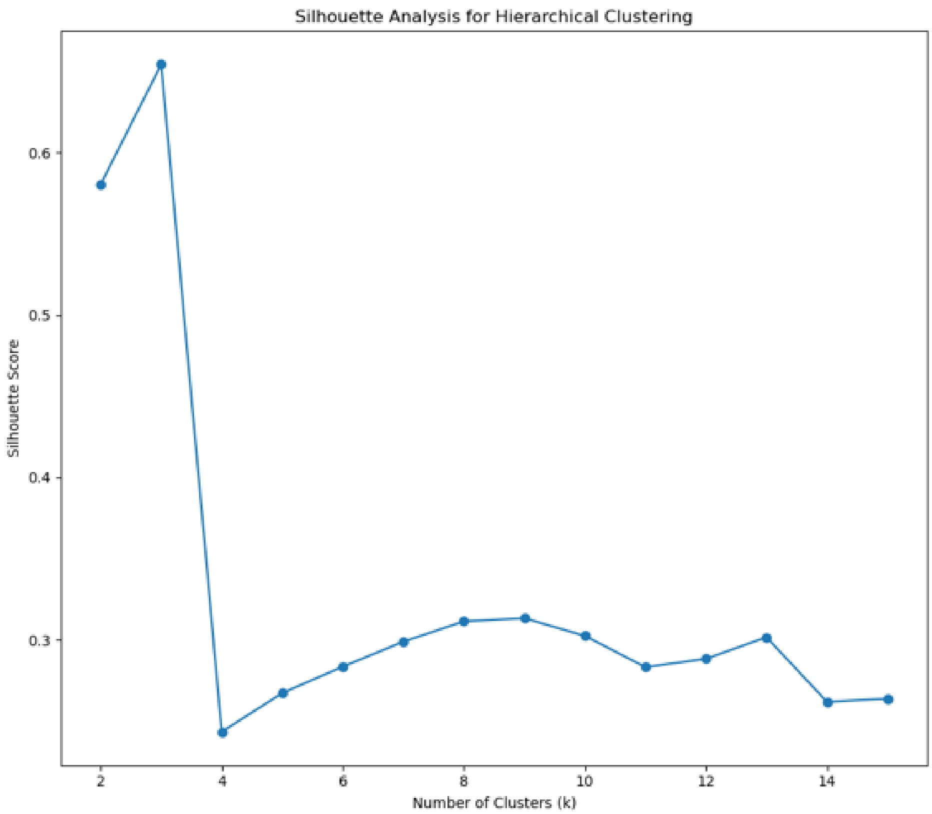


Figure 35 - Silhouette score of the hierarchical clustering

Three clusters Island divsion

After identifying the optimal number of clusters, which is 3, the particles were aggregated by calculating the mean values of each particle property within each cluster, excluding the coordinates. To provide a visual representation of the clusters, a column was added to each particle to identify its membership in a specific cluster.

In Figure 36, it is possible to observe the representation of the island of Pantelleria divided into 3 clusters, with each colour representing a distinct cluster.

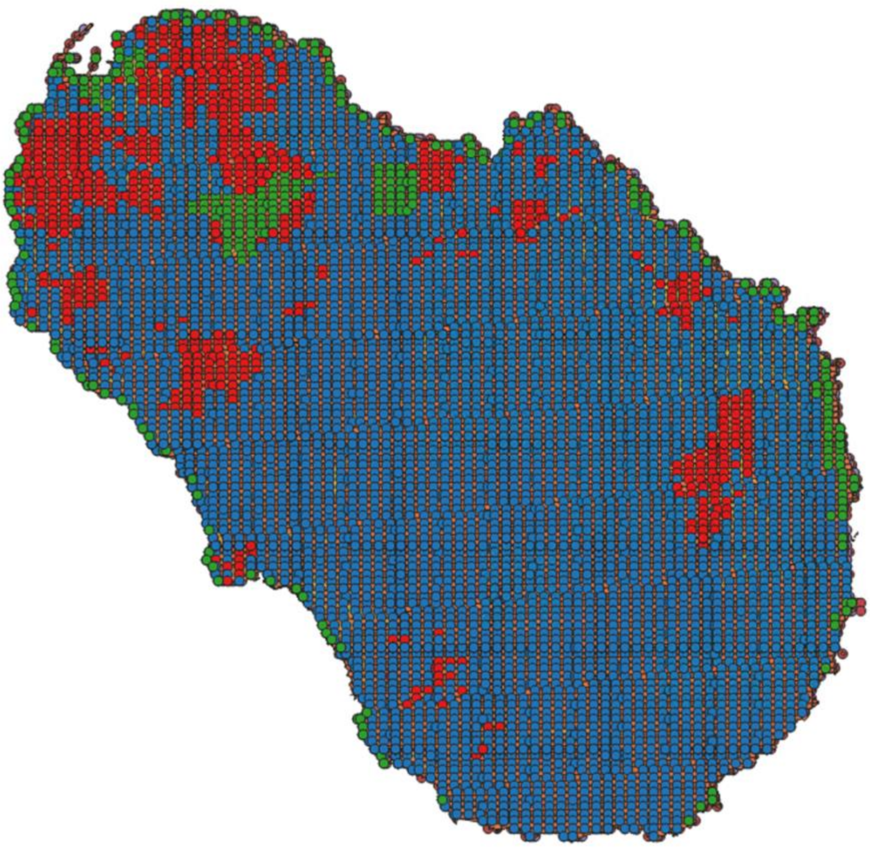


Figure 36 - Pantelleria division in three clusters (blue, red and green)

As highlighted in Figure 36, dividing the island of Pantelleria into three clusters would be overly simplistic, resulting in a significant loss of information regarding altitude and slope. Specifically, since one cluster would represent a non-cultivable area (green cluster) and another cluster would occupy most of the island (blue cluster), the characteristics of the technologies to be implemented in TEMOA would become too similar, undermining the purpose of the work carried out.

The decision to adopt three clusters has therefore been abandoned and a more suitable alternative has been tried.

Nine clusters Island division

Reanalysing the silhouette scores of both the k-means method (Figure 33) and the hierarchical method (Figure 35), it was observed that, despite the consistently low silhouette scores for any number of clusters, the option with 9 clusters (hierarchical method) yielded the highest silhouette score.

Therefore, the same parameters as the previous attempt were used, and the result of this second attempt at clustering the particles is represented in Figure 37.

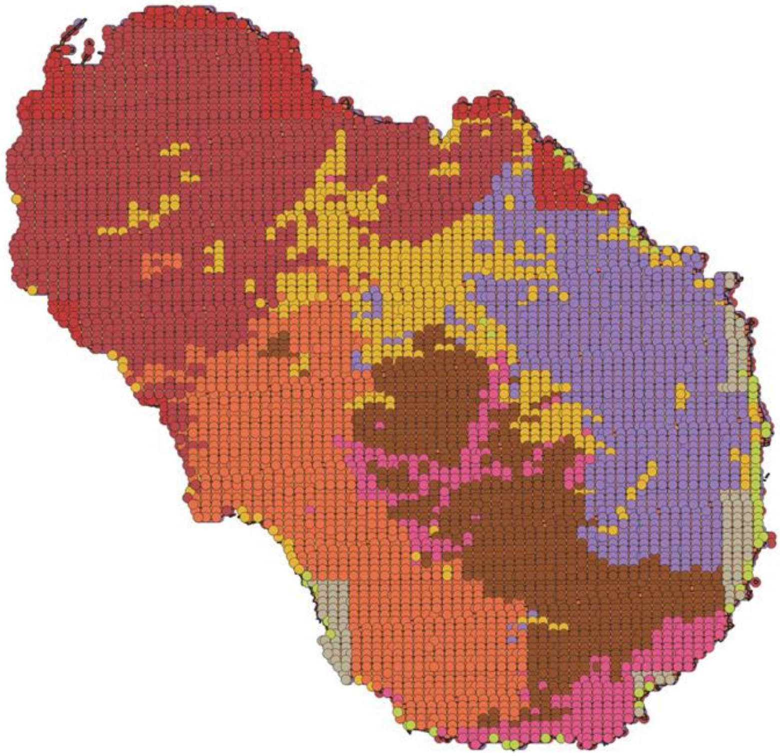


Figure 37 - 9 cluster division of Pantelleria island.

Examining the graphical representation of the various clusters and the average values of each characteristic (such as Altitude, Slope, Irradiance, etc.), it was observed that this clustering attempt led to very scattered and disorganized clusters. Additionally, no logical connection with CLC18 emerged, and the characteristics of each cluster appeared remarkably like one another. No significant distinctions were identified between potentially irrigable and non-irrigable clusters, or between clusters with high and low irradiance. Consequently, this second option was also discarded.

Five cluster Island division

The first attempt, adopting 3 clusters proved to be excessively limited. In the second attempt, with 9 clusters, the opposite occurred: the high number of clusters resulted in lacking unique characteristics, making them essentially similar to each other. Additionally, except for 3 clusters, the silhouette score consistently remained low.

The final decision was to embrace an intermediate approach between the first two attempts, opting for 5 clusters as depicted in Figure 38. In this case, the silhouette score for the K-means method is 0.247, while for the hierarchical method, it is 0.267. The preference was given to the hierarchical method due to its slightly higher silhouette score.

Figure 38 represents the island of Pantelleria divided into 5 clusters.

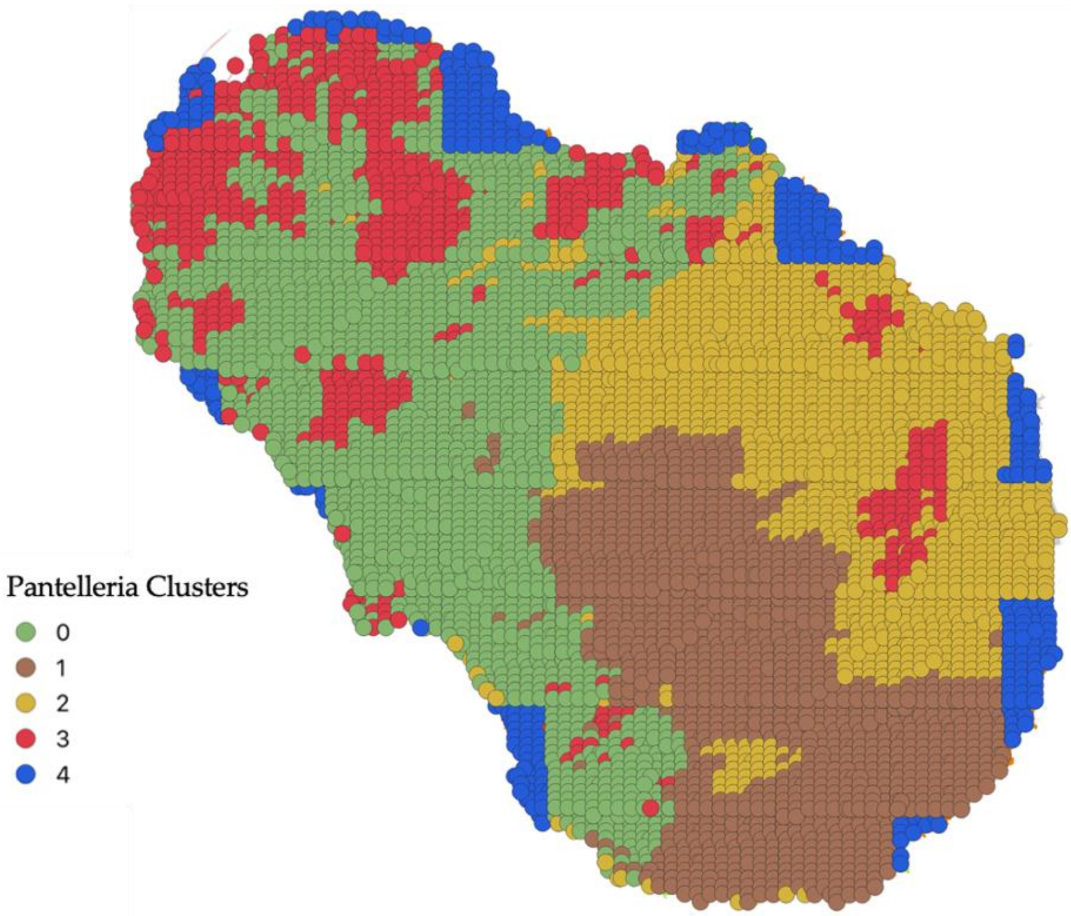


Figure 38 - 5 Cluster division of Pantelleria before the manual manipulation of the cluster

After analysing the 5 clusters, it was observed that cluster 4 (depicted in blue in Figure 38) is characterized by values of slope, CLC, irradiance, and wind producibility that make it impractical the installation of technologies in this cluster. As for cluster 3 (depicted in red in Figure 38), it exhibited altitude and slope values that qualify it as irrigable land.

To make the subdivision even more accurate and realistic, clusters 3 and 4 were manually manipulated. This manipulation was performed to designate Cluster 3 as irrigable, and Cluster 4 as completely excluded from the installation of any technology.

In cluster 3, only particles exhibiting the following characteristics were included:

- Slope <= 5°
- Altitude <= 200m
- CLC within:
    - Vineyards
    - Complex cultivation patterns
    - Land principally occupied by agriculture
    - Sclerophyllous vegetation

The threshold values for slope and altitude for irrigable land were determined based on the limits observed in Sicily beyond which irrigated lands are not present. Regarding the land type in CLC, these types of terrain can feature cultivated lands according to the CLC [91].

In Cluster 4 have been included all particles with a CLC18 land type among the following:

- 111 – Continuous urban fabric
- 112 – Discontinuous urban fabric
- 123 – Port areas
- 124 – Airports
- 332 – Bare rocks
- 512 – Water bodies

In these types of terrain according to Dodge et al. [109], none of the technologies considered by this thesis can be installed.

Pantelleria Island is thus divided into 5 clusters, each with distinct characteristics, including three simply cultivable, one cultivable and irrigable, and one non-cultivable (see Figure 39).

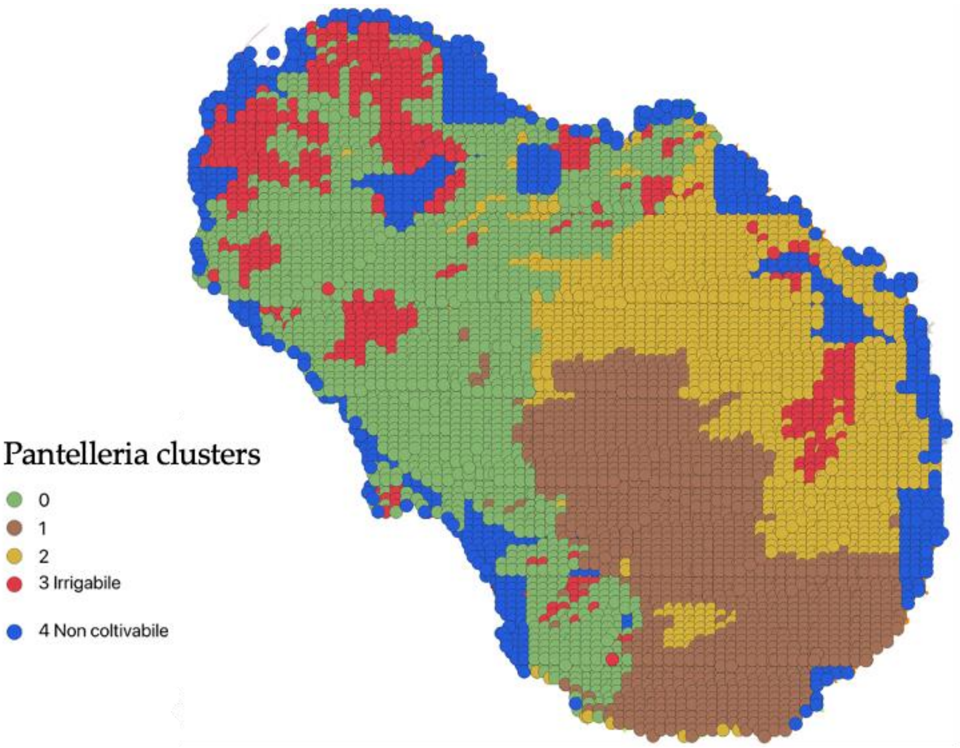


Figure 39 - Cluster division of Pantelleria after the manual manipulation of the cluster

In the following table, Table 13, the characteristics of each cluster are reported.

Table 13 - Cluster characteristics

Cluster	Area [km²]	Yearly irradiance [MWh/km²]	Wind Prod. @100m [MWh/MW]	Slope [°]	Mean hub distance [m]
0	24,87	1,29	5927	9,73	540
1	19,00	1,35	6197	16,18	1261
2	18,53	1,22	6339	13,52	335
3	8,49	1,29	5992	3,69	370
4	13,64	1,24	5115	11,98	343

As can be observed from the table, in addition to clusters 3 and 4, respectively irrigable and non-cultivable, the slope and altitude characteristics differ among the other three clusters, as do the values of wind prod and distance from the grid. Therefore, in the upcoming chapters, it will be possible to influence and modify the crop yield and energy yield based on the cluster on which each technology will be installed.

5 Model configuration

5.1 Land-use sector implementation in TEMOA

Following the data aggregation process is now possible to implement the land use sector into the model.

As previously anticipated, the land characteristics aggregated in each cluster cannot currently be implemented in the model. The model lacks parameters that characterize the specific spatial features of the land. This implies the need to make modifications to the TEMOA code to incorporate the concept of "land area" and to define how this area may be utilized by the technologies.

In the current model formulation, there are no sets suitable for describing land as a natural resource. It would be inappropriate to model the land consumed by plant installations as a commodity, for two main reasons. First, a commodity typically denotes something exchanged between processes as input or output. However, in this context, the role of land is to host its associated technology (under certain conditions of capacity factor and cost) for the lifetime of the technology. Second, commodity consumption is usually linked to the activity of a plant, involving efficiency considerations (e.g., natural gas consumption proportional to the activity of a combined cycle plant). In the case of land, consumption occurs when new capacity is installed and becomes available again once the installed technology on that land reaches the end of its lifespan. As outlined in (7) and (8) the new TEMOA set is referred to as "Land Cluster," and it is associated with a "Land Area" value, describing the available area for the land cluster "l".

$$Set = Land\ Cluster\ (LC) \tag{7}$$

$$Attribute = Land\ Cluster_l \tag{8}$$

It is also needed to incorporate into the model a novel parameter and corresponding constraint, establishing a connection between the installation of new capacity and land utilization. As illustrated in (9), the Land Use Intensity (LUI) parameter serves as a pivotal link, connecting land clusters "LCi" with the associated technologies "j." It quantifies the land requirements for deploying a unit of technology, such as a megawatt of wind or solar power or kilograms for crops. The LUI parameter ensures that the model's solutions not only optimize economic considerations but also considers spatial feasibility. The absence of an LUI for a particular technology in each land cluster indicates that the technology cannot be installed in that cluster, thereby introducing a direct spatial constraint into the optimization process.

$$LandArea_{LCi} \geq \sum_{j=1}^{n} Capacity_{T_j} * LUI_{i,j} \tag{9}$$

After the definition of this new parameters, it is now essential to characterize both energy technologies and crops based on the cluster where they are installed. This process will enable the model to consider the distribution of resources and territorial constraints more accurately in its predictions and decisions.

To adapt the technology characteristics to each cluster, it was necessary to create a specific technology for each cluster. In this case, we transition from a single technology for example solar panels to five technologies (e.g., PV_LandCluster1, PV_LandCluster2, etc.). Regarding crops, these should also be distinguished between irrigated and non-irrigated crops. In this case, we transition from a single technology, for example, grape, to 10 technologies for crops (e.g., Grape_Irrigated_LandCluster1, Grape_NonIrrigated_LandCluster1, ..., Grape_Irrigated_LandCluster5, Grape_NonIrrigated_LandCluster5).

Crop characterization

As previously said the crop will be characterized by the following characteristics:

- Crop yield
- Energy consumption for cultivation
- Machinery
- Fertilizers
- Energy consumption for irrigation
- Economic output

  Their adaptation to each cluster is reassumed in Table 14.

Table 14 - Technologies modification based on the cluster on which are installed

	Cluster n.0	**Cluster n.1**	**Cluster n.2**	**Cluster n.3**	**Cluster n4**
Mean altitude [m]	160,44	391,26	267,54	108,84	97,04
Mean slope [°]	9,73	16,18	13,52	3,685	11,98
Non-irrigated crop yield [kg/m^2]	Standard Value	-30%	-15%	Standard Value	/
Irrigated crop yield [kg/m^2]	/	/	/	Standard Value	/

The crop yield of each crop will be influenced by the cluster in which it is installed. Indeed, crops cultivated on more hostile terrains (at higher altitudes and with steep slopes) will be less performant compared to those cultivated on flat terrain.

The crops installed on cluster 1, with higher values of altitude and slope, will have a crop yield lowered by 30%. In this cluster, it will not be possible to install irrigated technologies.

The crops installed on cluster 2 will instead have a decreased crop yield by 15%, and once again, irrigated technologies cannot be installed.

Crops installed on clusters 0 and 3 will have a standard crop yield for non-irrigated crops, and cluster 3 is the only one where irrigated technologies can be installed.

Irrigable crops will have higher energy requirements because they are the only ones that present energy consumption for irrigation. However, they will also have a higher crop yield due to greater water availability for cultivation, as shown in Table 10.

The crop yield of each technology will be added to the model as LandUseIntensity, so each crop technology will have a LUI value that will be the reciprocal of the crop yield calculated in (10).

$$LUI_{crop} = \frac{1}{crop\ yield} \left[\frac{m^2}{kg}\right] \tag{10}$$

The LUI is multiplied by the capacity, see Equation (9), which in the case of crops is represented by the amount of crop installed [kg].

Crops, once produced, are sold, representing a profit for the system rather than an expense. Therefore, they have been characterized by a negative variable cost that impacts the objective function, reducing it.

Energy characterization

In ESOM, technologies are characterized by attributes regarding their costs and their potential. As highlighted by Moscoloni et al. [110], the correct estimation of the renewable energy potential for a specific region passes through the analysis of five components:

- Theoretical potential: the amount of energy that is physically usable in each region and over a given period.

- Geographic potential: the area available for energy production, considering constraints such as protected natural areas and other land uses such as urban structures and transportation routes.
- Technical potential: the amount of capacity that can be installed under technical constraints in each region and over a given period.
- Economic potential: the technical potential that can be realized economically in each region and in each time period.

The primary focus of this work is to assess the production potential of renewable energy sources, specifically photovoltaic and onshore wind technologies, without delving into the economic and technical aspects of PV plants. These aspects are already integrated into the TEMOA-Pantelleria database. The analysis is limited to these two technologies due to their significant role in both regional and national energy scenarios and their high land use intensity compared to other energy sources like hydro, biomass, or gas. In this context, the potential assessment phase aims to combine the energy potential with the land consumption of these technologies, highlighting the direct correlation between increased productivity and land usage in the case of wind and photovoltaic energy sources.

Among these factors only the Capacity factor has been the only one dependent from the land characteristics. The efficiency, or the energy production of a technology can vary based on the specific region of the island where it is installed. The capacity factor depends strongly on the annual solar irradiation for the solar photovoltaic systems and from the wind producibility for the wind turbines.

The capacity factor for each cluster is calculated using the following formula (11):

$$CF_{PV,i} = \frac{AEP_{PV,i}}{P_{PV,rated} * T} \tag{11}$$

Where:

- $P_{PV,rated}$is the power density of the solar PV system. In this study, we utilized a value of 32 MW/km2 for a fixed-tilt utility-scale solar system using monocrystalline silicon cells, the most common in the current market [87].
- T are the total number of hour in a year equal to 8760
- $AEP_{PV,i}$ is the Avarage Energy Production of each cluster and is calculated as in (12):

$$AEP_{PV,i} = \frac{GHI_i * \eta_{PV} * PR * A_{PV,i}}{SF} \tag{12}$$

Where:

- GHI_i represents the average annual global horizontal irradiation (kWh/m2/year).
- $A_{PV,i}$ indicates the area of the cluster 'i' suitable for PV implementation (m^2).
- η_{PV} represents the efficiency of the PV module in converting sunlight to electricity, with an assumed value of 21%.
- PR denotes the performance ratio for the solar module, set at 0.85. This ratio accounts for the disparity between performance under standard test conditions and the actual system output, factoring in losses due to conduction and thermal effects.
- SF is the spacing factor or the ground cover ratio for the PV system, indicating the ratio of the total land requirements to the actual surface area covered by PV panels. In our calculations, we assumed a value of 5 [87].

The capacity factor is therefore modelled for each PV technology based on the cluster in which it is installed.

Wind

The capacity factor for the wind turbines is calculated as in (13):

$$CF = \frac{prod_{100}}{T} \tag{13}$$

Where:

- T are the hour in a year equal to 8760
- $prod_{100}$ represents the wind turbine producibility, as explained in Chapter 4.4.2.

The capacity factors of PV and Wind turbines are reported in Table 15.

Table 15 - Capacity factors for RES technology for each cluster

Technology	Capacity Factor
PV_Cluster 0	0.355
PV_Cluster 1	0.328
PV_Cluster 2	0.334
PV_Cluster 3	0.190
PV_Cluster 4	0
Wind_Turbine_Cluster 0	0.677
Wind_Turbine_Cluster 1	0.707
Wind_Turbine_Cluster 2	0.724
Wind_Turbine_Cluster 3	0.676
Wind_Turbine_Cluster 4	0

5.2 Model calibration

To calibrate TEMOA-Pantelleria, an alignment between the model and historical data from 2014 to 2022 is necessary. Unfortunately, comprehensive data is not available for all the milestone years. The energy consumption and production data for Pantelleria are only accessible for the year 2018 [75],[111]. Despite the limited data, efforts were made to calibrate the model using the available information.

RES calibration

In line with the Pantelleria Agenda [75], the electricity generation on Pantelleria in 2018 was facilitated by the diesel plant, distributed photovoltaic systems, and mini and micro wind plants. Table 16 illustrates the installed capacities of these power plants. All these data have been incorporated into the TEMOA framework as constraints.

Table 16 - 2018 Power plant capacity in Pantelleria island

Power plants capacity [MW]	
Diesel power plant	23
Photovoltaic plants	0.72
Wind plants	0.03

Crop calibration

Regarding crops, since only vineyards are present in Pantelleria, it was chosen to calibrate the model by imposing an initial share for each crop modelled (even the one not originally present in Pantelleria). Indeed, aim of this analysis is to test model capability in terms of land use and energy sector combined optimization. Therefore, a minimum of technological diversity is necessary. The distribution of crops was selected based on the share of the same crops on the island of Sicily. The minimum share was then defined according to the values in Table 17Table 17, still allowing the model some flexibility to optimize crop selection.

Table 17 - Minimum crop production share

Minimum crop production share [%]	
Grape	24
Tomato	4
Lemon	9
Orange	23
Potato	3

For the future years, the model was free to optimise the use of land for crop production and also for RES installation maximising the objective function and so the economic return. A small amount of grape production, equal to 10% of the total crop production, was imposed on the model throughout the simulation to make land use on Pantelleria slightly more realistic. It is important to note that currently, on the island of Pantelleria, the agricultural sector consists solely of vineyards and capers, with a majority of the former.

6 Results

Once the land use sector was integrated into TEMOA, energy and land use sector were checked to understand how the model optimizes crop production and the installation of renewable energy systems (RES) on the land of Pantelleria. This section will explore how the model manages land use, how and where it decides to install RES and will analyse the results obtained in terms of agricultural production and energy output.

In Figure 40, the electricity production from the power plant present in Pantelleria island is plotted through the years.

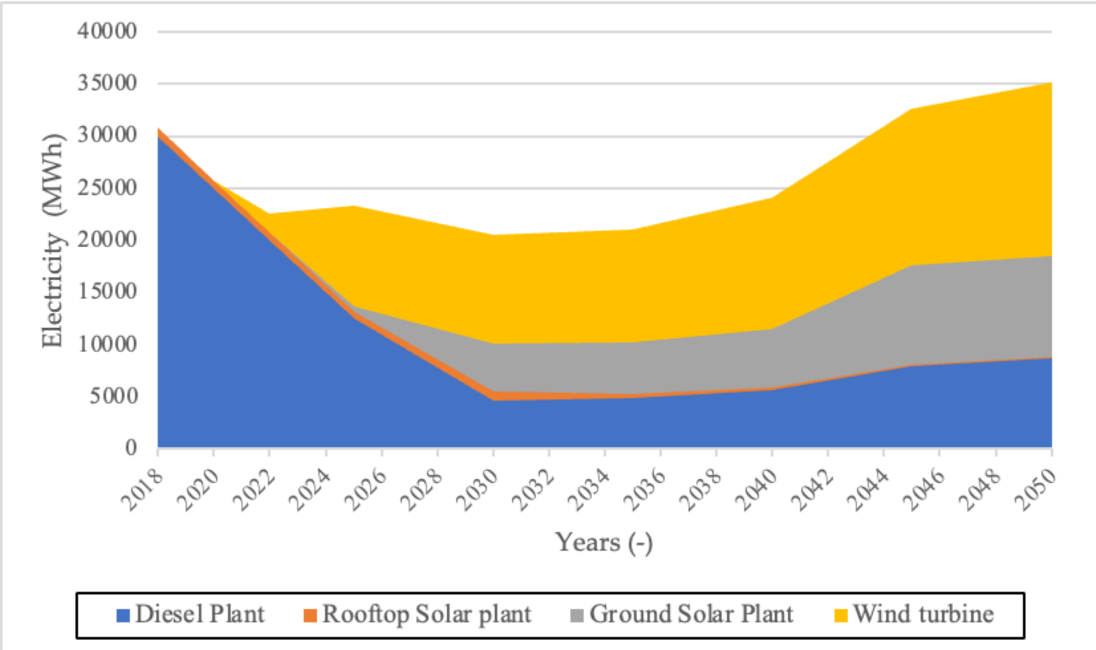


Figure 40 - Electricity production by technologies

It can be observed from Figure 40 that electricity generated from fossil fuels tends to decrease in the first 10 years, until 2030, and then stabilize in the following years. The diesel turbine remains operational as a base load until the end of the simulation. This happens because the island requires a constant and consistent supply of electricity that renewable energy sources (RES) may not always be able to provide. Numerous services depend on an uninterrupted and reliable supply of energy, one that remains unaffected by weather conditions.

Renewable resources, on the other hand, increase their share over the years. Wind energy is the most utilized, given the high wind productivity on the island, followed by ground-mounted solar power plant, with only a very small percentage of solar panels installed on rooftops.

From 2040 onwards, there is an increase in electricity demand. This phenomenon is attributed to the increased production of drinking water through declinators. The model chooses to increase the desalination, as shown in Figure 41, leading to a consequent increase in energy demand, while decreasing the quantity of water imported to the island.

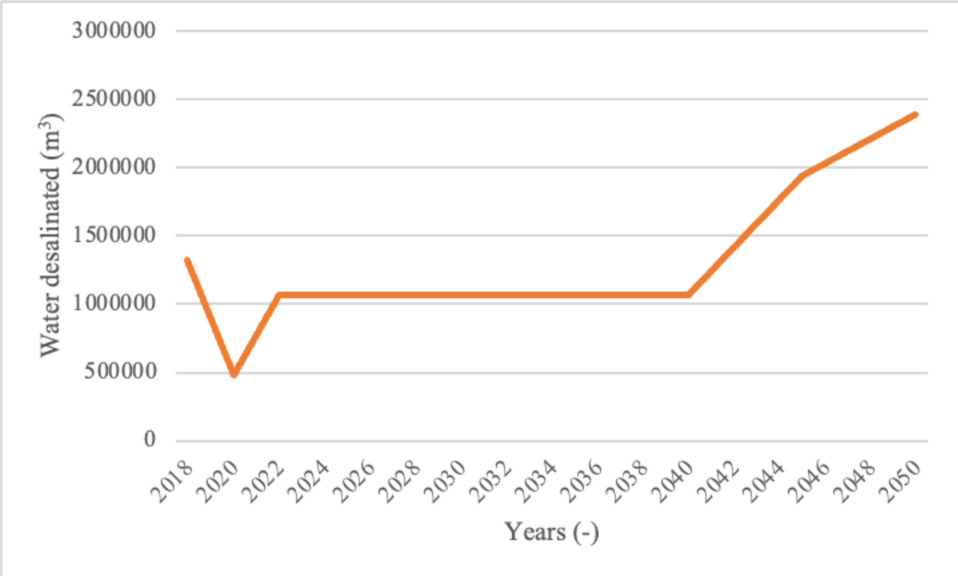


Figure 41 - Water desalinated through the years

In Figure 42, the upstream sector composed by all the imported fossil fuels is observable.

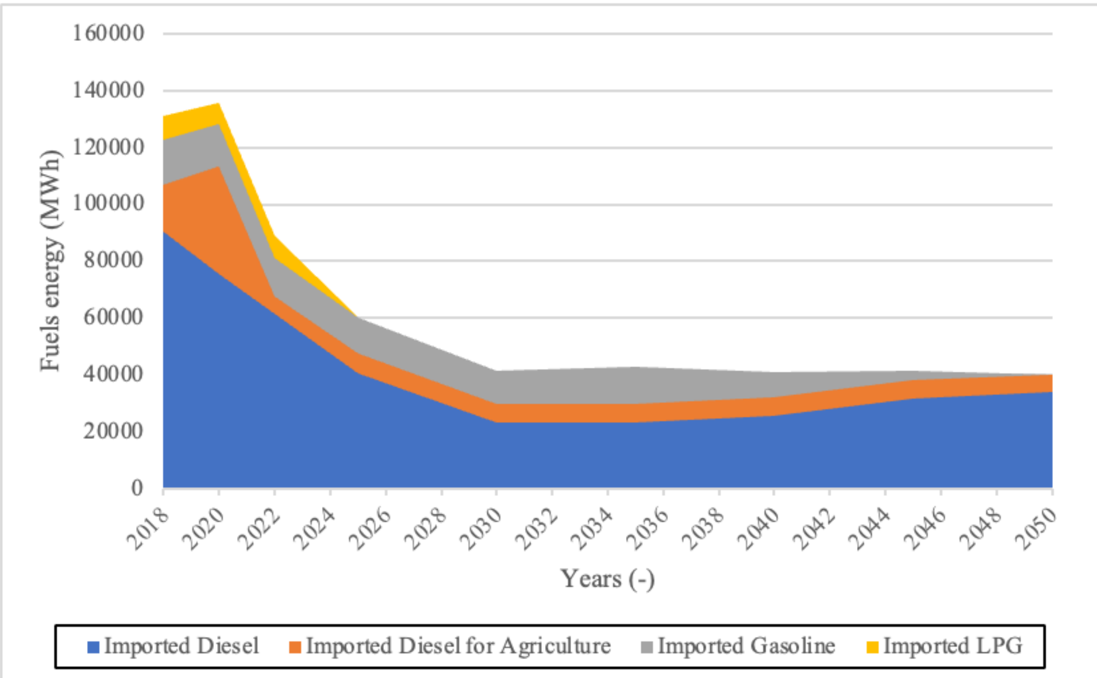


Figure 42 - Imported Fuels

Concerning imported fuels, there is a significant decrease over the years. The reduced demand for diesel for electricity production, coupled with the increasing use of electric vehicles, results in a reduction to a third of the initial fossil fuel imports.

Regarding imported diesel for agriculture, excluding a slight increase in the first years due to the installation of the initial crops, it remains constant throughout the simulation, increasing its share in the total imported fossil fuels.

The model tends to utilize all available space on the island for the installation of the most profitable crops relative to their energy consumption. Since crops have a negative cost, the model aims to install as many as possible in the exploitable area to reduce as much as possible the objective function. Once the extensive energy technologies are installed, the model fills all remained land on Pantelleria with crops.

As evident from Figure 43 and Figure 44, except for the initial years where the model is forced to install a certain percentage of each crop type, as explained in Section 5.2, subsequently, the model tends to install the most profitable technologies, lemon for non-irrigated land and tomatoes in the irrigated cluster, phasing out less profitable crops as potatoes and oranges.

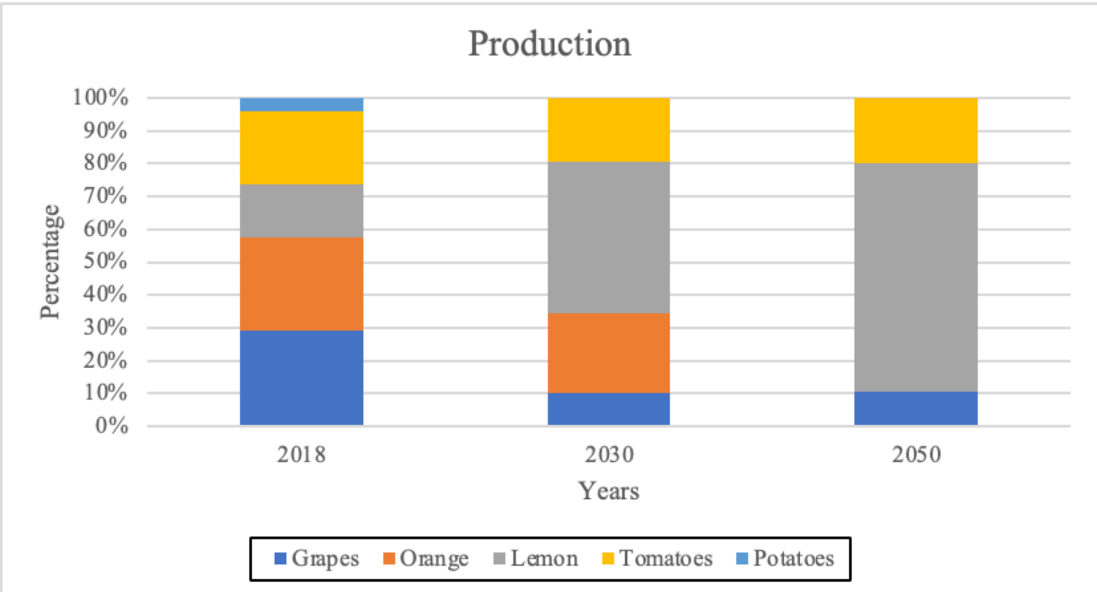


Figure 43 - Total production of crops over the years

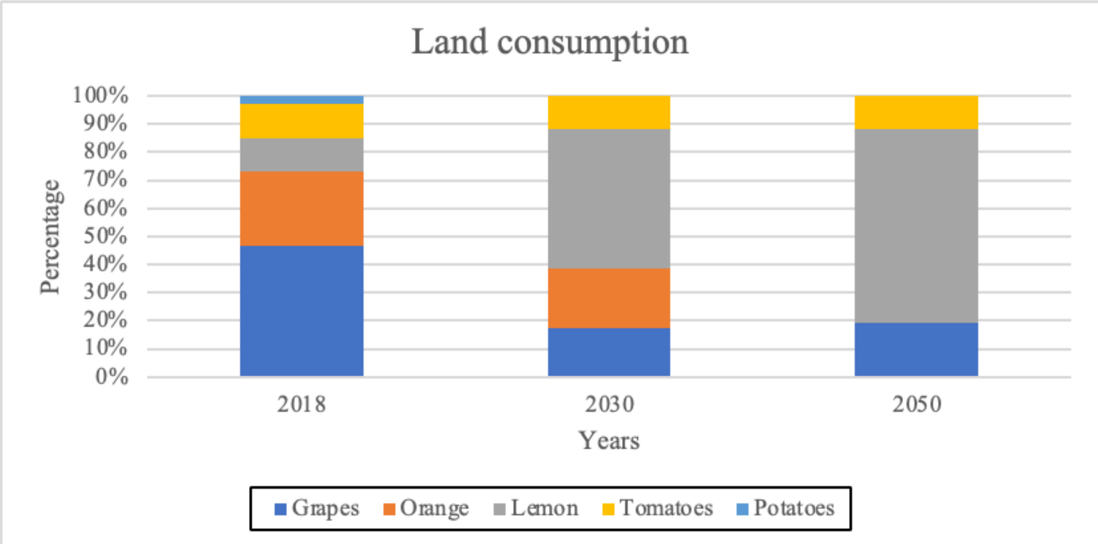


Figure 44 - Land consumed by each crop over the years

By examining the graphs representing the percentage distribution of production of the crops, referred to as Figure 43, and comparing them with the land allocation share, it is evident that the most produced crops do not necessarily coincide with those occupying the largest land area. This contrast is noticeable when comparing Figure 43 and Figure 44, where grapes occupy almost half of the available space but represent less than a quarter of the total crop production. Therefore, a careful analysis of the following graphs clearly reveals the disconnection between the production share and the land occupation share.

In the following 2 graph the total crop production, Figure 45 and the total revenues, Figure 46 are reported.

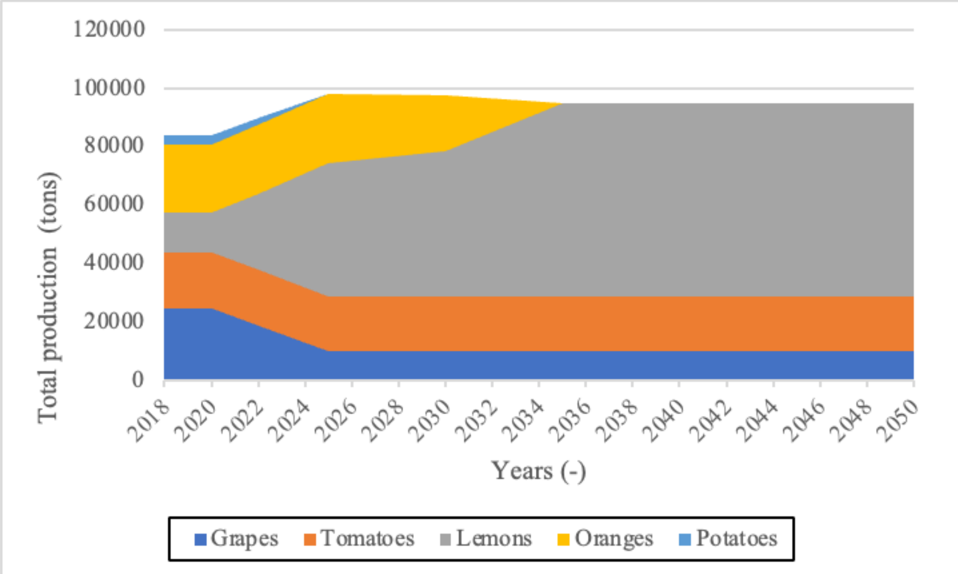


Figure 45 - Total crop production through the years

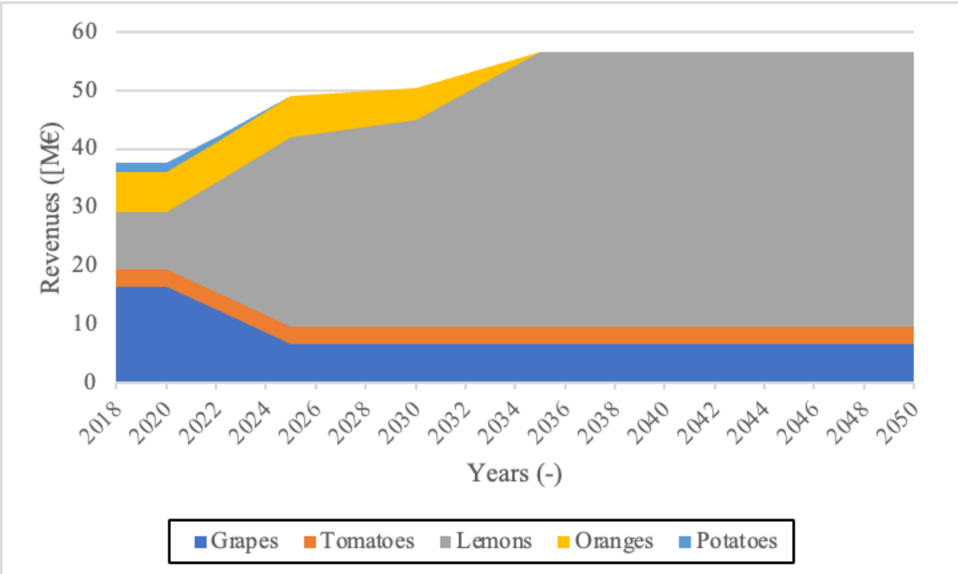


Figure 46 - Total crop revenues through the years

From these two graphs is possible to clearly note how the model tends to maximize the revenues by decreasing a little bit the production by increasing the revenue. The model, as soon as it has the freedom to install the desired technologies, begins to increase profits. Subsequently, once the land use is optimized, it maintains the best crop distribution available from 2035 to 2050.

7 Discussion

Analysing the implemented model and the obtained results, some considerations can be done.

In this chapter, a critical analysis of all the steps involved in the integration of the land-use sector into the TEMOA-Pantelleria model will be presented, starting from the input data passing through the data manipulation and the model implementation to end with a discussion on the results.

One of the main issues in modelling the land-use sector, as explained in section 1.3.1, is the lack of availability of input data such as soil chemical characteristics and crop yields. Currently, the primary database for soil-related data is the Harmonized World Soil Database, a raster database with a resolution of 30 arc-seconds and over 15,000 different soil mapping units that combines existing regional and national updates of soil information worldwide. This database provides numerous details about the type of soil, from elevation to slope to soil nutrient characteristics.

However, the problem with this database is that the resolution is not detailed enough for the case study considered in this thesis. Pantelleria Island, in the Harmonized World Soil Database [112], is described as a single type of soil with uniform characteristics across the entire island.

In the Island, rainfall data are collected from a single weather station, making it impossible to characterize some areas of the island as more suitable for crops requiring a higher amount of water.

The energy requirements of the crops were derived from various studies as reported in section 4.4.1. However, as these studies were carried out in limited areas and not on a global scale, an average of the values collected was considered necessary.

Therefore, starting with a low amount of data led to multiple assumption in the other steps of the work.

Although the use of satellites to map land use and its properties is progressively increasing the availability of data for studying this sector, at present, data availability is still a big problem.

During the data transformation, the principal difficulty involved establishing the best possible number of clusters used. One of the significant hurdles encountered during the implementation of the land-use sector into a bottom-up energy model, known to have a detailed description of the sector, was determining the level of precision that was necessary to portray the technologies or, in this scenario, the parcels of land. choosing too few clusters results in superfluous simplification and the omission of substantial land-related data. Conversely, many clusters pose a risk of inadequate differentiation as they may exhibit common characteristics.

Five clusters proved to be suitable for the case study. Nonetheless, it is crucial to note that this challenge may increase significantly in national or global contexts, where the amount of data to be considered is higher.

Criteria were adopted for the selection of irrigable lands, but there is no empirical verification or literature support for these criteria. Currently, there are no evident morphological limitations to irrigation.

In Table 14 was proposed a hypothetical reduction in crop yield across various clusters based on their morphological characteristics. In reality, crop yield is partially linked to morphological factors such as altitude and slope, but it is primarily dependent on the chemical characteristics of the soil and the density of nutrients present in it. The factors influencing crop yield are, therefore, diverse, and more complex than those considered in this thesis. However, due to the previously explained lack of data, providing a more precise estimate of crop yield is not feasible.

The first and primary challenge in implementing the land-use sector in a bottom-up energy optimization model is the proliferation of technologies. This is because it is necessary to introduce, for each implemented technology, several technologies equal to the number of clusters. To model each crop or each photovoltaic technology, it is necessary to define in the model an N number of technologies, where N is the number of clusters. This approach proves to be applicable, albeit in a limited manner, in confined contexts such as the island of Pantelleria but becomes unfeasible in larger scenarios, such as national or European contexts.

While modelling extensive technologies different challenges occurs.

One of the primary challenges in incorporating the land-use sector into a bottom-up energy optimization model is the proliferation of technologies. This is attributed to the requirement of introducing, for each implemented technology, several technologies equivalent to the number of clusters. For example, to model a photovoltaic technology (PV_tech), there are needed in the model a number of technologies equal to the total number of clusters N (PV_tech1, PV_tech2, ..., PV_techN). This occurs because each cluster has different characteristics, and the technologies installed on that cluster will have different features from those installed on another cluster.

While this approach is feasible to some extent in confined contexts, such as the island of Pantelleria, its applicability becomes impractical in more extensive scenarios, such as national or European contexts.

Implementing a technology with a negative cost is feasible but risky. The model tends to install as many instances of this technology as possible because it reduces the overall cost in the objective function. However, it would be advisable to consider other factors such as the preservation of final products and any expenses incurred if these products are not consumed. Another important consideration is that the revenues from crops are subtracted from the objective function, which mainly includes only energy costs. This operation is not entirely correct, and a modification of the objective function would be necessary to consider each sector separately.

In this model is highlighted the lack of the possibility to simultaneously implement multiple technologies that are compatible with each other in the same space, such as an agri-voltaic system or the cultivation of crops in the same area occupied by wind plant. This restriction is intrinsic to the model constraint that prohibits two technologies from sharing the same space, as once a technology is installed, it "occupies" a space that can no longer be used. One potential solution to this problem could be the addition of new technologies with multiple outputs, such as combining energy production with agricultural product output. However, this solution would entail a further increase in the overall number of technologies in the model.

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Appendix A

GTAP

GTAP is a comparative static, global general equilibrium model designed for introductory use, yet it is appropriately complex for a diverse range of policy analyses, serving as a foundation for specialized extensions. In its capacity as a CGE and not a Partial Equilibrium Model, GTAP diverges from simplifying production and consumption into a single or a limited number of stylized goods. Instead, it depicts an economy with a multitude of goods produced across various sectors.

It is a static and global model, the simulation remains constant over time, and the economic responses are modelled at a single point in time, all countries are fully represented but some are grouped into bigger regions [113].

This model stands out for its ability to represent sectors producing multiple products, such as by-products from biofuel production, and allowing multiple sectors to produce the same or closely substitutable products, such as electricity from various generation sources.

To address the representation of agricultural and land use sectors, an extension of the GTAP model called GTAP-AEZ was introduced. GTAP-AEZ, incorporating 'Agro-Ecological Zones' (AEZ), Agro-ecological zoning involves dividing a land parcel into smaller units based on agro-ecological characteristics such as moisture and temperature patterns, soil types, landforms, and other relevant factors. Essentially, each zone exhibits a comparable combination of limitations and opportunities for land utilization. The model considers the land use sector only with an economic approach, identifying a distinct production function for each sector utilizing land within a particular Agro-Ecological Zone (AEZ). It is assumed that the transition of land within a particular Agro-Ecological Zone (AEZ) can only take place among sectors for which the land is suitable. Also, the emissions related to each sector are considered in the model [114].

TIMES

TIMES (an acronym for The Integrated MARKAL-EFOM1 System) is a partial equilibrium economic model generator that offers a technology-rich framework for depicting energy dynamics. Typically employed for analysing the entire energy sector, TIMES is versatile enough to focus on individual sectors, such as electricity and district heat. This adaptability allows for comprehensive studies of energy dynamics at both the macro and micro levels.

The model can simulate scenarios up to 2100 and can be divided into a user-selected number of time periods. The spatial resolution can range from local to national, multi-regional, or global energy systems.

For what concerns the land use sector, The TIMES-WEF model introduces an innovative application of the water-energy-food nexus approach within the ETSAP-TIMES framework. In this model, land use is treated as an independent driving parameter that connects soil availability with input/output commodities. The primary objective is to achieve optimal territory management, enhancing the utilization of endogenous resources, increasing the agri-food sector's resilience to climatic events, and facilitating the implementation of agricultural, energy, and environmental policies [114].

The Used Agriculture Area (UAA) and the Forestry Area (FA) serve as output commodities. Specifically, the UAA represents the total area (hectares) utilized for agriculture, encompassing arable land, permanent meadows, permanent crops, and vegetable gardens based on Eurostat data [114].

The model incorporates new elements, including water, fertilizers, pesticides, and CO2 capture from forestry, among the input commodities of a standard TIMES model.

Each agricultural activity was modelled with two consecutive processes:

1. The first process involves the consumption of water, energy (electricity, diesel, natural gas), pesticides, and/or fertilizers. It produces crops (measured in tons) or cattle (measured in livestock units (LSU)).
2. The second process converts the output of the first process into hectares of used agricultural/livestock area using a yield parameter. The cumulative outputs of the second processes across all ten categories of agricultural activities determine the demand for end-use [114].

MAgPIE

The Model of Agricultural Production and its Impact on the Environment (MAgPIE) is a global land use allocation model integrated with the grid-based dynamic vegetation model LPJmL. The model incorporates regional economic factors such as demand for agricultural commodities, technological advancements, production costs, and spatially explicit data on potential crop yields, land, and water constraints (sourced from LPJmL). Utilizing this information, MAgPIE generates specific land use patterns, yields, and total costs of agricultural production for each grid cell.

It has a spatial resolution of 0.5°x0.5° and it operates with a 10-year time step in a recursive dynamic mode for future projections.

The primary objective of the land use model is to minimize the total cost of production for a specified regional demand for food and bioenergy. Regional food energy demand is determined for 10 food energy categories.

Food and feed energy in MAgPIE are produced through 20 cropping activities and 3 livestock activities. Variable inputs include labour, chemicals, production costs and other capital measured in US dollars are sourced from the Global Trade Analysis Project (GTAP) Database [115].

The land-use pattern from one period becomes the initial constraint for the next. If needed, additional land from non-agricultural areas can be converted into cropland at additional costs. Potential crop yields are computed at a 0.5° resolution using LPJmL, considering irrigated and non-irrigated production. Land-conversion activities allow for potential expansion and shifts of agricultural land, constrained initially to the area currently used within each grid cell. Cropland can be converted into rangeland and vice versa, with additional land sourced at extra costs if demand requires. Land conversion is considered only when land becomes scarce, or the benefits of conversion outweigh the costs [116].

MESSAGEix-GLOBIOM

Between the IAMs one of the most important models is the so called MESSAGEix-GLOBIOM.

The framework is a comprehensive global modelling platform designed to assess the long-term effects of energy, climate, and land-use policies on the worldwide economy and environment. It combines five distinct models or modules: MESSAGEix (energy sector), GLOBIOM (Land-use sector), GAINS (Air pollution and greenhouse gas), GAINS (macroeconomic modelling) and MAGICC (climate projections model). All these models are linked and connected to deliver an integrated and thorough analysis of the long-term consequences of policies across each model domain [116].

Market equilibrium is established via mathematical optimization, which strategically assigns land and various resources to optimize the combined surplus of consumers and producers [116].

The model has a time horizon from 2010 to 2100 with time steps of 5 to 10 years. It has a spatial resolution of 11 up to 30 regions representing the whole world.

The land use sector is simulated in the GLOBIOM model, it specifically models the competition among various land-use activities, providing a detailed representation of the agricultural, forestry, and bio-energy sectors.

This sophisticated modelling approach integrates grid-cell information on biophysical constraints and technological costs. Production adjustments to meet demand are implemented at the level of 30 economic regions. The determination of market equilibrium involves mathematical optimization, strategically allocating land and other resources to maximize the combined consumer and producer surplus [116].

The modelling framework places a particular emphasis on crop production, encompassing over 30 globally significant crops. Average yields for each crop in each country are derived from FAOSTAT, while yield coefficients related to management practices, accounting for fertilizer and irrigation rates, are explicitly simulated using the EPIC model. The modelling framework accommodates four distinct management systems (with a focus on irrigated and rainfed only). However, crop yields are subject to change in response to external socio-economic drivers [116].