Master's degree in Environmental and Land Engineering

Master's degree Thesis:

Modeling the Energy and the Water Systems in an Open-access Energy System Optimization Model: The Pantelleria case study

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A Maria,

vento che spinge le mie vele.

A Carla,

per donarti un mondo migliore.

Alle donne dell'anima mia.

Summary

List of Acronyms

a.g.l./a.s.l.: Above Ground Level

a.s.l.: Above Sea Level

CE4EUI: Clean energy for European islands

CLEWs: Climate, land, energy, water systems

CPMR: Conference of Peripheral Maritime Regions

DL: Losses Decreasing

EDR: Electrodialysis reversal

EMT: Electricity Mix Transition

ESOM: Energy System Optimization Model

ETU: Ecosystemic Transition Unit

EU: European Union

GHG: Greenhouse gas

IAMs: Integrated assessment models

IL: Losses Increasing

ISEAP: Island Sustainable Energy Action Plan

ISLENT: European Islands Energy and Environment Network

IWPC: Increasing Water Production Capacity

LP: linear programming

MC: Mechanical steam Compression

NEMT: No Electricity Mix Transition

O&M: Operation and maintenance

OFMSW: Organic fraction of municipal solid waste

PNRR: Piano Nazionale di Ripresa e Resilienza

PoI: Pact of Islands

RE: Renewable Energy

RES: Reference Energy System

RES: Reference energy system

RO: Reverse Osmosis

RWS: Reference Water System

SIS: Smart Islands Strategy

TS: Total Solids

WPUC: Water Production Unchanged Capacity

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Abstract

In the framework of the Integrated Assessment Models (IAMs), the nexus approach is a systematic way to explore the interaction and interdependency between the climate, land, energy, and water (CLEW) systems in terms of synergies and trade-offs among them. The exploitation of dynamic relationships between CLEW domains should allow informed planning and policy decisions. The aim of the thesis is to perform an integrated water-energy system assessment for an isolated Mediterranean area, the Pantelleria island. A flexible, open access energy system optimization modeling framework (the Python-based TEMOA) has been selected to integrate the energy system and water system modeling. The structures of energy and water systems are first modelled considering production, distribution, and demand sectors, with a detailed sub-sectorial description. Like the energy system, composed of the supply-side (upstream and power sector) and the demand-side (buildings and transport), also the water system includes processes for water production (rain, seawater, imported water and the desalination plant) and consumption (representing the seasonal and the fixed water demand of the island). Long-term scenario projections of the two systems have been performed separately. For the energy system, first an electricity mix transition scenario and a second one without any fossil-fuel electricity generation constraints have been implemented; also for the water system two scenarios have been assumed: the first one keeps in-situ water production capacity unchanged, the second one with no limits on desalination capacities, such that the system is free to choose to import or to produce on site. At a later stage, the integrated reference energy-water system (WES) has been developed to study the specific linkage of energy and water systems. The most relevant resources interconnections

are associated with the water production and distribution sectors. Therefore, to quantify how much the water and energy systems influence each other, two scenarios have been studied to analyze the consequences on water production and energy consumption due to water network conditions. The results obtained from analyzing both resources show a practical example of the importance of an integrated approach. The current TEMOA-Pantelleria model is a concrete implementation of a quantitative water-energy nexus approach and represents the starting point for a more comprehensive CLEW system modeling at regional and national level.

Chapter 1

Introduction

1.1 The role of islands in the European sustainable development policies

Since the 1990s, the European islands have played a fundamental role in the definition of sustainable development plans [1]. The islands represent an important resource for the European states in terms of tourism, environmental potential and biodiversity, culture, and historical testimony. However, these territories are the most vulnerable to the climate change consequences. In these areas extreme events are most frequent and have the greater impacts: heat waves, drought, tidal waves, and sea level rise threaten them and cause more serious effects than on the mainland.

Additionally, due to the natural insulation, the islands are often characterized by high transportation costs, isolated energy grid, in most cases fossil fuel-based, water scarcity and very limited economic diversification [2].

The European Union and the national and local authorities, for about thirty years, have been trying to turn the problem of isolation into an advantage by creating sustainable transition programs.

The first collaboration among the EU islands dates to 1993 [1]. The European Islands Energy and Environment Network (ISLENET) was founded by the Western Isles, Shetland, Portugues Islands and Canary Islands in conjunction with the Island Commission of the CPMR (Conference of Peripheral Maritime Regions). The aim of ISLENET was to create an EU island network and to reduce the energy dependency, increasing the access to reliable and affordable energy services, reaching the energy security, decreasing GHGs emissions and minimizing the impacts on climate change.

In 2007 EU Parliament member Francesco Musotto proposed a series of measures to promote the achievement of the EU islands' challenges such as exploitation of the renewable energy potential and the promotion of local sustainable energy projects[3]. About two years later, the ISLEPACT project started to concretize the sustainable energy planning at the island level developing Pact of Island (PoI) [4]. The Pact of Island was launched in 2015, later unifying with the Covenant of Mayors at the request of the European Union. The objective of the pact was to develop and implement Island Sustainable Energy Action Plans (ISEAPs) [4] and to achieve a minimum reduction of 20% of CO2 by 2020.

Subsequently, "to Enhance effective implementation of sustainable energy action plans in European islands through reinforcement of smart multilevel governance" the EU-founded SMILEGOV project took place [5]. The target of the project was to achieve the PoI goals through cooperation between different levels of governance (national, regional, and local).

The Smart Islands Strategy (SIS) is the main result of SMILEGOV [5]. In the SIS document, different activities such as the collaboration between the EU islands and strategies from EU institutions, industries, and civil society are proposed. The most relevant concept underlined in the SIS is the importance of understanding the value of the islands as potential host pilot projects that could be scaled up to bigger contexts.

Another islands sustainable development initiative, launched in 2017, is the Clean Energy for EU Islands (CE4EUI) that is part of the 'Clean energy for all Europeans' package. The CE4EUI is trying 'to provide a long-term framework to help EU islands generate their own sustainable, low-cost energy' [6]. The consequences of CE4EUI initiative should be:

- Reduction of energy costs and increased production of RE.
- Construction of energy storage systems and development of response systems demand.
- Energy security.
- Reduction of air – water – land pollution.
- New jobs and opportunities.

The CE4EUI secretariat is committed to supporting EU islands in developing clean energy transition agendas, decarbonization plans, and individual projects by providing technical and financial assistance, by access to an online collaborative platform.

Since 2018, the FEDARENE initiative (namely, the European Federation of Agencies and Regions for Energy and Environment) has been expanded with a new island college [7]. The college has the role to connect European Institutions and Member States to ensure technical and financial assistance necessary for the energy transition of islands.

Lastly, in 2022, The European Regional Development Fund has co-financed the Ecosystemic Transition Unit (ETU) model. ETU is a multilevel governance model which originated as roadmap for rural and island areas to perform energy transition through the social innovation [2].

The EU's growing interest in its islands is justifiable considering not only the enormous value of these areas, but also the strategic role they play. Creating pilot plans for relatively simple systems, that is islands, represents the starting point for larger-scale transition projects.

The Pantelleria island signed the Covenant of Mayors in 2014, beginning its energy transition process[8]. After, in the framework of the CE4EUI project, Pantelleria was elected as a pioneer island for energy transition in 2019. Subsequently, the Energy Transition Agenda was drafted in 2020 with the goal of total decarbonization by 2050 [8].

1.2 Energy System Modeling

Energy system modeling allows the creation of long-term energy scenarios. It may be a key instrument in guiding policy makers and investments choices for sustainable development. Indeed, to plan a concrete and robust sustainable development it is necessary to have the possibility to foresee the consequences of decisions made or to be made.

According to the IPCC an Energy System is "A system that comprises all components related to the production, conversion, delivery and use of energy"[9].

In Figure 1 it is possible to see a general example of an ideal Reference Energy System (RES). It shows the flow of energy, from the primary resources to the final consumption. A RES is articulated in several sectors, which in turn are divided into different subsectors. In the specific case of Figure 1, the sectors are:

- "Primary Energy" that represents the primary energy resources,
- "Conversion" in which the resource is transformed into an energy vector,
- "Transportation and Distribution" of energy
- "Final Energy Consumption" that represents the energy demand sector.

Example of subsectors are the energy demand sectors:

- Transportation,
- Industrial & Commercial,
- Residential.

Energy system models are mathematical models that recreate the energy system features in order to study and analyze them [10]. In general, the aim of the

RES modeling is to represent one or more energy system scenarios for the purpose of generating forecasts. They can be deterministic or stochastics. [11]

Energy system modeling turns out to be a very helpful tool for policy makers because it can provide relevant information on several aspects, such as economic or environmental features of the studied system.

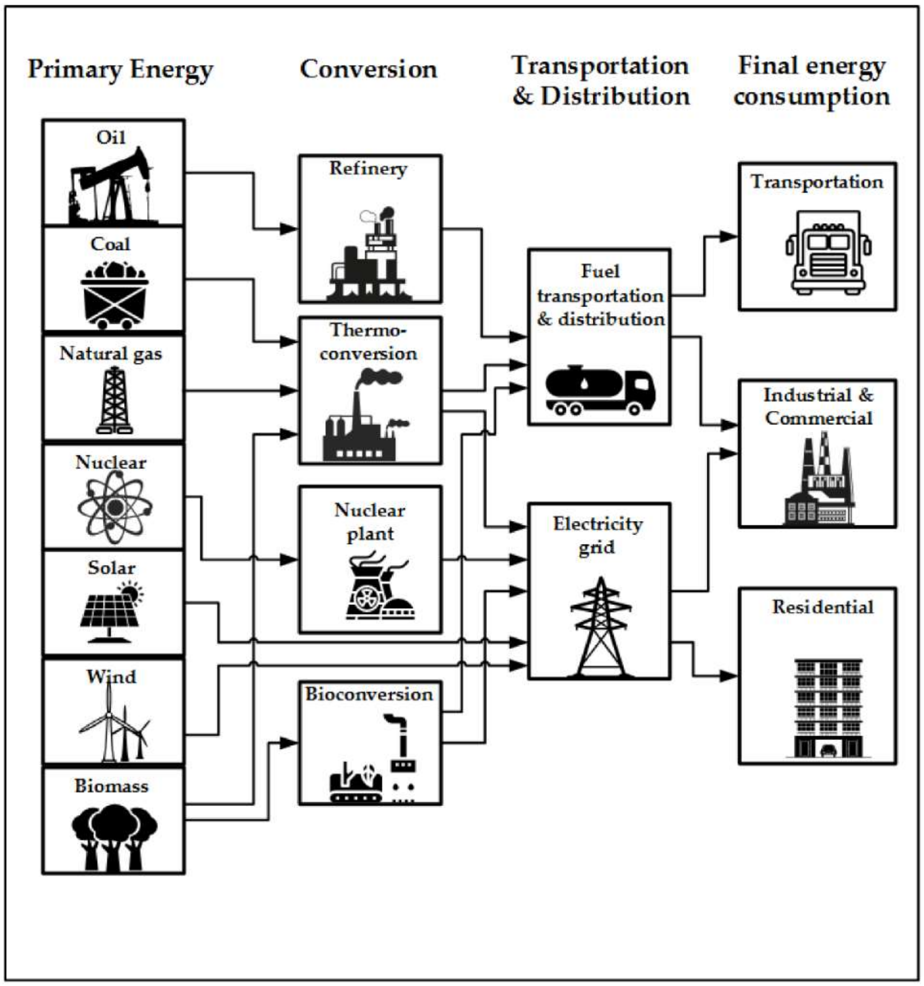


Figure 1. Energy system showing the flow of energy from primary energy supply to final energy consumption. [11]

1.2.1 Bottom-up Energy System Optimizations Models

According to discipline and level of technologies aggregation, the energy system models can be classified in different ways, as shown in Figure 2.

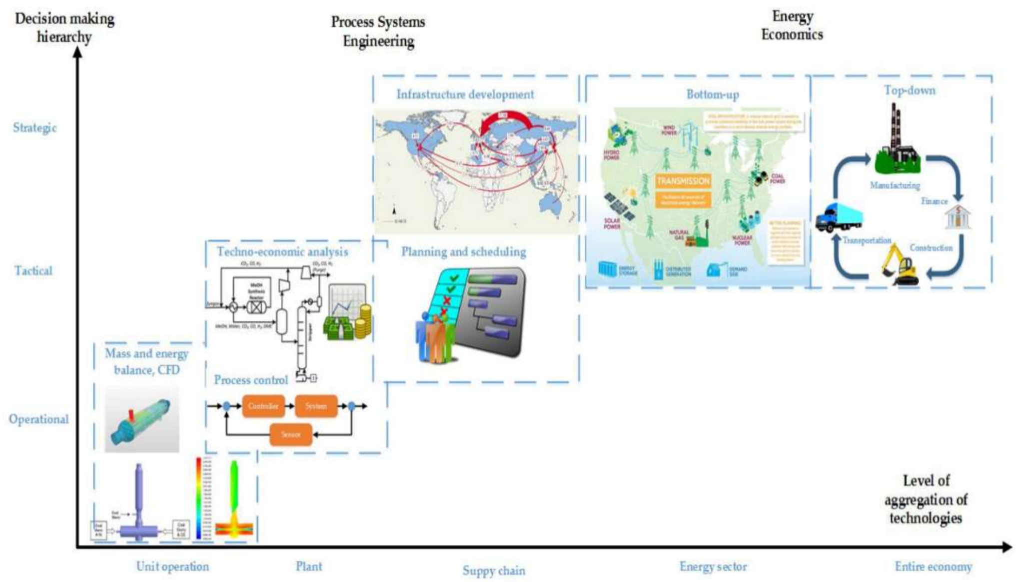


Figure 2. Classification of energy system models according to discipline and level of technological aggregation.[11]

Deterministic Energy system models at strategic level can be based on Top-Down or Bottom-up methodologies.

In top-down models, the RES is defined in a very aggregate way, while the economic aspects are much more detailed [11]. This type of model is suited to investigate energy-economy links and the boundaries conditions are economy-based.

The bottom-up models are characterized by very detailed energy sectors and aggregated economic aspects. These models assess the impact of the different subsectors or technologies [11]. This type of modeling is more in line with the need to determine scenarios that consider environmental, social and energy aspects.

The bottom-up models' family is based on 3 methodologies [12]:

- Accounting models: balance the fluxes of different commodities and technologies. These models are static.
- Simulation models: To a given set of data, they predict the response of the system, without finding an optimal configuration.
- Optimization models: Estimate an optimal configuration for all the decision variables. Often, the optimization function is the minimum cost of the technologies involved in the demand satisfaction.

Both simulation and optimization methodologies are based on accounting models and have the same main drives such as economic growth (GDP), energy prices or policy targets. But, while for the optimization models the main goal is the optimal configuration, for the simulation ones, the target is to compare two or more different scenarios [13].

The Bottom-up Energy System Optimization Models (ESOMs) are mostly used because they follow definite optimization criteria driven by their objective function, overcoming uncertainties related to the modeler's perception. They are able to simulate and investigate driving mechanisms that influence energy and investment choices in the future.

ESOMs use linear programming (LP) algorithms to minimize the system-wide cost of energy supply and demand. The elements of LP formulation are:

- Decision variables: obtained as results from the optimization model. In detail, they are new capacity additions, total installed capacity, and activities of each technology
- Objective function: criterion to be minimized/maximized
- Constraints: equations or inequalities involving the decision variables.

To develop an ESOM, a proper time horizon and a time grid should be selected: milestone years are chosen as representative for a period. The results are calculated for each milestone year.

As already mentioned, in the ESOMs, the objective function is driven by the costs, and it can be defined as Equation (1)

$$\min\ [GlobalDiscountRate * (\sum_{r,t,p} (Inv.cost_{r,t,p} + Fixedcost_{r,t,p} + Varcost_{r,t,p})] \quad (1)$$

1.2.2 An open-source ESOM: TEMOA

Among the ESOMs framework, great interest is on developing open-source modeling tools due to the following features:

- the linear structure of the database,
- simplified version of the optimization problem,
- possibility to model large-scale systems with high performances,
- the free access to open-source versions of commercial solvers. The most diffused open-source ESOMs are OSeMOSYS and TEMOA [14].

In this Thesis project, the case study model has been developed using TEMOA framework, mainly for four reasons: 1) its reliability has been demonstrated by the MAHTEP group of the Politecnico di Torino, comparing its results with a commercial model namely TIMES [14], 2) the possibility to use solver that allows the resolution of large-size modes (Gurobi), 3) because the use of python and all the correlated software packages and libraries (Figure 3), 4) because it is a multi-regional, highly detailed technology model.

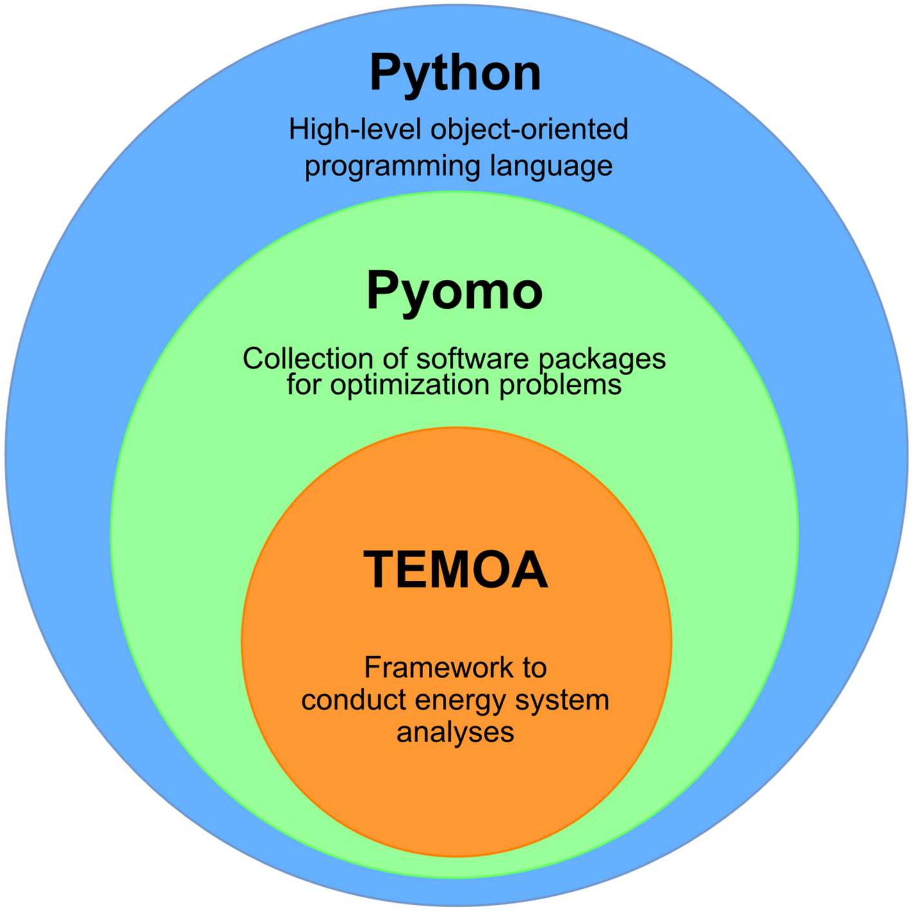


Figure 3. Temoa framework contextualization [15]

The reference energy system features must be reported in a SQL sheet, then transformed into SQLite to become the input file to TEMOA. Before running the TEMOA model, the SQLite database is filled by an automatic algorithm [16] to project the constraints avoiding data entering year by year. An external open-source solver must be called to solve the model (Gurobi) and within the TEMOA framework there are a set of Python-based files that allow the user to build and run model instances, see Figure 4.

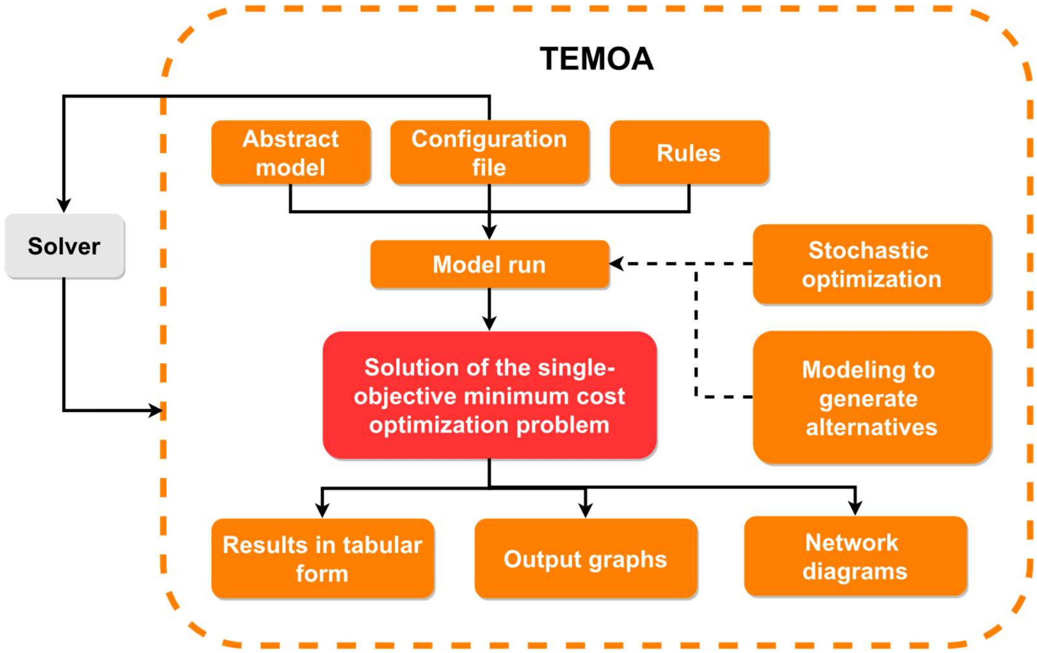


Figure 4. TEMOA framework working structure [15]

1.3 Modeling attempts

It is necessary to mention that for the selected case study, an energy system modeling attempt is already done. In February 2022, the Energy Center Lab and the MOREnergy Lab of the Politecnico di Torino collaborated one each other to develop a study to support strategies for decarbonizing local energy systems by de-risking renewable energy investments. This work was concretized by analyzing the case of the island of Pantelleria [17]. A long-term energy model (from 2020 to 2050) has been developed using the open-source framework OSeMOSYS and future energy scenarios have been implemented. In this text this model will be referred to as OSeMOSYS-Pantelleria. The energy system, however, includes accurate modeling of the supply-side only. The demand sectors are not modeled separately, but only general total electric demand is developed. The analyzed scenarios in the OSeMOSYS model, that basically consider a sustainable energy transition, analyses the consequences on the electricity demand according to the level of dissemination of roof-mounted distributed photovoltaic panels and electric vehicles.

The OSeMOSYS model has been considered in the final stage of the thesis project to compare the feasibility of the TEMOA-Pantelleria results related to the energy part.

1.4 Integrated assessment models: The nexus approach

Integrated assessment is a general term that includes evaluations related to multiple systems or sectors and considers synergies and trade-offs among them. Models implemented with the aim of understanding these interactions and quantifying them are called Integrated Assessment Models (IAMs)[18].

In the framework of the IAMs, the nexus approach considers interactions and interdependencies among the Climate, Land, Energy and Water sectors (CLEWs) (Figure 5) and the impacts that economic and social aspects have on them. The CLEWs synergies and trade-offs are underlined with the goal of understanding the sectors' relationships and dynamics in order to better manage the conflicts and exploit the opportunities among resources.

Indeed, the quantitative integrated analysis of the CLEW systems using modelling tools allows us to assess the overall solidity and reasonability of a particular strategy or policy. This, in fact, provides alternative development options and investigates the implications that choices related to a single sector have on the overall system.

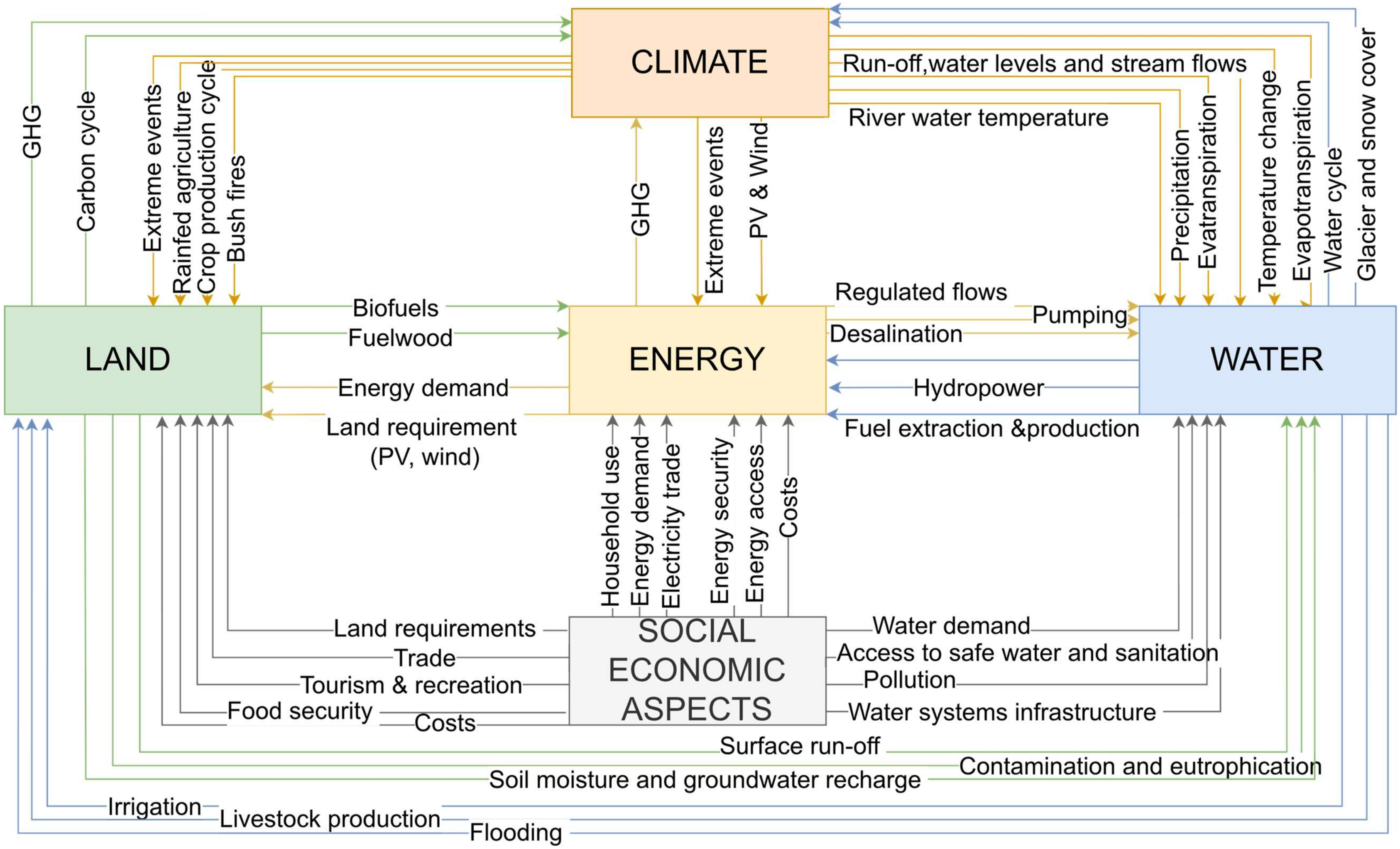


Figure 5. CLEW and social interactions and links [18]

1.5 Aim of the work

Considering what is reported in Section 1.1, the implementation of solution to promote islands sustainable development is a goal in line with the European plans and represents the first step toward the large-scale transition. Indeed, the isolated islands system is perfectly suited to be a pilot test for sustainable transition attempts.

The selected case study, namely Pantelleria island, is already included in the European sustainable development projects. Indeed, in 2020, in the framework of the project CE4EUI, the Pantelleria energy transition Agenda [19] has been developed to overcome the problem of fossil fuel-based power generation and develop a plan for the complete decarbonization in 2050.

However, the developed Agenda considers an only energy-based transition, disregarding interactions with other resources and serious issues on the island. Indeed, another important problem for Pantelleria, as well as for most European islands[2] is water scarcity. In particular, in Pantelleria, due to the total absence of other exploitable natural water resources[20] and the high price of transportation, most hydro potable water is derived from desalination [21]. Therefore, water production involves high energy consumption, which at present, derives from fossil sources and thus causes high pollution.

As reported in Section 1.4, it is crucial to adopt an integrated approach to promote sustainable development. Therefore, the aim of this work is to study the possibility of future island development introducing an integrated assessment, particularly with the goal of managing trade-offs between energy and water resources.

To do that, the TEMOA framework has been exploited to implement both energy and water systems. Once the integrated model, namely TEMOA-Pantelleria, has been built, to analyze the consequences of interconnections between the water-energy resources and to manage it in a more sustainable way, different scenarios (concerning the evolution of the interconnected sectors, i.e. the water production and distribution) have been developed.

The current TEMOA-Pantelleria model is a concrete implementation of a quantitative water-energy nexus approach. The thesis project is intended to be a starting point for a more comprehensive CLEW system modeling extendable to regional and national scale.

The thesis project has been structured as follows:

- Section 2: Pantelleria island contextualization
- Section 3: Pantelleria reference energy system features
- Section 4: Pantelleria reference water system features
- Section 5: Pantelleria integrated water-energy system,
- Section 6: Results analysis and comparison
- Section 7: Conclusions.

Chapter 2

Case study

2.1 Pantelleria

2.1.1 Geographic framework

Pantelleria is a Sicilian Island located about 110 km from Sicily and 65 km from Tunisia. The Pantelleria area is about 84.5 km^2, its maximum length is 13.7 km, while its maximum width is 8 km and is the fifth largest island in the Italian territory.

The island, which was born about 300.000 years ago, is of volcanic origin. Secondary volcanic phenomena are currently appreciable on the island. The highest peak on the island is the so-called 'Montagna Grande' and rises about 836 meters above sea level, followed by 'Cuddia Attalora' (560 m a.s.l) and 'Monte Gelkamar' (286 m a.s.l.). In Pantelleria there are two valleys ('Valle di Ghirlanda' and 'Valle del Monastero'), exploited to viniculture. There are no surface water resources on the island; the only natural lake is the so called 'Lago di Venere', that is of volcanic origin, and fed by meteoric waters and thermal springs.

Pantelleria is characterized by Mediterranean weather, with hot summers and mild winters. During the year, the temperature generally ranges from 11 °C to 30 °C and is rarely below 8 °C or above 34 °C. The average annual rainfall is about 352 mm. Rainy period in the year lasts 9 months. The rainiest month in Pantelleria is October, with average rainfall of 48 millimeters [22].

Figure 6. Pantelleria map [19]

2.1.3 Social and Political frameworks

In 2020, the Pantelleria island population was 7.366 residents (ISTAT). Within the island, there are three main population centers: 'Pantelleria Centro', 'Khamma-Tracino' and 'Scauri'. The main urban center houses 5000 permanent residents, while the other two areas are populated by about 1250 people each. The island is a renowned tourist destination; therefore, is subject to high seasonal flux: about 110,000 tourists/year [23].

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

In July 2016, the National Park "Island of Pantelleria" has been established. As showed in Figure 7, the park is divided into three parts of significant natural, landscape, agricultural and/or historical and cultural importance [24]:

- The first zone: with absence or minimum level of anthropization
- The second zone: with limited level of anthropization
- The third zone: with a high level of anthropization.

The goal of the establishment of Pantelleria national park is to safeguard the island's natural resources and to promote sustainable development.

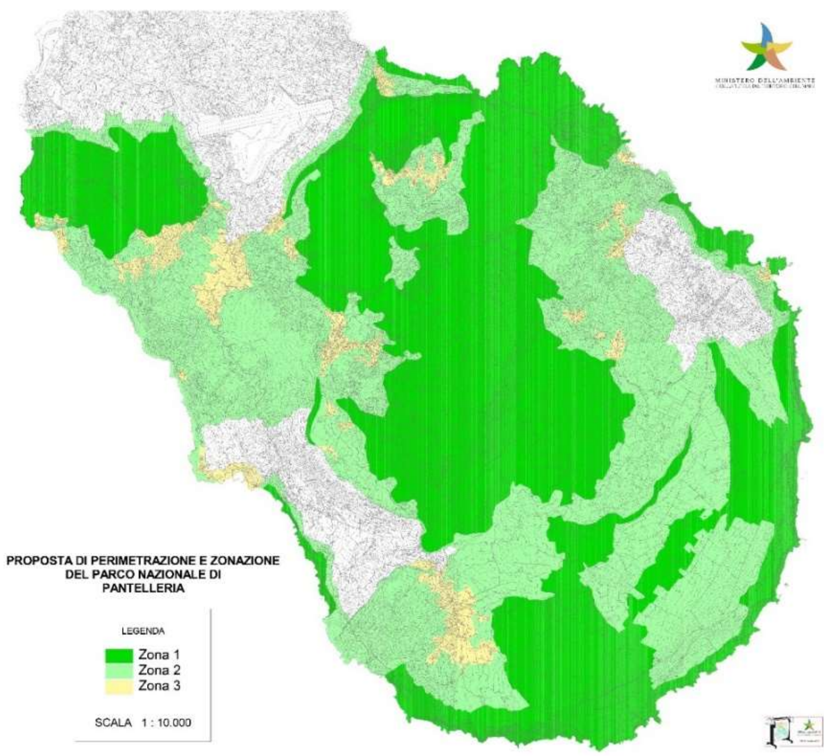


Figure 7. Pantelleria national park zoning [24]

2.1.4 Economic framework

The Pantelleria economy is based on viticulture, caper agriculture and tourism.

Agriculture

Pantelleria agriculture, which due to caper cultivation and wine production is one of the most economically viable sectors, had to adapt to a stony and arid land. Pantelleria farmers over the centuries have implemented several useful adaptation measures to defend the crop from strong wind gusts and to increase water resources utilization. For this reason, Pantelleria agriculture is defined 'heroic' [25]. For example, to create the cultivable hectares, now about 5700, bands of arable land were created by transforming the impervious nature of the island and creating the various dry-stone walls with stones removed from the ground [26].

Furthermore, the Pantelleria viticulture, which has always been central to the economy of Pantelleria, is a non-irrigated cultivation thanks to exploitation of the “alberello” configuration and techniques such as weeding, i.e., surface tillage of the soil.

In November 2016, the Zibibbo vine cultivation “alberello style” present on the island for several centuries, has been declared a world heritage site by UNESCO (Figure 8). The alberello agriculture is cultivated in conches about 20 cm deep that, in addition to protecting bunches of grapes against the wind, allows rainwater storage and the soil to be moistened [27].

Weeding has multiple functions such as the elimination of weeds that would compete with crops and elimination of soil compactness that would otherwise promote evapotranspiration and thus reduce soil water reserves.

Through weeding, air circulation can be improved, and the upper layer can be quickly dehydrated, interrupting the capillary rise of liquids and maintaining moisture in the layers below [25].

The most famous product of viticulture is the ‘Passito di Pantelleria’. Despite the still actual importance of the wine industry, grape cultivation has declined from about 7,000 hectares in 1940 to about 1,000 [Ha] in the 2000s[19].

Figure 8. "Alberello style" cultivation in Pantelleria

Pantelleria’s arid soil is an ideal environment for the cultivation of the caper, which in 1996 has received the IPG certification [28].

Tourism

The most profitable activity on the island of Pantelleria is tourism. The tourism boom on the Pantelleria island began in the 1970s. Nowadays, the tourist flow, present especially in the summer months, reaches up to 110 thousand people per year. The number of tourists has stabilized its maximum in the last decade, presenting small annual variations [29] (Figure 9).

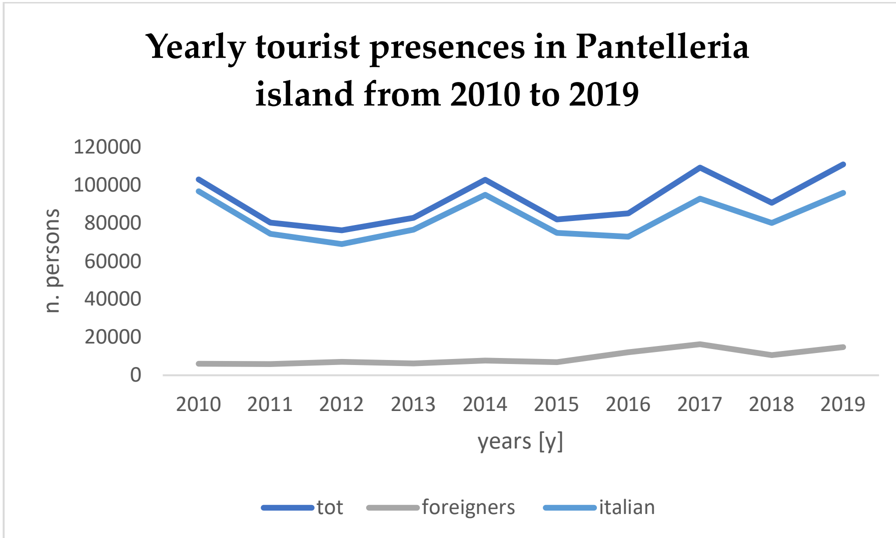


Figure 9. Yearly tourist presences in Pantelleria island from 2010 to 2019 [29]

Tourism has an extreme impact on the energy and water consumption of the island, as well as on CO_2 emissions. A sustainable transition, however, could benefit the sector by increasing the availability of energy and water resources.

Chapter 3

Reference Energy System

As already mentioned, the Reference Energy System (RES) is a schematic representation of all the processes involved in the energy transformation, transmission, and consumption from the primary source to the demand sector.

Modeling of the RES, through a bottom-up ESOM, involves the precise techno-economic characterization of both supply-side and demand-side sectors. Specifically, in the TEMOA framework, the energy system is represented as a network that convert the input energy commodities (e.g., oil or renewables potential) into end-uses services (e.g., cooking, heating or transport) exploiting intermediate commodities (e.g., electricity) and specific conversion (e.g., power plants) or utilization technologies (e.g., cookers, space heaters, vehicles). Technologies are defined using technical, economic and environmental feature (e.g., efficiency, costs, emission rate) [30]. The specific commodities and technologies defined in the energy system models are site specific, that is, they change depending on the area studied and also depending on the base year defined.

The Pantelleria RES TEMOA-model has been developed considering the specific energy system of the island (the existing technologies and commodities); however, for different assumption, such as the technological evolution or new technologies parameters, in absence of site-specific data, it was based on those from the mainland (TEMOA-Italy [16]).

3.1 Pantelleria energy system

3.1.1 Base year energy system

The Pantelleria energy system has been modeled starting from the 2013 (base year) (Figure 10). In 2013, the upstream sector (green) was composed of diesel, gasoline, LPG, and solar resources. The primary fossil resources were imported by shipping from mainland with high transportation prices. Gasoline was used only for the transport sector, LPG to meet cooking demand, and diesel was exploited for both transport and electricity production demands. Indeed, like several Mediterranean islands, the power sector is not-connected with the mainland and strongly fossil-fuel dependent.

In 2013, the Pantelleria power sector (in yellow in Figure 10) was composed by a diesel power plant and few distributed photovoltaic plants [31] The diesel plant with a total installed capacity of 22 MW, property of the S.M.E.D.E S.p.A. company, consists of six diesel units and two diesel gas turbines. The photovoltaic rated capacity was about 140 kW [31].

The distribution grid (in violet in Figure 10) subserves the demand-side sectors Considering the total absence of industry production hubs, the demand-side (in blue in Figure 10) involves buildings (in turn composed of residential, commercial, agriculture), transport and water production sectors.

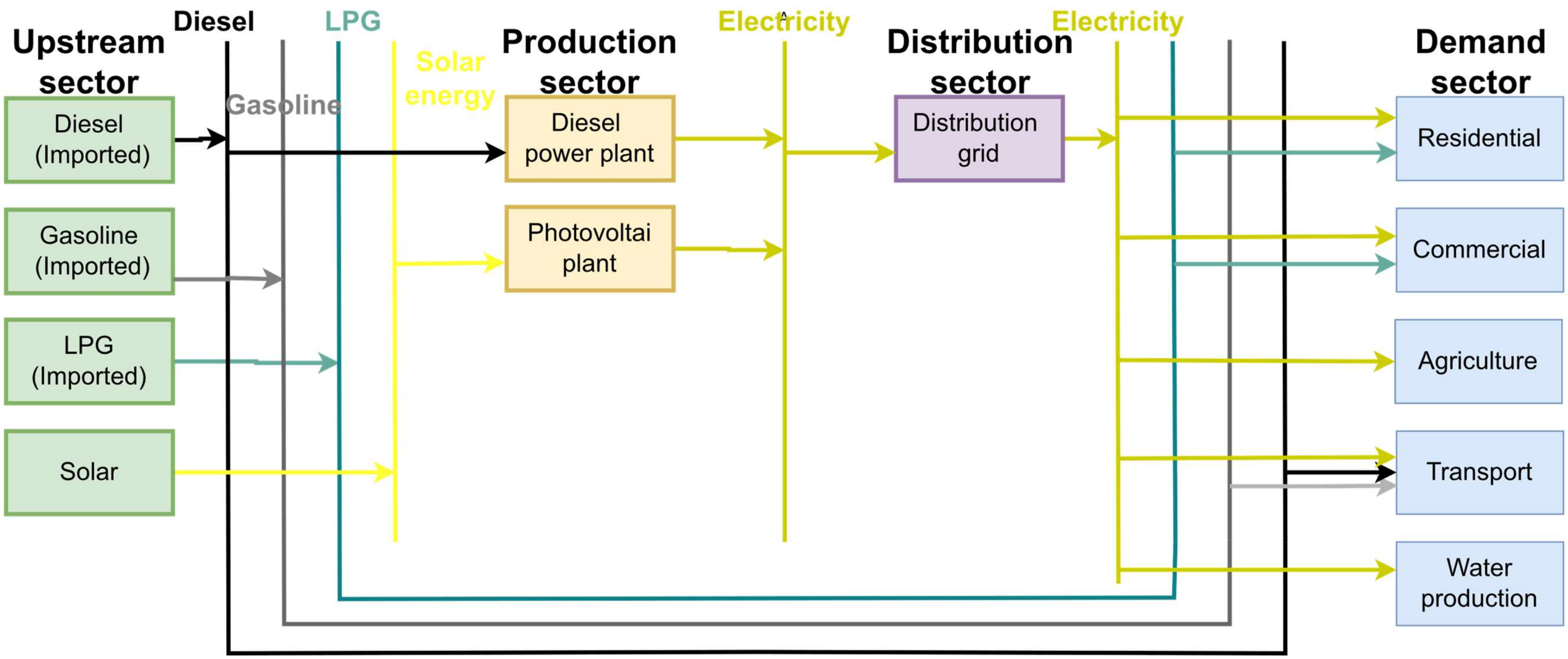


Figure 10. Pantelleria reference energy system (2013)

3.1.2 Renewable sources potential

Pantelleria has potentially one of the highest and varied Italian renewable sources availability [19] which must be considered in future evolution of the energy systems. The renewable resources of the island are solar, wind, geothermal, wave, and biomass. In 2013, namely the model base, only a very small fraction of solar potential was being exploited. Resources availability, that is specified in the next paragraphs, has been considered in order to construct the model consistent with reality.

Solar

The annual solar irradiance of Pantelleria in the horizontal plane is approximately 1800 kWh/m^2, while that on the optimal inclination plane (32°) is about 2000 kWh/m^2 [19].

The monthly solar irradiation on the horizonal plane and on the optimal inclination are represented respectively in blue and red in Figure 11. The annual radiation on the ground, without considering obstacles beyond the ground surface (buildings or trees), is shown in Figure 12.

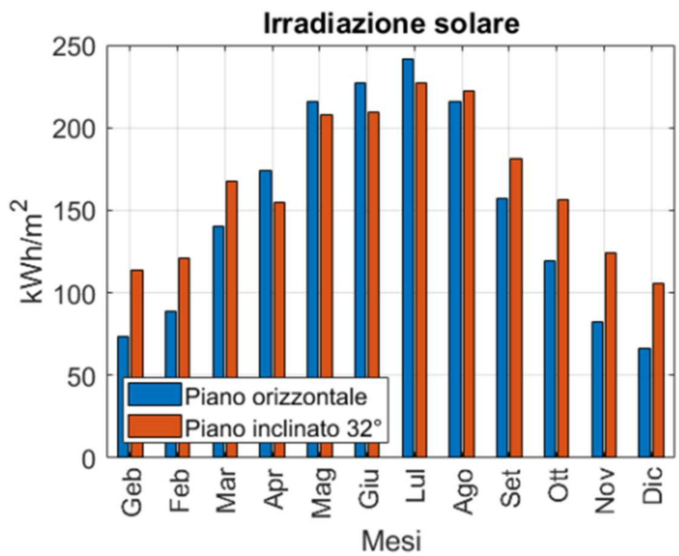


Figure 11. Monthly solar irradiation on the horizontal and inclined plane at 32° [19]

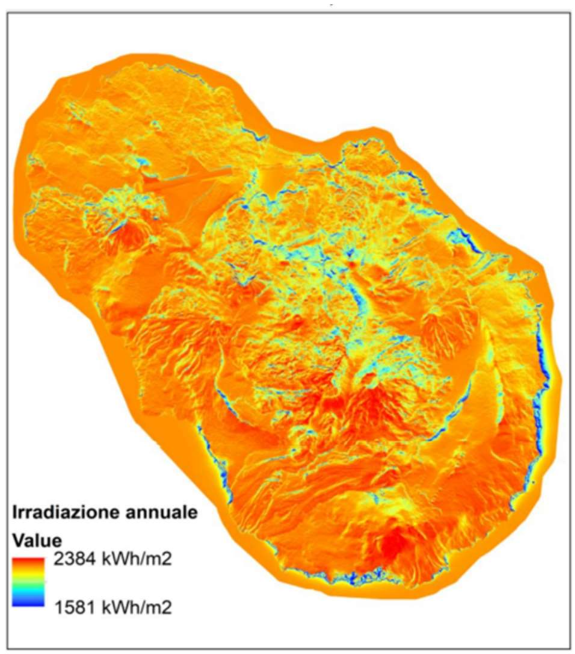


Figure 12. Map of solar radiation on Pantelleria [19]

Wind

In Pantelleria island, due to its location in the center of the Sicilian Channel the wind blows very strongly. The average annual wind speed (on- and off-shore) at 50 m a.g.l./a.s.l. is shown in Figure 13. The annual average velocity, depending on the area, ranges mainly between 7-8 m/s (yellow) and 8-9 m/s (pink) [32].

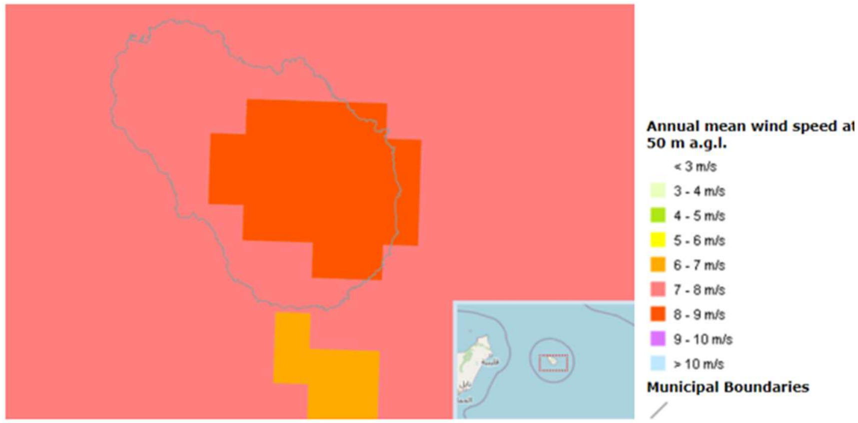


Figure 13. Annual average wind speed map of the island of Pantelleria [32]

Geothermal

The island of Pantelleria is the summit of a currently active underwater volcano. According to the Pantelleria Agenda [19], between 1996 and 1999, executive plan was implemented to improve the exploitation of geothermal resources with the goal to build a small-scale power plant (2.5 MW), but at present, no project has ever actually been implemented.

Wave

The island of Pantelleria, along with the western area of Sardinia, is among the most energetic spots in the Mediterranean Sea. The average annual incident energy flux in the northwest area of the island is approximately 7 kW/m, referring to the unit length of the wave front [33].

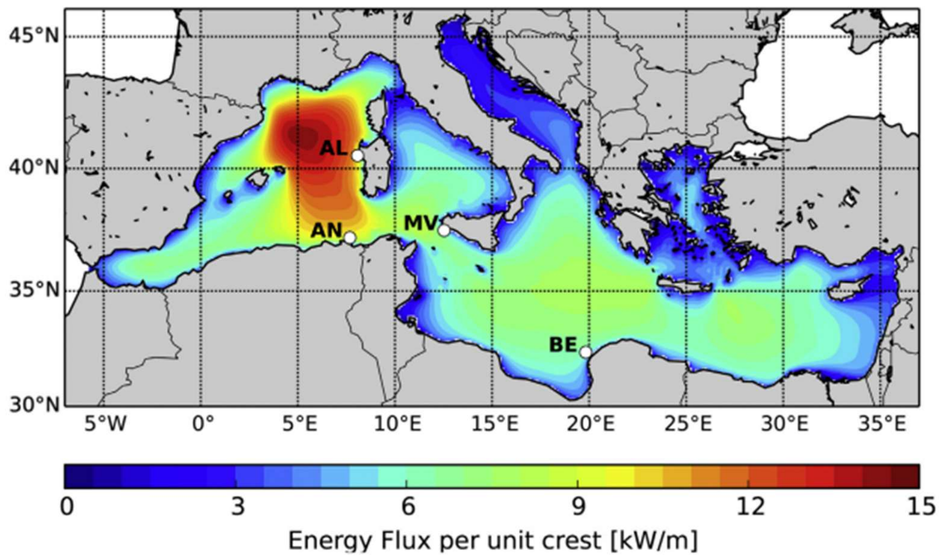


Figure 14. Mean energy flux per unit crest [Kw/m] between 1979 and 2013 [33]

Biomass

Pantelleria has biomass resource availability from organic residues of forestry, agricultural, organic fraction of municipal solid waste (OFMSW) [19]. The biomass from agricultural waste is estimated to be about 950 t/year of viticulture waste and about 400 t/year of oil production waste. The estimation of the total biomass from forest residues available on the territory is about 6000 t/year, but only 15% can be exploited due to the difficulty in recovering. Finally, on the island about 1100 t/year of organic fraction of municipal solid waste is produced.

3.2 Modeling in TEMOA

The just-quoted Pantelleria energy system has been modeled within the TEMOA framework. It is an isolated model and all the interaction with Italy have been modeled by import parameters.

The time horizon is divided into different time-periods, represented by the milestone years. They are differentiated in past and future years. The first time-period is the base-year in which the features of the reference energy system in 2013 have been reproduced. After 2013, the defined future milestone years are 2014, 2015, 2016, 2017, 2018, 2020, 2022, 2025, 2030, 2035, 2040, 2045, 2050. According to the milestone years, the model's output can be divided into Past RES evolution and Future RES evolution. The results of the model for the past period follow the historical evolution of the system, while the future system evolution represents the development of the model following the implemented scenarios. In Figure 15, a schematic representation of the different evolution is shown.

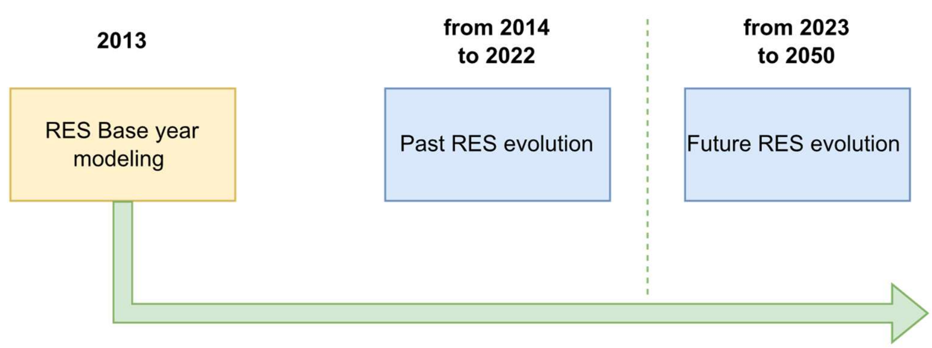


Figure 15. Schematic representation of the RES evolution

To represent the intermittent nature of the supply side (due to the renewable sources productivity) and end-use (due to the variable period of use of different end-use services during the year or day) additional time-slices have been provided: seasons, times of the day. In particular, to achieve realistic modeling of energy consumption and production, as in TEMOA-Italy, also in

TEMOA-Pantelleria all the milestone years are subdivided into four seasons, each of which representing ¼ of the year, and each 24 hours divided in day, night and peak with different shares according to the periods of the year in Table 1 [14].

Table 1. Time-slice subdivision of the year

Season / Time	Spring	Summer	Fall	Winter
Day	$\frac{1}{4}*\frac{11}{24} = 11.5\%$	$\frac{1}{4}*\frac{12}{24} = 12.5\%$	$\frac{1}{4}*\frac{11}{24} = 11.5\%$	$\frac{1}{4}*\frac{10}{24} = 11.5\%$
Night	$\frac{1}{4}*\frac{12}{24} = 12.5\%$	$\frac{1}{4}*\frac{11}{24} = 11.5\%$	$\frac{1}{4}*\frac{12}{24} = 12.5\%$	$\frac{1}{4}*\frac{13}{24} = 13.5\%$
Peak	$\frac{1}{4}*\frac{1}{24} = 1\%$	$\frac{1}{4}*\frac{1}{24} = 1\%$	$\frac{1}{4}*\frac{1}{24} = 1\%$	$\frac{1}{4}*\frac{1}{24} = 1\%$

The demand in year t,$D_t$is associated to the drivers and elasticities following the Equation (2), where D_{t-1} is the demand of the year before, the term δ represents the associated driver relative in the same years and$e_t$is the elasticity value of this specific demand.

$$D_t = D_{t-1}[1 + \left(\frac{\delta_t}{\delta_{t-1}} - 1\right) * e_t] \tag{2}$$

The structure of TEMOA-Pantelleria RES is represented in Figure 16.

The following paragraphs describe in detail the base year modeling and prospects of the Pantelleria energy system.

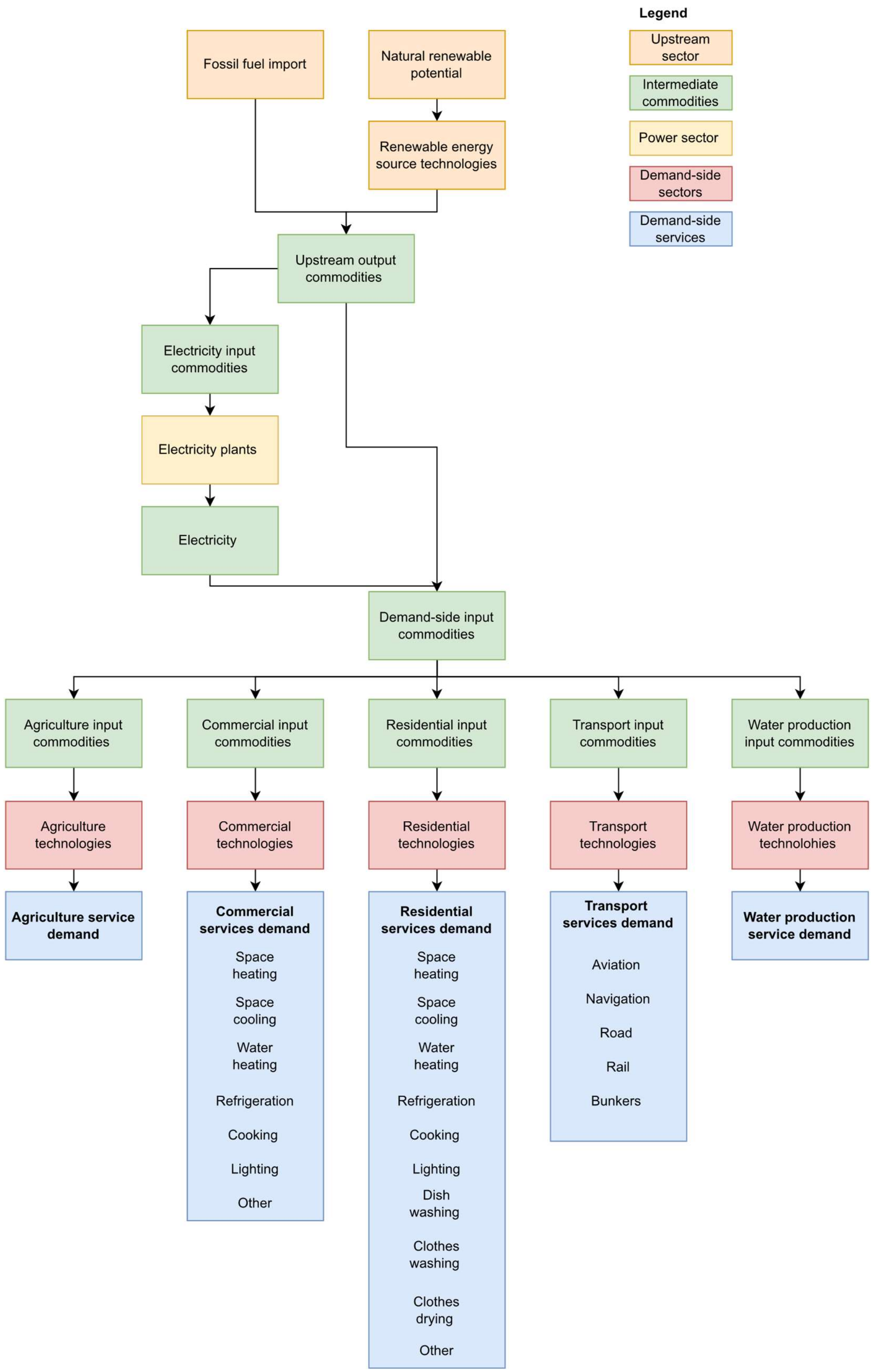


Figure 16. Pantelleria reference energy system structure

3.3 Base year modeling

2013 has been chosen as the base year due to the availability of data and the possibility of calibrating the RES past evolution with the data reported in the Pantelleria Energy Transition Agenda, based on 2018 data [19].

The base year has been constructed knowing the final energy consumption by sectors and the produced or imported energies. Starting from this data, as already mentioned, the model relies on the same technological characterizations (efficiencies, life, costs, etc.) implemented in TEMOA-Italy [14].

3.3.1 Upstream and power generation

The upstream and the power sector constitute the supply side of the RES. In the supply-side, the primary energy resources are transformed into energy vectors (through the technologies), that becomes the input commodities to the demand-side sectors.

3.3.1.1. Upstream sector

Generally speaking, in ESOMs the upstream sector is the one that comprises all processes of resources extraction, fuels production and import that represent the input commodities to the other sectors.

Concerning fossil resources, the Pantelleria system does not include any type of extraction technology. The fossil fuels are imported from Italy and they constitute an input from outside the energy system [31]. Therefore, it is associated an import price to the modeled intermediate technologies that represent the import. The fuels import price has been considered 25% higher than the Italian average value, consistently with the energy transition Agenda [19], to consider the additional cost of transportation. Table 2 reports the price of the main oil products (diesel fuel, gasoline and LPG) related to the base year (2013). It has been assumed an import prices variation through the years consistent with the Italian one [16], but always increased by 25%.

Table 2. Fuels medium Italian and Pantelleria importation prices in the base year

Fuel category	Fuel	Italian importation price [M€/MWh]	Pantelleria importation price [M€/MWh]
Oil products	Diesel	9.7E-5	1.21E-4
	Gasoline	9.7E-5	1.21E-4
	LPG	9.7E-5	1.21E-4

The natural potential of renewable energy sources has been modelled using technology representing them in order to associate parameters (namely, the cost and boundaries to the exploitation), and to set constraints. The only one renewable source exploited in 2013 is solar and its parameters have been summarized in Table 3.

Table 3. Technologies parameters representing natural potentials of renewable sources

Technology category	Parameters	Value
Solar potential	Extraction cost	0.36E-3 €/MWh [16]
	Lower boundaries	0 MW
	Upper boundaries	15 MW

As is shown in Table 3, the solar potential limits have been assumed by [19].

3.3.3.2 Power Sector

In general, the output commodities of the power sector are electricity and heat. In 2013, the Pantelleria power sector was composed only of electricity production plants. Indeed, the heat-related final demand was only satisfied through final technologies consuming electricity, without an heat production in the supply-side subsequently distributed to the demand-side of the system. As already introduced, in the base year the electricity was produced by the diesel power plant and the photovoltaic plants.

The two power plants typologies have been modeled in TEMOA framework as technologies and characterized by the following parameters, summarized in Table 4:

- Input commodities.
- Output commodities.
- Base year efficiency and its evolution.
- Base year installed capacity.
- Fixed operation and maintenance cost.
- Variable operation and maintenance cost.
- Activity constraints.

Table 4. Main power sector technologies parameters for the base year

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

In 2013 the Diesel plant produced 44 GWh of electricity, consuming 11 GWh of fuel (about 10000 tons). The annual production of electricity from solar was about 0.2 GWh [31].

3.3.2 Demand

The base-year demand has been modeled in detail sector by sector, knowing details of electricity consumption on the island, reported in detail in two Municipality assessments done in 2014 [34] and in 2015 [31]. Starting from the available data, energy consumption has been associated with every single end-use. The modeling steps of demand commodities and associated technologies have been detailed in the paragraphs below.

3.3.2.1 Residential

In 2013, according to [31], the residential sector energy consumption was about 15 GWh. In Table 5 the residential end-uses have been reported.

Table 5. Residential end-uses demand

Residential end-uses
Space heating
Space cooling
Water heating
Refrigeration
Clothes drying
Cooking
Clothes washing
Dishwashing
Lighting
Other

The energy consumption of the residential sector is associated only with the electricity and LPG vectors. The shares and consumption of the two fuels have been derived from [31] and shown in Table 6.

Table 6. Residential energy consumption per energy vector [31]

Energy vector	**Fractional energy vector share [%]**	**Energy consumption E_f^f [GWh]**
Electricity	77	11.8
LPG	23	3.5

LPG is used to power most cooking, the rest of the consumption is electric, including heaters. In the pie chart represented in Figure 17, the electricity fractional end-uses shares of Pantelleria residential sector, derived by [31], have been showed.

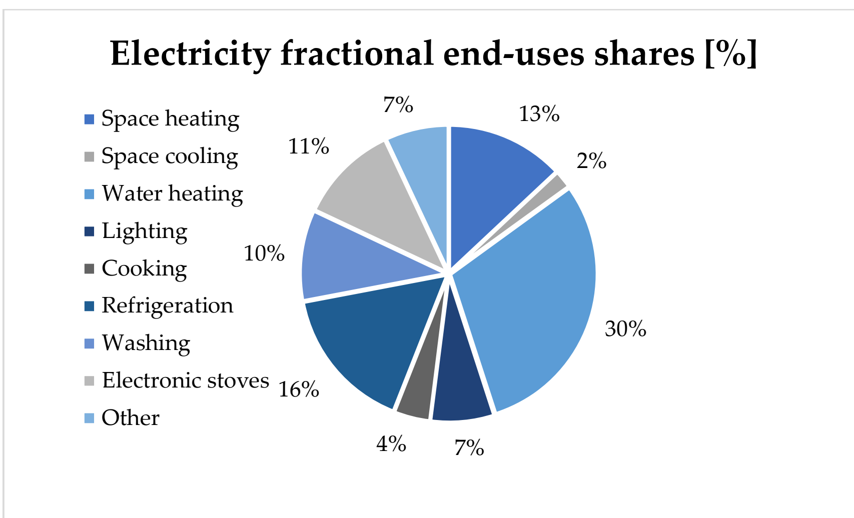


Figure 17. Fractional end-uses shares of electricity in the Residential sector [%] [31]

To calculate the end-use energy consumption $E^f_{eu,f}$, it is necessary to multiply the residential fractional end-uses and the energy consumption per vector (Equation (3)).

$$E^f_{eu,f} = f_{eu} * E^f_f \tag{3}$$

In Table 7 and Table 8 the fractional end-uses shares f_{eu} [31] and the residential end-use energy consumption $E^f_{eu,f}$ have been reported.

Table 7. Residential fractional end-uses shares

Fractional end-uses shares f_{eu} [%]										
Fuel	**Space heating**	**Space cooling**	**Water heating**	**Refrigeration**	**Clothes drying**	**Cooking**	**Clothes washing**	**Electric stoves**	**Other**	**Lighting**
Electricity	13	2	30	16	5	4	5	11	7	7
LPG						100				

Table 8. Residential end-uses energy consumption

End-uses energy consumption $E^f_{eu,f}$[MWh]										
Fuel	**Space heating**	**Space cooling**	**Water heating**	**Refrigeration**	**Clothes drying**	**Cooking**	**Clothes washing**	**Electric stoves**	**Other**	**Lighting**
Electricity	1535	236	3543	1189.6	590.5	472.4	590.5	1299	827	827
LPG						3527.7				

Only in the Residential sector, the heating end-use has been in turn split to consider the different specific consumption associated with the building construction period. To determine the heating consumption for each construction period, the fractional space heating share reported in the Municipality report [34] relative to 2011 have been assumed the same for the model base-year (2013).

The fractional space heating shares depending on the era of construction have been showed in the pie chart in Figure 18.

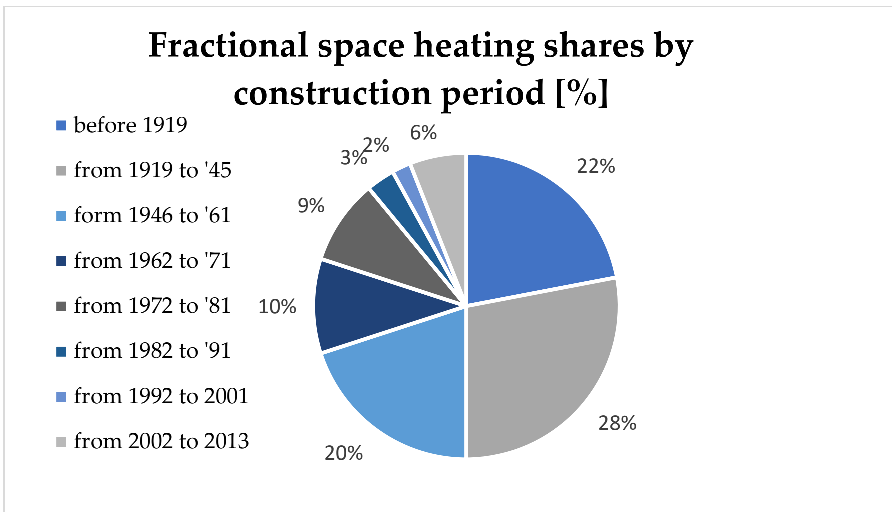


Figure 18. Fractional space heating shares in the residential energy consumption [34]

The Equation (4) shows the calculation of energy consumption by building type.

$$E^{f}_{bt,eu,f} = f_{bt} * E^{f}_{eu,f} \tag{4}$$

The results of Equation (4) have been showed on Table 9.

Table 9. Residential base year space heating energy consumption by building type

Construction period	Energy consumption [MWh]
before 1919	337.8
from 1919 to '45	429.9
from 1946 to '61	307.1
from 1962 to '71	153.5
from 1972 to '81	138.2
from 1982 to '91	46.1
from 1992 to 2001	30.7
from 2002 to 2013	92.1

The final energy consumption associated to each technology, $E_{tec\ ,eu,f}^{f}$, has been calculated using Equation (5) for the space heating and Equation (6) for all other end-uses, where f_{tech} represents the input commodity share.

$$E_{tech,eu,f}^{f} = f_{tech} * E_{bt,eu,f}^{f} \tag{5}$$

$$E_{tech,eu,f}^{f} = f_{tech} * E_{eu,f}^{f} \tag{6}$$

The technology useful energy has been calculated knowing the efficiency (eff) [16] of each technology (Equation (7)).

$$E^{u} = eff * E_{tech,eu,f}^{f} \tag{7}$$

All the base year technologies by energy services, and the associated parameters have been summarized in Table 10. In the absence of specific data for Pantelleria, it has been assumed the same input commodity share of TEMOA-Italy [16]. Also, the technology efficiencies have been considered the same of the mainland, except those related to lighting that were expressly reported in a technical report on energy efficiency [34].

Table 10. Demand-side technologies by residential energy end-uses

Demand-side technologies by Residential energy services						
Energy service	**Technology**	**Input commodity share f_{tech} [%]**	**Input commodity**	**Final Energy $E^{f}_{tech,eu,f}$ [MWh]**	**Efficiency [%]**	**Useful energy E^{u} [MWh]**
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

In the residential sector, there are some services that are not expressed in energy terms. Therefore, it is necessary to define some conversion parameters (eff_{conv}) to calculate the final demand (Equation (8)).The conversion parameters are the same of TEMOA-Italy, but converted to the unit of measurement coherent with the TEMOA-Pantelleria database (Table 11).

Table 11. Conversion parameters for end-use expressed in non-energy terms for the residential sector

Conversion parameters	
Clothes washing	9.38E-4 Mlav/MWh
Dishwashing	6.48E-4 Mlav/MWh
Clothes drying	2.52E-4 Mlav/MWh
Lighting	4.43E-4 Mlav/MWh

In Figure 19 it has been represented the conceptual scheme that it has been followed to calculate the end-use demand for a specific sector, in this case the residential one.

$$D_{RES} = eff_{conv} * E^u \tag{8}$$

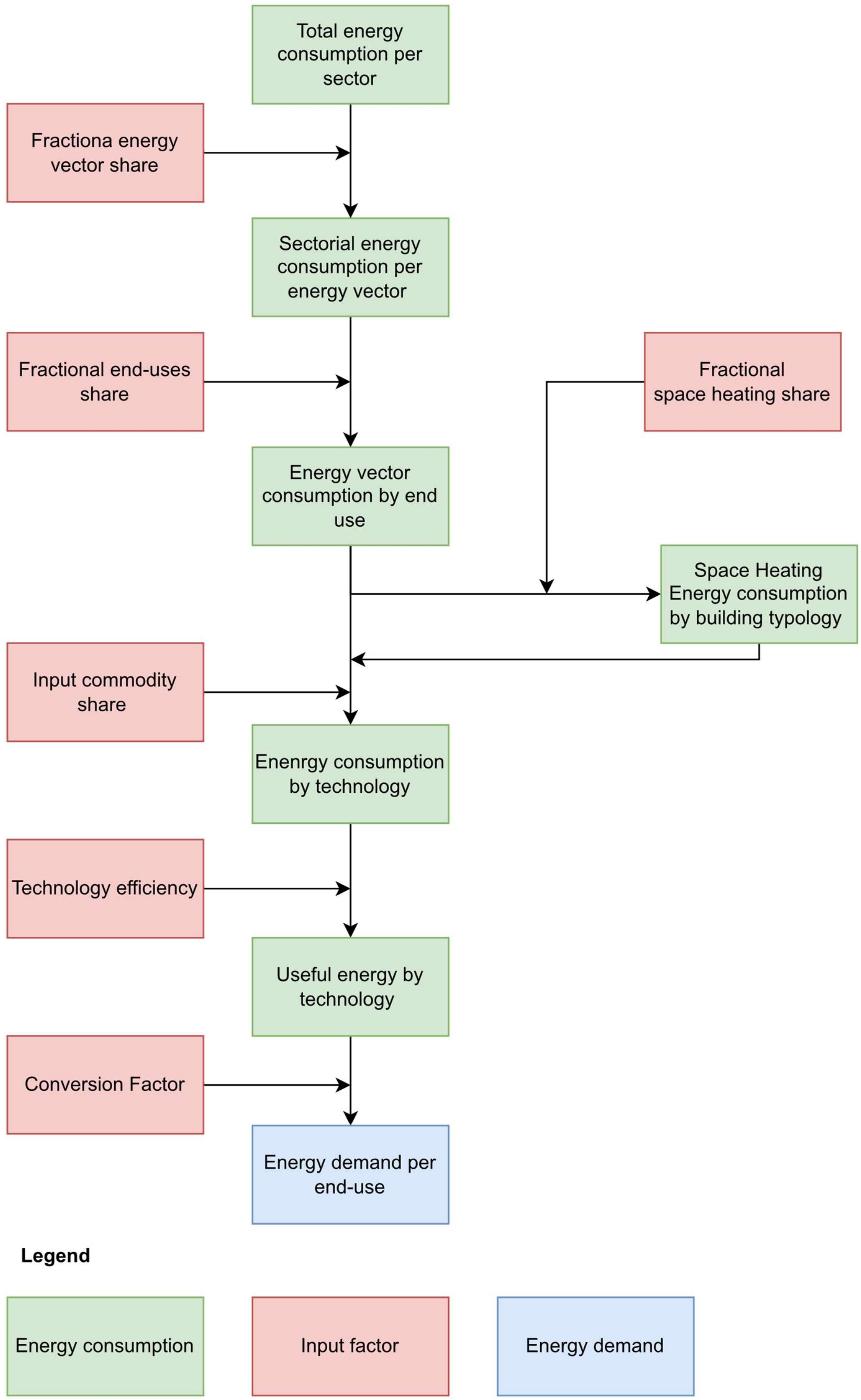


Figure 19. Schematic representation of the end-use demand calculation

3.3.2.2 Commercial

To calculate the commercial sector demand, starting from the known sector energy consumption [31] the same procedure of residential has been implemented. The steps represented in Figure 19 have been followed, other than the division of the buildings in period construction.

In 2013, according to [31], the commercial sector energy consumption was about 13 GWh. In Table 12 the commercial end-uses have been reported.

Table 12. Commercial end-uses demand

Commercial end-uses
Space heating
Space cooling
Water heating
Refrigeration
Cooking
Lighting
Electric office equipment

As the residential sector, according to [31] ,the energy consumption of the commercial sector is associated only to the electricity and LPG vectors. The shares and consumption of the two fuels are shown in the Table 13.

Table 13. Commercial sector energy consumption per energy vector

Energy vector	**Fractional energy vector share [%]**	**Energy consumption E_f^f [MWh]**
Electricity	77	11810
LPG	23	3528

The energy consumption must be split into the different services (end-uses) of the sector. As in the case of the residential sector, fractional shares of end-use are multiplied by the energy consumption per fuel (Equation (9)).

The specific data for Pantelleria are not knowing, therefore fractional shares have been assumed equal to the TEMOA-Italy values [15].

$$E^{f}_{eu,f} = f_{eu} * E^{f}_{f} \tag{9}$$

In Table 14 and Table 15 the fractional end-uses shares f_{eu} and the residential end-use energy consumption $E^{f}_{eu,f}$ for the commercial sector have been reported.

Table 14. Residential fractional end-uses shares [15]

fractional end-uses shares f_{eu} [%]							
Fuel	Space heating	Space cooling	Water heating	Refrigeration	Cooking	Electric equipment	Lighting
Electricity	8	13	5	7	1	36	30
LPG					100		

Table 15. Residential end-uses energy consumption

End-uses energy consumption $E_{eu,f}^{f}$ [MWh]							
Fuel	Space heating	Space cooling	Water heating	Refrigeration	Cooking	Electric equipment	Lighting
Electricity	924.5	1502.3	577.8	808.9	115.6	4160.2	3466.8
LPG					1004.9		

The final energy consumption associated to each technology, $E_{tech,eu,f}^{f}$, has been calculated using Equation (10), where f_{tech} represents the input commodity share.

$$E_{tech,eu,f}^{f} = f_{tech} * E_{eu,f}^{f} \tag{10}$$

The technology useful energy has been calculated knowing the efficiency (eff) [15] of each technology (Equation (11)).

$$E^{u} = eff * E_{tech,eu,f}^{f} \tag{11}$$

In Table 16 all the base year technologies by energy services and the associated parameters have been summarized. It has been assumed the same input commodity share of TEMOA-Italy [15]. Also, the technology efficiencies have been considered the same as the mainland.

Table 16. Demand-side technologies by commercial energy services

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

The final commercial sector demand $D_{com,j}$ of j[th] end-use, is equal to the sum of all technologies useful energy of the j[th] service, as is showed in Equation (12). In the Equation (12), N is the number of all the technologies associated to the service.

$$D_{com,j} = \sum_{i=0}^{N} E_i^u \tag{12}$$

The results of Equation (12) are showed in Table 17.

Table 17. Commercial sector demand divided by energy end-uses

Commercial sector demands for energy service	
End use	$D_{com,j}$ $[MWh]$
Space heating	9967.2
Space cooling	6311.0
Water heating	1051.6
Lighting	4333.9
Cooking	502.4
Refrigeration	231.1
Electric office equipment	577.8

3.3.2.3 Agriculture

In 2013 the agriculture energy consumption was about 1507 MWh [31]. The only one energy vector associated to the agriculture sector was the electricity.

The efficiency assumed for the agriculture sector technology was assumed equal to one. Therefore, for this sector, the final energy demand D_{Agr} is equal to the energy consumption, namely the used electricity. The agriculture demand is about 1507 MWh.

3.3.2.4 Transport

The Pantelleria transport sector in 2013 was composed by several end-uses that are listed in Table 18 [31], [34]. The transport sectors fuel are gasoline, diesel, and aviation gasoline. The energy consumption of the transportation sector in the base year is reported in Table 19.

Table 18. Transport end-uses demand

Transport end-uses
Domestic aviation
Road
Domestic navigation
Bunkers

Table 19. Transport energy consumption by fuel [31]

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

The categories of the transportation sector are divided in turn into different vehicles, each with a specific share. The share factors for transportation modes f_{tm}, determined by [34], have been listed in Table 20.

Table 20. Share factor for the transportation modes

Share factors for transportation modes f_{tm} [%]				
Transport modes		*Motor gasoline*	*Aviation gasoline*	*Diesel*
Road	Cars	0.76		0.95
	2 wheels	0.04		0.05
	Trucks	0.20		
Navigation	Domestic navigation			0.29
	Bunkers			0.71
Air	Domestic aviation		1.00	

In order to split the energy consumption by energy vector to the transport services, the Equation (13) have been implemented. The results have been reported in Table 21.

$$E_{tm,af} = f_{tm} * E_{af} \tag{13}$$

Table 21. Splitting by transportation end-uses

Splitting by transportation end-uses $E_{tm,af}$ [MWh]				
Transport modes		*Motor gasoline*	*Aviation gasoline*	*Diesel*
Road	Cars	14040.2		16497.3
	2 wheels	739		868.3
	Trucks	3694.8		
Navigation	Domestic navigation			316.7
	Bunkers			791.7
Air	Domestic aviation		24120	

The final energy consumption associated to each technology, $E^{f}_{tec\ ,tm,f}$, has been calculated using Equation (14), where f_{tec} represents the input commodity share.

$$E^{f}_{tech,tm,f} = f_{tech} * E_{tm,af} \tag{14}$$

In Table 22 all the base year technologies by energy services and the associated parameters have been summarized. Also, for the transport sector, without site-specific data, it has been assumed the same input commodity share of TEMOA-Italy and the technology efficiencies have been considered the same as the mainland [15].

Table 22. Demand-side transport technologies by transportation modes in the base-year

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

The final demand for transportation by service D_{Tra} is not expressed in energy terms; therefore, the conversion parameters have been assumed for each technology. These conversion parameters have been sourced from TEMOA-Italy [15]. The conversion factors and final demands, calculated with the Equation (15) are showed in Table 23.

$$D_{TRA} = eff_{conv} * E^{f}_{tech,tm,f} \tag{15}$$

Table 23. Conversion factors and service demands for transport technologies

Conversion factors and service demands for transport technologies.

Transport modes		*Technology*	UDM	Efficiency conversion eff_{conv}	Service Demand D_{Tra}	UDM
Road	Cars	Diesel car	Bvkm/MWh	1.3E-6	2.1E-2	Bv* km
		Gasoline car	Bvkm/MWh	1.1E-6	1.5E-2	Bv* km
	2 wheels	Moped diesel	Bvkm/MWh	4.7E-6	1.3E-3	Bv* km
		Motorcycle diesel	Bvkm/MWh	3.7E-6	2.2E-3	Bv* km
		Moped gasoline	Bvkm/MWh	4.7E-6	1.1E-3	Bv* km
		Motorcycle gasoline	Bvkm/MWh	3.7E-6	1.9E-3	Bv* km
	Trucks	Trucks gasoline	Bvkm/MWh	8.7E-7	3.2E-3	Bv* km
Navigation	Domestic	Domestic navigation	MWh/MWh	1	3.17E+2	MWh
	Bunkers	Bunkers	MWh/MWh	1	7.92E+2	MWh
Air	Domestic	Domestic aviation	MWh/MWh	1	2.41E+4	MWh

3.3.2.5 Water production – Desalination

The TEMOA-Pantelleria includes one more demand sector than the TEMOA-Italy [16]. It has been decided to create a separate sector for water production in perspective to the modeling of the reference water system. The only energy services associated with the Pantelleria water production is the desalination process and the pumping system of the distribution water grid (already counted in the energy needed by water production sector).

As explained in detail in Chapter 4, one of Pantelleria biggest problems is water scarcity. To overcome this problem, two desalination plants have been built. In 2013, these plants used two different technologies [21]. The larger was composed of two evaporative modules with mechanical vapor compression, the smaller exploited the EDR (electrodialysis with reversed polarity) technology. In this demand sector, the technology capacities and activities have been expressed in terms of m^3 to represent water production.

In the RES, the demand of the water production sector has been expressed simply as the m^3 of water produced in the year, evaluated using the procedure reported in Figure 20. At this stage, namely the energy system modeling, differentiated water demand by sector and its annual variability have not been considered.

The only one energy vector used in the water production sector is electricity. The energy consumption of the desalination technologies in the base-year was about 11260 MWh [31].

In Table 24 all the base year technologies and associated parameters, determined by the Pantelleria technical desalination plants report [21], have been summarized. In the same table, the conversion coefficient and the base year demand have been reported. In the case of desalination, the conversion coefficients also include the efficiency of the technology. Indeed, conversion coefficients, expressed as m^3/MWh, represent the m^3 of water already treated per MWh.

The final energy consumption associated to each technology, $E^{f}_{tech,eu,f}$, has been calculated using Equation (10), where f_{tech} represents the input commodity share, determined by [21]. The final energy demand for the water production has been calculated multiplying the conversion coefficient $coff_{DES}$ to the final energy consumption $E^{f}_{tech,eu,f}$ (Equation (16)).

Table 24. Demand-side technologies by commercial energy services

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 $coff_{DES}$ [m^3/MWh]*	*Water production demand D_{DES} [m^3]*
Desalination	EDR	27.5	Electricity	696.3	3.03E-4	2.11E+5
	MC	72.5		10564	5.26E-5	5.56E+5

$$D_{DES} = coff_{DES} * E^{f}_{tech,eu,f} \tag{16}$$

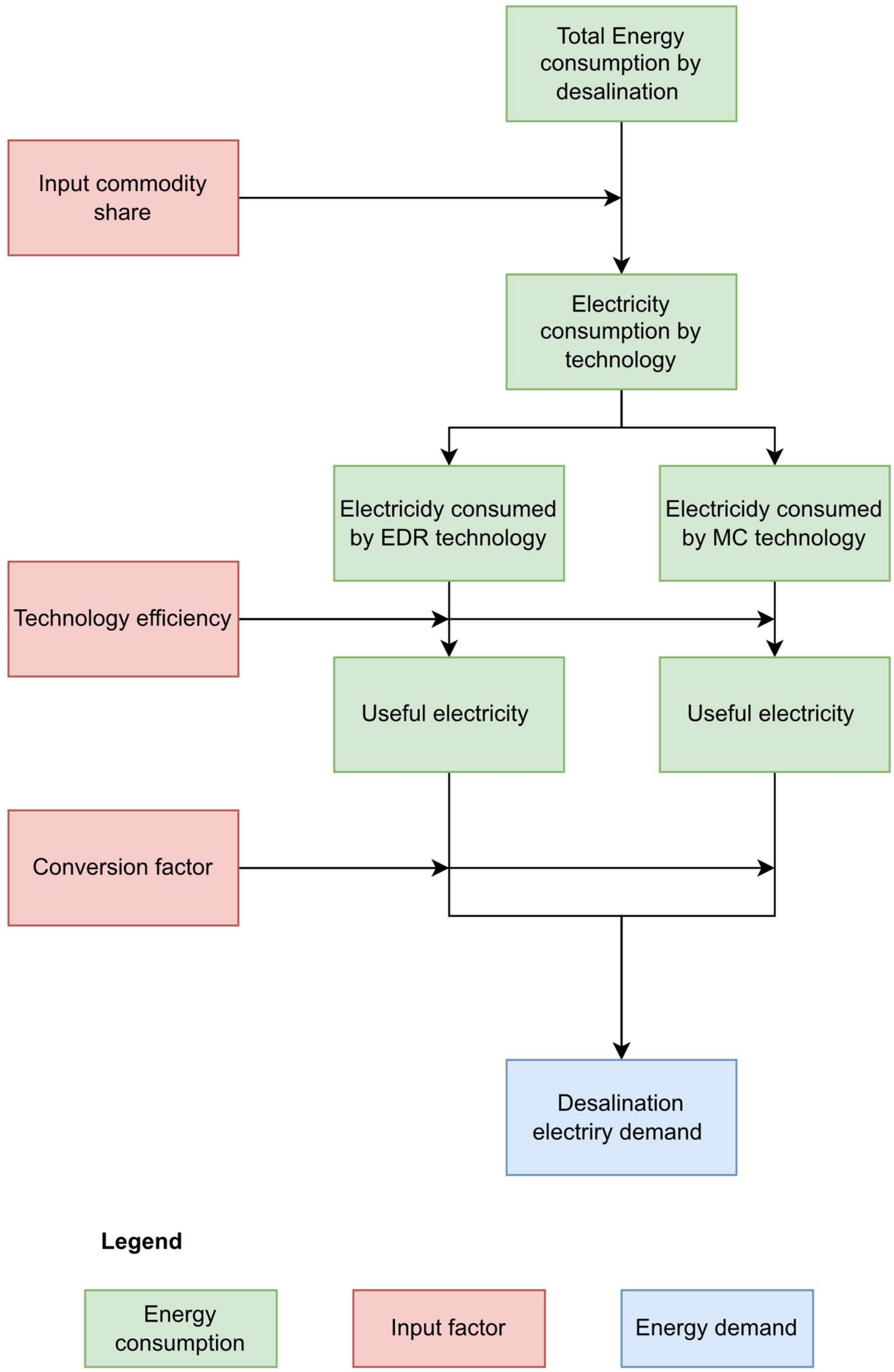


Figure 20. Specific flow-chart representing the water production energy demand modeling in the base year

3.3.3 Emissions

In the TEMOA framework, it also has included the emission computation. The emissions can be distinguished in two different categories: the fuel consumption emissions and the process emissions. The first emissions category is a combustion consequence, while the second type can be due to chemical transformation of raw materials or fugitive emissions [35].

The fuel consumption emissions are "commodity-based". Therefore, in order to associate an emission to a commodity, in the TEMOA framework the parameter "CommodityEmissionFactor" (CEF) has been defined [35]. The CEF is calculated per unit of energy.

The "technology-based" emission, namely the process emissions, are considered by the "EmissionActivity" (TEF) parameter. This emission factor is expressed per unit of output commodity produced by the technology (namely, the activity).

In order to obtain a total emission factor, it is necessary that the commodity-based and technology-based emissions are comparable. Therefore, the CEF must be divided by technology efficiency. In the TEMOA framework the Equation (17) has been implemented [35], the script overwrites the manually inserted EmissionActivity table (namely, TEF) and the output of the model is a total emission factor.

$$Emission\ Activity = \frac{CEF}{Efficiency} \tag{17}$$

The considered emission commodities are CO_2, CH_4, N_2O. In Table 25 are showed the specific-sector Commodity Emission Factors for the base year commodities and technologies.

Table 25. Emission factors by sector for base year commodities

Commodity Emission Factor [t/MWh]	
Residential	
Commodity: LPG	
CO_2	0.23
CH_4	0.18E-1
N_2O	0.36E-3
Commercial	
Commodity: LPG	
CO_2	0.23
CH_4	0.18E-1
N_2O	0.36E-3
Transport	
Commodity: Aviation kerosene	
CO_2	0.25
CH_4	0.22
N_2O	0.25E-1
Commodity: Gasoline	
CO_2	0.25
CH_4	0.25E-1
N_2O	0.24E-1
Commodity: Diesel	
CO_2	0
CH_4	0.47E-2
N_2O	0.22E-1
Electricity production	
Commodity: Diesel	
CO_2	0.28
CH_4	0.3E-5
N_2O	0.1E-4

3.4 Future prospects

As already mentioned, there are two types of reference energy system future prospects (Figure 15): The past RES evolution and the future RES evolution.

Past RES evolution

For TEMOA-Pantelleria, the data calibration should be between the model and the historical data from 2014 to 2022. However, there is no data availability for all milestone years. The only data on Pantelleria energy consumption and production are for 2018 [17], [19]. An attempt was made to calibrate the model, based on the available data.

Future RES evolution

To determine the future projection from 2023 to 2050 of Pantelleria energy system, scenarios must be analyzed. In particular, for the energy system two scenarios have been implemented:

a. The Electricity Mix Transition (EMT) scenario: fossil fuel constraints have been imposed on the power sector in order to model how the system achieves the renewable penetrations target set by the Pantelleria CE4EUI Agenda [19].
b. The No Electricity Mix Transition (NEMT) scenario: no constraints have been imposed on the power sector to analyze how the system would evolve without any constraints on fossil fuels.

3.4.1 Upstream and power generation

Past RES evolution

According to the Pantelleria Agenda [19], the electricity generation in Pantelleria in 2018 occurred through the diesel plant, distributed photovoltaic and mini and micro wind plants. In Table 26 the installed capacities of the power plants are shown. All these data have been implemented in the TEMOA-framework as constraints.

Table 26. 2018 power plants capacity in the Pantelleria

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

Future RES evolution

To model the energy system scenarios, different constraints to the power sector have been imposed.

Concerning the EMT scenario, a maximum output from diesel plant has been imposed by 2030, equal to 20% of the overall electricity mix. Indeed, despite the Pantelleria C4EUI Agenda [19] set a 100% renewable electricity mix by 2050, a minimum share of electricity produced from dispatchable technologies must be considered [36]. Specifically, in the Temoa-Pantelleria it has been set coherent with [36] and to the OSeMOSYS model [17]. In the NEMT scenario, the diesel plant capacity has been assumed unchanged and no limits on the productivity have been set in order to leave the model completely free to optimize the electrical mix and then compare it with the EMT scenario.

To implement the future scenarios, new renewable sources of energy have been defined. For all the new energy production technologies, the main parameters have been defined:

- Efficiency
- Investment cost (according to the year of installation)
- Fixed O&M costs
- Variable O&M costs
- Availability factor
- First year of availability
- Lifetime

All these parameters have been assumed equal to those for Italy [16], since, not having specific data for the island, it was considered reasonable to use the national average meters, except for wave energy plants. Indeed, in the TEMOA-Pantelleria, the wave energy source has also been modeled.

Italy, in fact, does not have a high wave resource potential, therefore, considering the high costs associated with the technology, it is appropriate to not consider it among the available Italian sources. The case of Pantelleria, however, turns out to be an exception [33]. For several years the Politecnico di Torino University has launched different studies on the island related to the creation of wave energy plants as it turns out to be a suitable site.

In fact, there are currently full-scale prototypes on the island [37], and it is therefore appropriate to include wave energy among future resources. All plant data were taken from [17]. Being a renewable source, wave energy resource is intermittent. As with all renewable sources, a capacity factor technology has been modeled within TEMOA-framework that accounts for the annual variability of the resource.

In order to have a realistic evolution of the energy system, maximum renewable potential has been imposed. Indeed, constraints listed in Table 27 have been introduced into the model.

Table 27. Maximum future renewable potential assumed in Pantelleria island

Maximum renewable rated capacity	
Solar onshore	15 MW
Wind onshore	0.3 MW
Biogas	0.12 MW

The solar and wind onshore constraints have been assumed by the Pantelleria Agenda for energy transition [19].

The biogas potential has been estimated considering the annual production of organic solid wastes on the island and the energy produced by an anaerobic digestor with an OFMSW input feed. The feed parameters (namely, Total Solid percentage (TS%), Volatize Solid, sludge temperature) and the biogas plant standards (namely, hydraulic retention time HRT, biogas specific production, digestor temperature, etc.) have been assumed by literature.

For the upstream sector, the same level of electrification has been imposed for both scenarios, and in particular:

a. a gradual phasing out in LPG import has been imposed by 2030 replacing its in commercial and residential with the electrification of cooking end-use, to achieve the goal of CLE4EUI Agenda [19] on the self-sufficiency of the island and for consistency with the OSeMOSYS model [17].

b. it has been modeled also gasoline and diesel import reduction for transportation purpose, replacing traditional fuel vehicles with hybrid and electric ones in order to achieve the goal of CLE4EUI Agenda [19] on the transport sector transition and for consistency with the OSeMOSYS model [17].

3.4.2 Demand

Concerning the demands projections, as already mentioned, Equation (2), the **drivers** (Figure 21) and **elasticities** have been assumed.

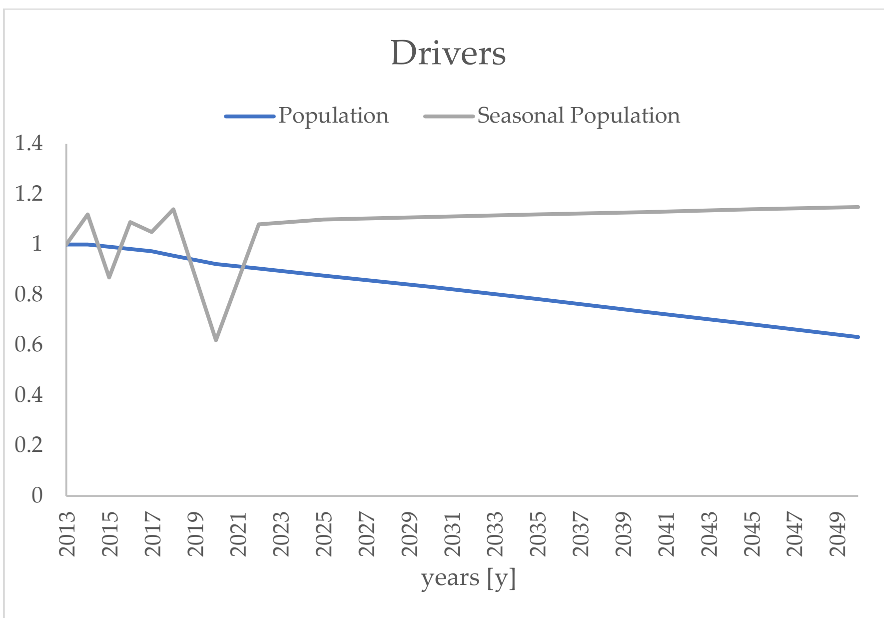


Figure 21. Driver's behavior evolution

New technologies have been defined also in the demand-side sectors to achieve the goals already mentioned in the future upstream sector description. Indeed, the demand-side technologies powered by fossil fuels have been gradually substituted with electric alternatives. For example, in the transport sector, a stepwise electrification has been imposed with the goal to achieve 100% of electric road vehicles in 2050 and the LPG cookers have been gradually replaced by the electric ones by 2030.

For technologies already powered by electricity in the base-year, higher efficiencies have been imposed, according to Italian trend [16], or more sustainable alternatives have been provided. For example, in 2013, the space heating demand was satisfied only by electric devices. New technologies powered by solar thermal or geothermal energy have been defined in the TEMOA-framework.

Chapter 4

Reference Water System

Consistent with how the Reference Energy System (RES) has been defined, a Reference Water System (RWS) comprises all components related to the production, conversion, delivery, and use of water.

In the thesis work, an ESOM (namely TEMOA framework) has been re-adapted to develop water system optimization model. As in the RES case, it consists of techno-economic characterizations of supply-side and demand-side water sectors.

However, the cycle of water is conceptually different from the energy production and use. Consequently, the modeling approach must consider the different nature of the water system. To understand how to model the water system, its cycle has been explored in depth, and differences and similarities with respect to the energy system have been analyzed.

Analogous to RES, also in the RWS the commodities from the supply-side contribute to the water demand satisfaction. However, not all water resources can meet every demand indifferently. Depending on the origin, water is classified in several categories, each of which is able to satisfy different demand end-uses.

As primary energy resources, natural water reservoirs must be transformed to satisfy a water need. Indeed, water reservoirs, such as superficial water, groundwater, or seawater, are treated to achieve a certain level of quality and are then distributed to meet buildings, agriculture, and industrial water needs. Depending on the demand sector and the end-use which is to be served, water must reach different specific quality standards. These standards are set according to certain parameters that define the level or type of water and determine the treatment to which it must be subjected.

Once treated, water, like energy, is distributed to the various technologies that service the end-use commodities. While the energy cycle ends after the satisfaction of demand, the water cycle must continue but at the time, the model does not involve the wastewater treatment plant and water reutilization.

Indeed, depending on its end-use, the water output from the services (e.g., wastewater) is classified according to the parameters mentioned in the following and consequently it needs to be subject to treatment again. Based on the source of the wastewater, these treatments may be for disposal or reuse.

The parameters that discriminate the water level are physical, chemical, and biological. The most important physical parameters of water and wastewater are the Total Solids (TS) content (namely, the floating, in suspension and colloidal matter), the turbidity, the odor, the color and the temperature. The main chemical parameters are pH value, electrical conductivity, oxidation reduction potential, dissolved oxygen, and hardness. But it is necessary also to consider the chloride content, the surfactants, fat, grease, and oil content, metals and micropollutants, sulfur compounds, phosphorus and nitrogen compounds causing eutrophication. Lastly, the biological elements to consider are bacteria, viruses, protozoa, helminths, and pathogens.

Water standards associated with these parameters are set by national legislation. In Italy, the reference regulations related to water and wastewater treatment are “Testo Unico Ambientale”, namely Legislative Decree No. 152 of

2006 [38] and Law No. 167 of 2017 (European transposition) [39]. Drinking water standards are regulated by Legislative Decree No. 31 of 2001 [40].

4.1 Pantelleria water system

All aspects of water management have been considered in the modeling of Pantelleria water system. The system is relatively simple, and therefore has been analyzed in detail.

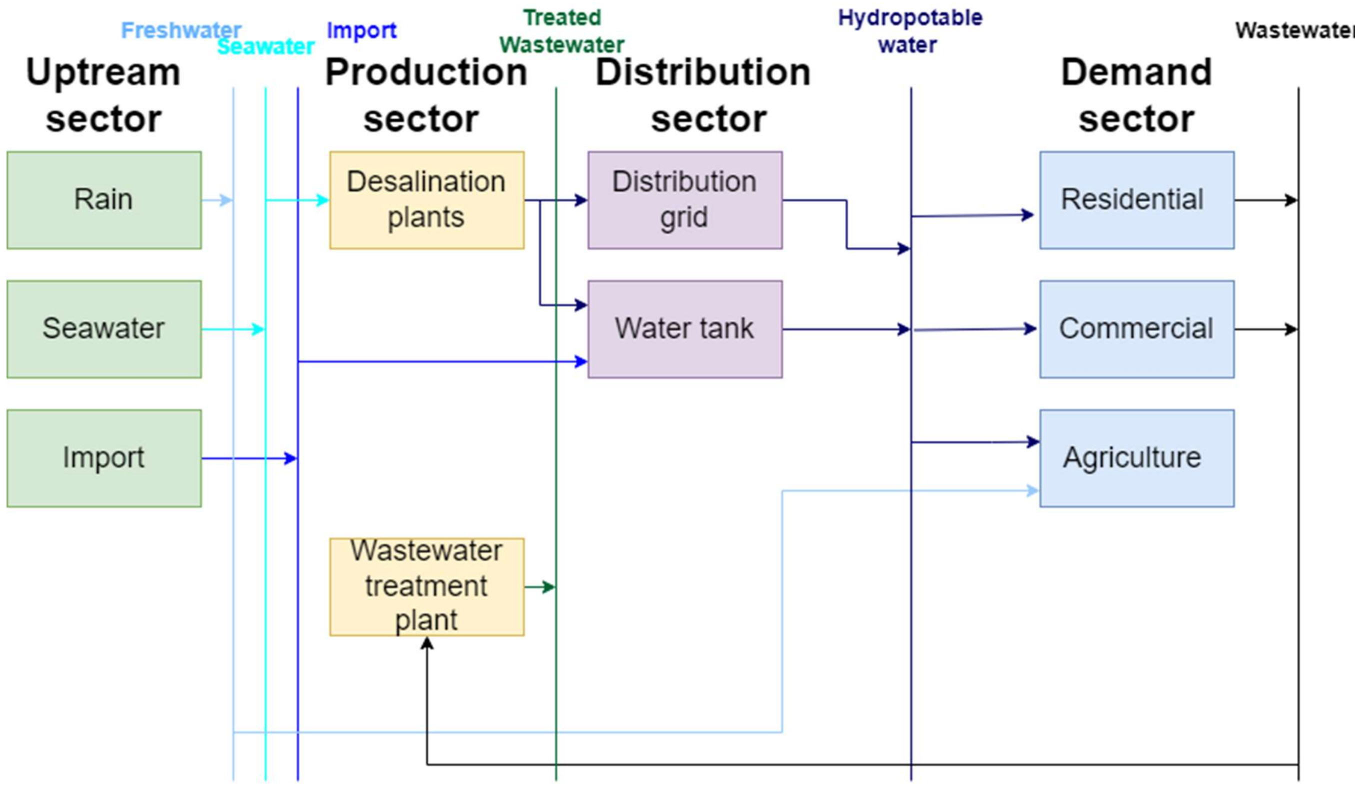


Figure 22. Pantelleria Reference Water System (2013)

In Figure 22 the schematic representation of Pantelleria RWS in 2013 has been represented.

As already mentioned, one of the biggest problems of Pantelleria is water scarcity. Pantelleria is an isolated system, characterized by almost total absence of superficial waters and highly permeable soil. Indeed, on the island there are not any rivers and the only one lake is the so called "Specchio di Venere", that has volcanic origin and clayey bottom, therefore, it cannot be used for hydro potable purposes. The soil instead, is divided into two classes [20]:

- Permeable soils due to medium to high grade porosity: due to the interconnectedness of these voids, water infiltrates the soils by flowing out rapidly.
- Permeable soils due to high cracking: the cracks of soils of volcanic origin have been generated during cooling. Such lithotypes usually are good aquifers, but in the Pantelleria case the absence of an impermeable level leads to the exclusion of the formation of exploitable groundwater.

The only primary water sources available in Pantelleria are seawater and rain. The drinking water is imported and during the summer, the hydro potable water that arrives by tankers is increased to meet the needs of tourists [21]. Rain is exploited for agricultural uses, aridoculture is practiced [27].

Seawater is pumped in the desalination plants and after treatment is in part distributed by the aqueduct system to the different demand sectors and is in part stored [41]. The wastewater output from the different services is treated to achieve environmental standards and then discharged to the sea [42]. In the TEMOA-Pantelleria RWS the wastewater treatment plant has not been modelled because its energy consumption is negligible, indeed it is not mentioned among the island energy use [31], and the treated water is not reused.

4.2 Modeling in TEMOA

The structure of the TEMOA-Pantelleria RWS model is the same as the already mentioned RES. The milestone years and time slices (seasons, portions of day, peak) are the same as the RES.

As in the building of the RES, the RWS model has also been developed, defining first the base year features and then the future projections constraints. Also in this case, the model can be schematized into Past RWS evolution (constituted by the past future years) and Future RWS evolution (represented by the future years projections).

Thanks to the past RWS evolution, namely the projections from 2014 to 2022, it can be checked that the system follows historical trends and thus that future RWS evolution provides reliable future results (Figure 23).

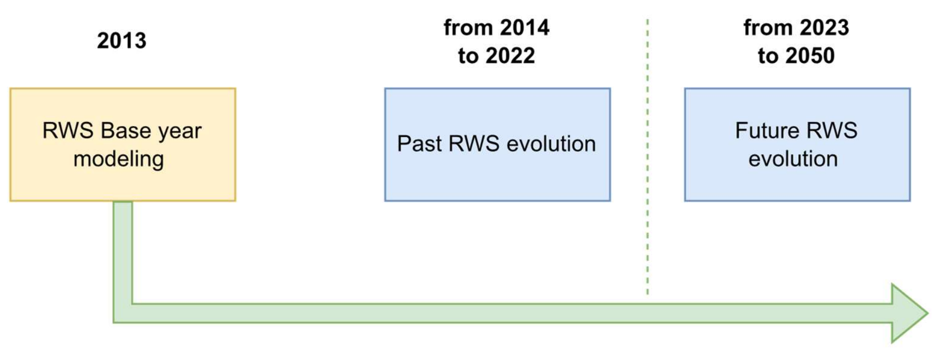


Figure 23. Schematic representation of the RWS development

To take into consideration the intermittency of the water primary resources (rain), of the end-uses, the same time slices of the reference energy system have been implanted also in the water module (Table 1). Indeed, rainfall is not a constant resource throughout the time span of a year but has seasonal variations; even end-uses do not have unique annual value (e.g., services associated with fluctuating population).

As in the RES, the future demand is calculated considering the drivers and defining the elasticity (Equation (2)). In the RWS, the defined drivers are the resident population and the touristic one. Indeed, as it will explain in much detail subsequently, in the water system, the influence of tourism on water consumption has been considered. The TEMOA-Pantelleria RWS structure has been represented in Figure 24.

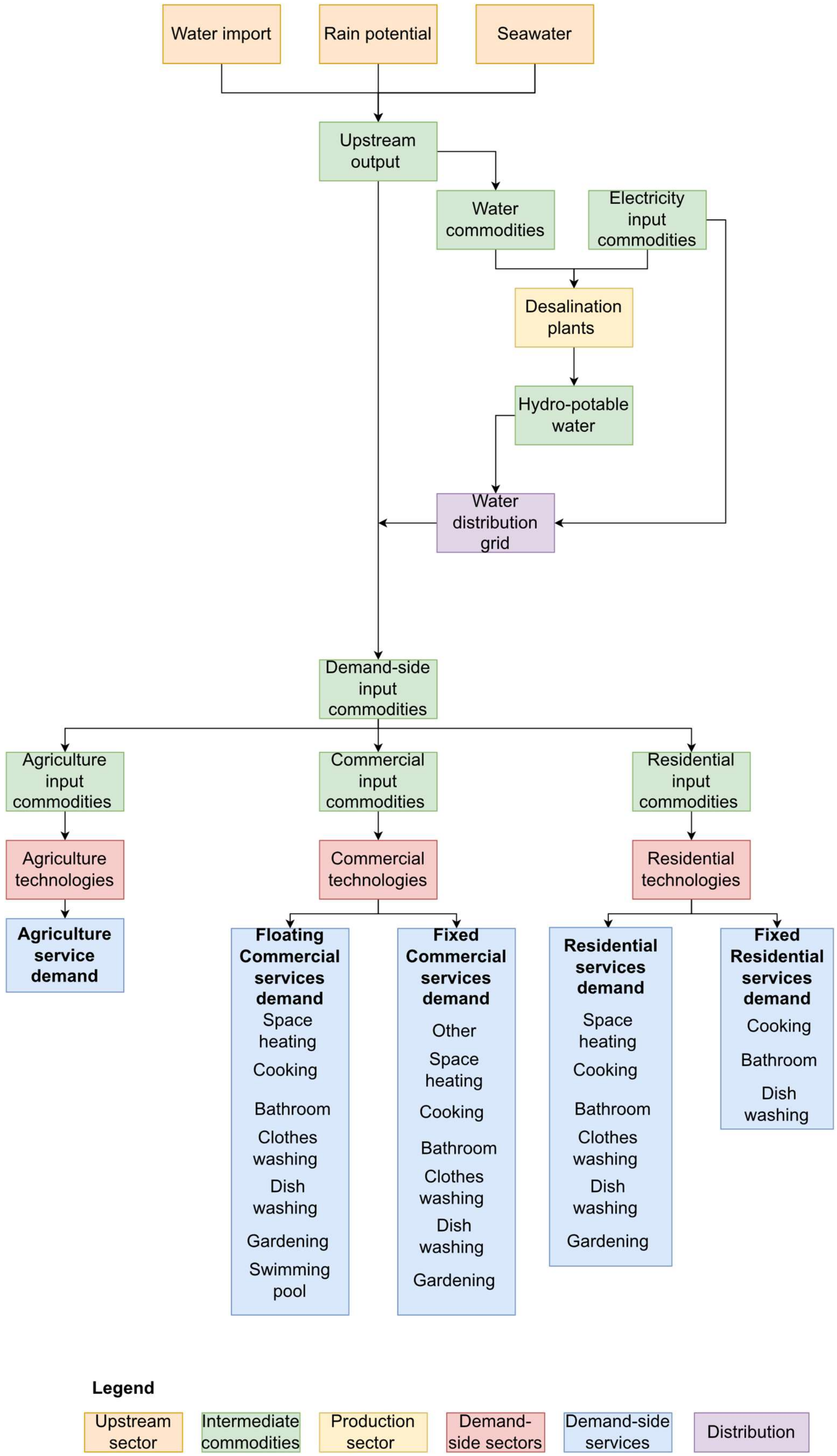


Figure 24. Pantelleria reference water system structure

4.3 Base year modeling

The base year of the RWS, as the RES, is 2013. All the information about the real structure of the water system of Pantelleria have been taken from the Pantelleria Municipality technical reports [21], [41].

In the water model the capacities and the activities have been defined in terms of m^3.

4.3.1 Water supply-side

The upstream sector consists of all water production and distribution elements and represents the RWS supply-side. Through these elements, the primary water sources are converted or transmitted in the form of water vectors that represent input commodities to the demand side sectors.

4.3.1.1 Upstream: External sources

The upstream sector includes the primary water sources modeling. This sector has the purpose of introducing in the model the available e resources that satisfy the demand side. As mentioned before, the Pantelleria primary water commodities are rain, seawater, and imported water. A quantitative analysis of the resources has been reported below:

Rain

To estimate the potential rainfall in 2013, average rainfall has been considered [22]. The Pantelleria rainfall data are showed in Figure 25 and reported in Table 28 for clarity.

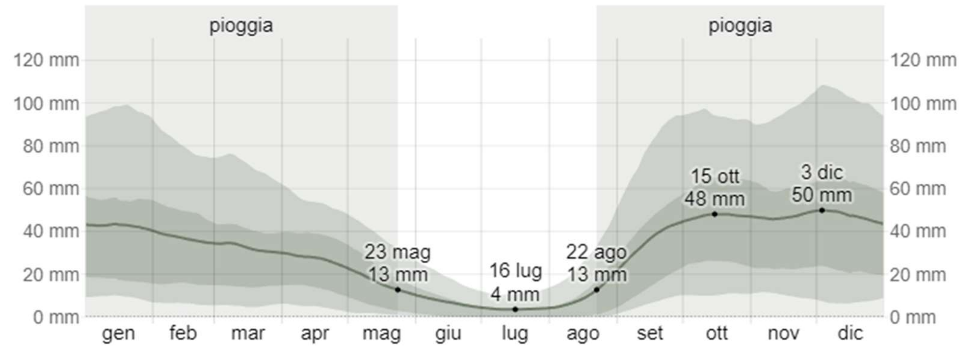


Figure 25. Average monthly rain at Pantelleria Airport © WeatherSpark.com

Table 28. Average monthly rain data

Average monthly rainfall data [mm]											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
42.8	36.8	32.2	27.9	15.4	7	3.5	8.7	36.2	47.8	47	47

Knowing the data in mm, an indicative volume [m^3] of available water from rainfall has been estimated: one millimeter of rainfall measured inside the rain gauge is equal to one liter dropped on an area of one square meter. The estimation has been made considering 5700 arable acres.

To estimate the real rainwater availability for agriculture purposes, it is necessary to consider the effective seeped rainwater. To do that, a complete hydrogeological balance should be performed. However, at the state of the TEMOA-Pantelleria RWS, to simply consider the rainwater-soil dynamics, only the infiltration coefficient has been considered which depends on the soil geology. Considering the volcanic origin of Pantelleria [20], an infiltration coefficient equal to 0.9 [43] has been multiplied by the annual volume of rainwater.

It is possible to model the availability of rainwater by an analogy with renewable sources. Rain, like renewables, does not have a constant temporal availability during the time slices of a year. Therefore, a capacity factor technology has been defined considering seasonal rainfall over the total. Table 29 shows its values.

Table 29. Capacity factor technology to split rain to the year time slices

Rain capacity factor technology [%]	
Winter	32
Spring	14
Summer	14
Fall	40

Seawater

Seawater is the most available source of the island and is exploited for most of the water supply. Within the model, seawater, at least in the case of small volumes consumed in Pantelleria, does not need quantitative constraints.

Import

According to the technical reports of the Pantelleria municipality's desalination plants [21], until 2015 the plants were unable to meet the water demand peak in the summer due to the tourist population. The available imported water data refers to 2011 [21]. The data have been assumed to be almost constant and took as the base year values. In Table 30 the monthly imported data is reported. Hydro potable water is imported into the island using takers vessels.

Table 30. Estimated volumes of water imported per month to Pantelleria in 2013

Estimated water import in 2013 [m³]	
Jan	0
Feb	0
Mar	0
Apr	0
May	0
Jun	14700
Jul	30600
Aug	24500
Sept	14100
Oct	0
Nov	0
Dec	0

The imported commodities modelled in the TEMOA environment have been reported in the table below:

Table 31. Parameters implemented in TEMOA

Modeling parameters – water import		
Name	Description	Cost [€/m³]
Ethos	Ethos is a generic indication for an input **commodity.** In this case it represents the input commodity of the 'import technology'	0
Import	**technology** that represents the import price	2.2

The import price has been calculated considering the transport prices [44] and the sale price of water per m³ of the company 'Sicilia Acque' in 2010 [45].

Desalination

The biggest part of the water demand is satisfied with two desalination plants placed in the districts of Maggiuluvedi and Sataria.

In 2013, the Maggiuluvedi plant was characterized by two desalinations units. The first one equipped with Electrodialysis Reversal (EDR) technology, the second one was based on Reverse Osmosis (RO) [21]. The EDR was composed of two lines in parallel with a rated capacity of 450 m^3/d each while the RO modulus had a total capacity of 120 m^3/d. The brine discharge from the EDR unit supplemented with about 25% of seawater was used as feed for the RO plant. Due to the high silica content, RO membranes were subjected to very high maintenance costs and therefore the reverse osmosis modulus was phased out. The Sataria seawater-fed plant consisted of two evaporative modules with Mechanical steam Compression (MC) each with a nominal capacity of 1600 m^3/d [21]. The costs associated to the desalination plants in the base year are only related to the water production since, as it will explain in the next paragraphs, given the upgrade that will occur in 2015, it is not necessary to specify an investment cost.

The input commodities of the desalination plants are electricity and seawater. But for modeling purposes, it is sufficient to consider only electricity since the seawater resource, for limited consumption, can be assumed to be infinite. The energy consumption of EDR technology is about 3.3 kWh/m^3, while for the MC plant it is around 19 kWh/m^3. In the individual RWS module, electricity should be defined as an 'ethos' commodity because it is considered only as a primary source and not obtained from a production process.

The two desalination plants produce the same output commodity i.e., the treated water which is then pumped into the aqueduct grid.

The Sataria and Maggiuluvedi plants, in the base year, have been modelled in TEMOA-environment using different technologies because, they used two different desalination technologies. All the parameters used to define the desalination plants in the water database have been summarized in Table 32.

Table 32. Parameters used to define in TEMOA environment the desalination plants

Modeling parameters – desalination plants					
Parameter	Description	Energy consumption [MWh/ m^3]	Annual Production 2013 [m^3]	Rated capacity [m^3]	Water Production cost [€/ m^3]
Electricity	Input commodity (electricity)				
Treated water	Output commodity from the two desalination plants (treated water)	-			
MC desalination technology	Transformation Technology to represent MC desalination plant	19	5.56E+5	1.17E+6	1.42
EDR desalination technology	Transformation Technology to represent EDR desalination plant	3.3	2.11E+5	3.29E+5	0.87

Distribution Grid

As mentioned before, the treated water from the desalination plants is distributed to the final water demand sectors through an aqueduct grid. The distribution network is composed of the adduction system, storage tanks, and pumping systems. The aqueduct system is modeled as a single technology in the TEMOA-environment.

The total length of the pipeline system is about 60 km. The system of the external adducts of Pantelleria (28 km) consists of the main branch, served by the Sataria plant, and three main ramifications that feed the various populated areas of the Island [41]. The storage system has a total capacity of about 25000 m^3 and all the pumping system parameters have been reported in Table 33.

Table 33. Pumping system parameters [46]

Pumping system parameters					
System	Working	Number	Flow rate [l/s]	Head [m]	Power [kW]
Sataria - Kaffefi	Yes	1	41.6	355	250
Sataria - Scauri	Yes	1	23.6	25	10
Scauri - Sataria	Yes	2	9	10	7.5
Kaffefi - Gelfiser	Yes	2	40	148	86
Gelfiser – ex Vedetta	Yes	1	25	20	18.5
Maggiulivedi - Arenella	Yes	1	8	120	22
Maggiulivedi - Kuddia	Yes	1	24	45	22
S.Elmo - S.Anna/Mursia	Yes	1	25	20	18.5

In distribution grid modeling, it is important to consider the losses. The losses that need to be considered in general in an aqueduct system are the hydraulic ones and the leakages due to aging of pipes. Hydraulic-type losses, concentrated or distributed, can be neglected in the modeling because they have been already considered in sizing the pumping system. In order to consider the physical losses due to the pipeline aging, the output water is calculated as Equation (18), where PL is a coefficient that represents the water leakage. The physical losses have been imposed equal to 0.5 [23] (mean value associate to the islands in the ISTAT report [47].

$$Water_{output} = Water_{input} * PL \tag{18}$$

As is possible to see in Table 33, the pumping system required an electricity input (about 1000 MWh in 2013). Therefore, the input commodities of the distribution grid are the treated water and electricity (Figure 26).

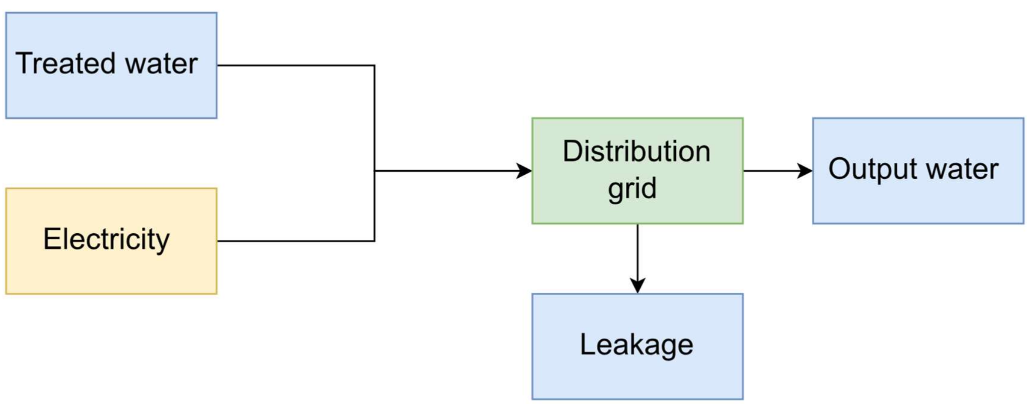


Figure 26. Distribution grind schematic representation

Because the input commodities are different in nature, it is necessary to impose on the technology representing the distribution grid a dummy efficiency that takes into account the share between these two carriers. This distribution grid parameter has been calculated using Equation (19), where:

- ELC_TOT represents the electricity used by the water grid,
- UP_TW represents the water in input to the water grid
- TW represents the output water from the water grid

$$Efficiency = \frac{TW}{(ELC_{TOT} + UP_{TW})} \tag{19}$$

In order to meet different water demands, the distribution network is subdivided into different output commodities that serve different demand sectors, as is represented in Figure 27.

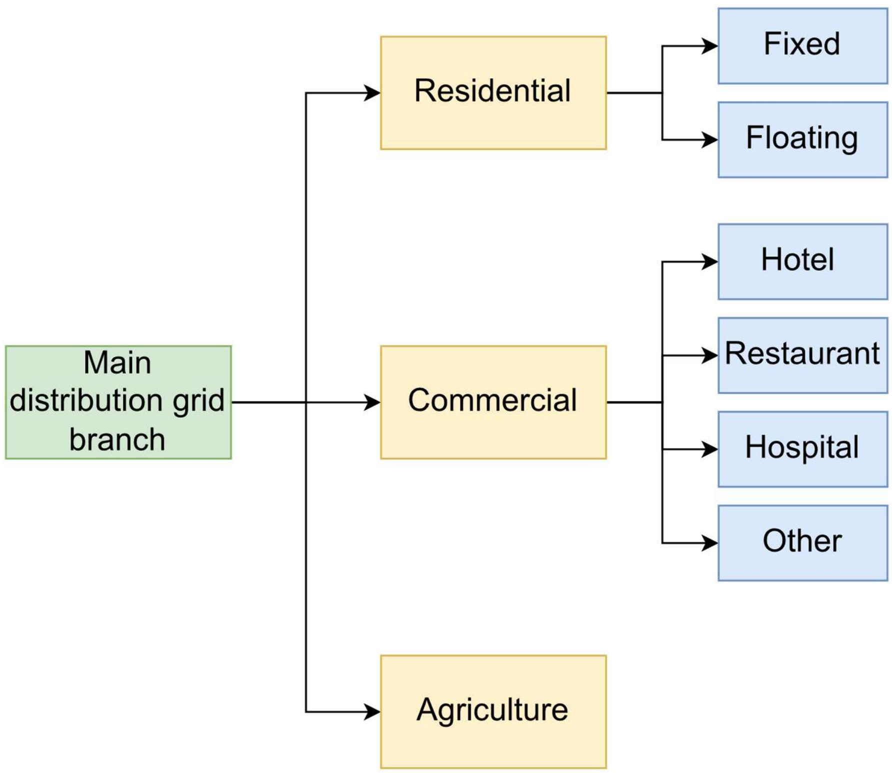


Figure 27. Branching of the distribution grid

All parameters related to the modeling of the distribution grid have been summarized in Table 34.

Table 34. Modeling parameters of the distribution grid

Modeling parameters of the distribution grid	
Parameter	Description
Electricity	Input **commodity** the distribution grid
Upstream Treated water	Input **commodity** the distribution grid
Distribution grid	**Technology** needed to model the distribution grid
Treated water	Output **commodity** from the distribution grid
Floating residential treated water	Output **commodity** from the distribution grid to satisfy the floating population demand
Fixed residential treated water	Output **commodity** from the distribution grid to satisfy the fixed population demand
Hotel treated water	Output **commodity** from the distribution grid to satisfy the hotel demand
Restaurant treated water	Output **commodity** from the distribution grid to satisfy the restaurants (and bar) demand
'Other' treated water	Output **commodity** from the distribution grid to satisfy the 'other' subsector demand
Hospital treated water	Output **commodity** from the distribution grid to satisfy the hospital demand
Agriculture treated water	Output **commodity** from the distribution grid to satisfy the agriculture demand

4.3.2 Demand

No data on actual water consumption in 2013 for Pantelleria has been found, therefore the base year water demand has been evaluated considering the hydro potable supply for user type [41]. The different demand subsectors and the yearly requirements [m^3] have been summarized in Table 35. Thus, water consumption is not modeled based on historical consumption data but based on specific water demands. For example, in the case of residential, the specific water demand is expressed per person, while in the case of restaurants per unit of m^2.

Comparing the water supply data [21] and the demand estimated as reported above, it was found that desalinated and imported water (for example, in 2011) is lower than the estimated water needs, but by the same order of magnitude (0.8 Mm^3 and about 1.3 Mm^3). Therefore, this results in conservative modeling that reflects reality and always ensures water availability.

One important aspect in evaluation of water modeling is the importance of tourism on Pantelleria. As already mentioned, Pantelleria has a very high tourist inflow during the summer months. It is therefore essential, in order to obtain a true-to-reality modeling, to take into account resident population (fix) and the seasonal one (fluctuate).

In the Pantelleria case, therefore, the distribution of fluctuating demand is not homogeneous throughout the year. This aspect has been modeled in the TEMOA environment by exploiting the 'DemandSpecificDistribution' function. In Table 35, the distribution shares of tourist demand over the year are shown. The distribution shares have been calculated considering the seasonal presences over the annual touristic flux [29].

Table 35. Daily and yearly water supply [41]

Subsectors	Utilization Time	Daily water supply	Daily requirement [m3]	Yearly requirement $W_{y,s}$ [m3]
Stable population	365	250 l/person	1936	7.07E+5
Seasonal population + swimming pools	90	250 l/person	2110	1.90E+5
Hotels	365	250 l/person	416	1.52E+5
Restaurants	365	100 l/m2	323	1.18E+5
Bar	365	100 l/m2	100	3.65E+4
Offices	365	130 l/person	26	9.49E+3
Schools	270	80 l/person	103	2.78E+4
Military barracks	365	160 l/person	24	8.76E+3
Hospitals	365	700 l/person	70	2.56E+4
Agriculture	60	2500 l/m3 of wine	1250	7.50E+4
Others	365	200 l/person	34	1.24E+4

Table 36. Tourist water demand specific distribution throughout the year [29]

Demand Specific distribution [%]	
Spring	23
Summer	61
Fall	10
Winter	6

Residential

The residential subsector includes the fixed population and the fluctuant one. By fluctuating residential sector that part of non-negligible water consumption attributed to summerhouses and bed & breakfast is meant. Whitin the model, the consumption of the tourists has been referred as 'floating' and that of the Pantelleria residents as 'fixed'.

The floating residential water consumption has been evaluated considering a daily water requirement of 250 l/day person, 8000 beds in b&b accommodation and about 90 days of use [41]. Fixed population water demand has been calculated considering the same water consumption, 365 days of use and the number of resident people. Considering the total water demand of the island, the residential sector accounts for about 66 percent. Specifically, the resident population consumes about 52%, while the floating population consumes 14%. The yearly residential sector water requirement has been summarized in the Table 37.

The end uses of water are different depending on if the residential sector is considered seasonal or fixed. For example, in the case of seasonal uses, it has not been considered water consumption for gardening or washing machine as it was assumed that the population does not use these end services. In Table 37 residential end uses have been reported for the two types of population.

Table 37. Yearly water requirement for residential sector

Yearly water requirement $W_{y,r}$ [m^3]	
Fixed	7.07E+5
Floating	1.90E+5

Table 38. Residential end-uses

Residential end-uses	
Fixed population	Cooking Dish washing Bathroom (utility drain/shower) Washing clothes Gardening
Floating population	Cooking Dish washing Bathroom (utility drain/shower)

The water consumption data is split into end-uses of residential sector. To do that, the fractional end-uses shares have been determined by [48] and are reported in

Table 39. Using Equation (20), the end-uses water consumption has been calculated.

Table 39. Fractional end-uses shares for residential sector

Fractional end-uses shares f_{eu} [%]	
Fixed population	
Cooking	10
Dish washing	17
Bathroom (utility drain/shower)	33
Washing clothes	30
Gardening	10
Floating population	
Cooking	30
Dish washing	10
Bathroom (utility drain/shower)	60

Table 40. End-uses water consumption for residential sector

End-uses water consumption W^{f}_{eu} [m³]	
Fixed population	
Cooking	7.07E+4
Dish washing	1.20E+5
Bathroom (utility drain/shower)	2.33E+5
Washing clothes	2.12E+5
Gardening	7.07E+4
Floating population	
Cooking	5.70E+4
Dish washing	1.90E+4
Bathroom (utility drain/shower)	1.14E+5

$$W_{eu}^{f} = f_{eu} * W_{y,r} \tag{20}$$

Within the model, as it is actually the case in Pantelleria, the demand for water in the resident sector is set to be met by water produced by the two desalination plants and, in the summer months, by imports, as is discussed in more detail in the previous paragraphs.

Commercial

The commercial demand is composed of several subsectors. As mentioned before, the economy of Pantelleria is based on tourism, but there are also some business sectors that depend only on the resident population. In Table 41 commercial end uses have been reported for all the subsectors [41].

Table 41. Yearly water requirement for commercial sector

Yearly water requirement $W_{y,c}$ [m³]	
Hotels	1.52E+5
Restaurants and bars	1.54E+5
Hospitals	2.56E+4
Others	5.85E+4

The commercial sector, as already anticipated in Figure 27, within the water model is split in five different subsectors. All these subsectors are listed and described in Table 42.

Table 42. Water system commercial subsectors description

Commercial subsectors	
Hotel	accommodations not already considered in seasonal residential, (hostels, hotels, etc.)
Restaurant	restaurants and bars
Hospital	hospital and emergency rooms
Others	public offices, street washing, military barracks, schools.

The commercial subsectors, as represented in Figure 28, are in turn divided into end uses. Table 43 shows the assumed fractional end uses shares (f_{eu}) of all the subsectors [49]–[51].

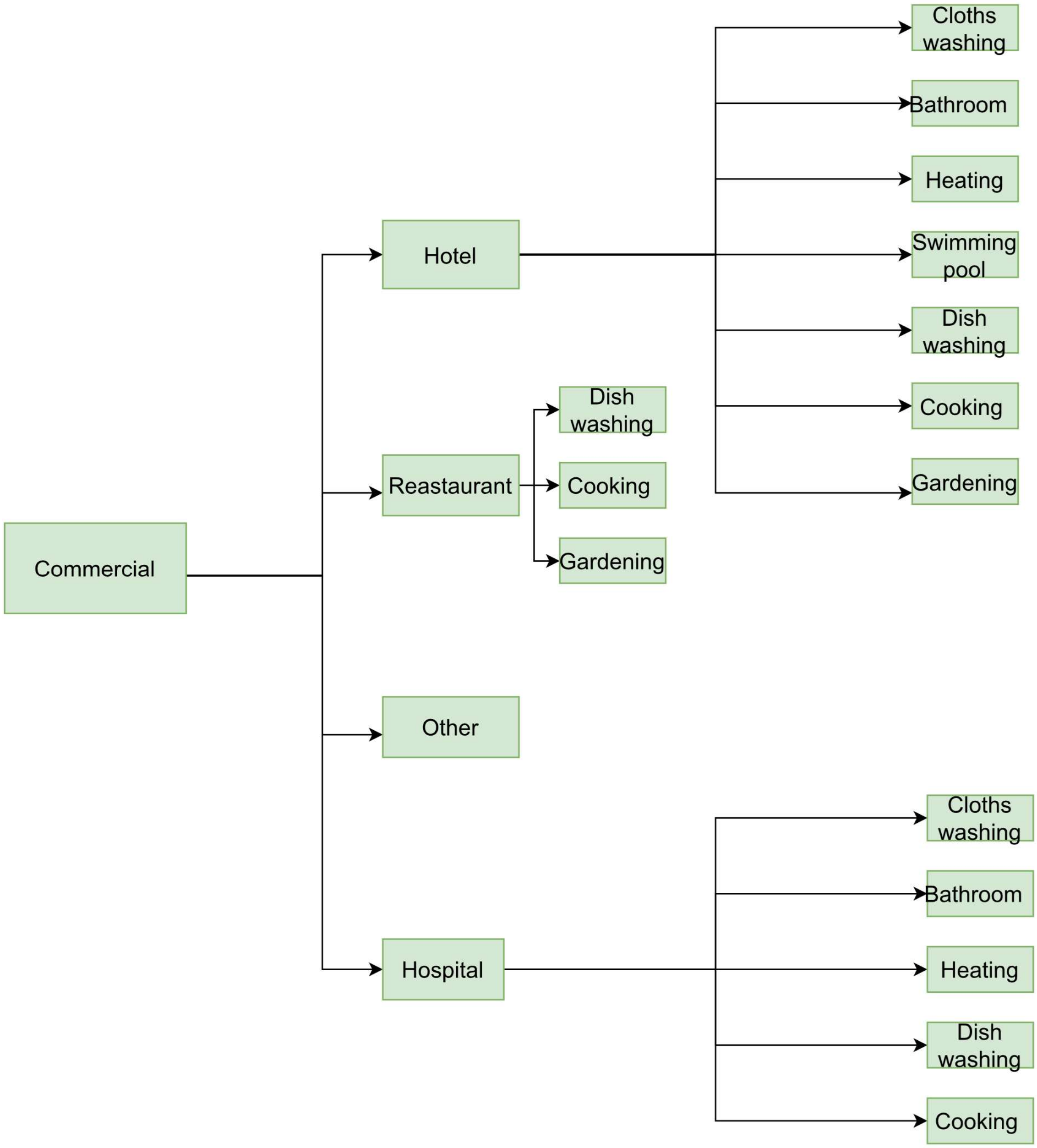


Figure 28. Schematic representation of the division of the commercial sector into sub-sectors and end uses.

Table 43. Fractional end-uses shares for commercial sector

Fractional end-uses shares f_{eu} [%]	
Hotel	
Cooking	17
Dish washing	4
Bathroom (utility drain/shower)	54
Washing clothes	12
Gardening	6
Swimming pool	2
Heating	5
Restaurant	
Cooking	52
Dish washing	17
Bathroom (utility drain/shower)	31
Hospital	
Cooking	3.5
Dish washing	3.5
Bathroom (utility drain/shower)	64
Washing clothes	9
Gardening	20
Other	
Other	100

The commercial end uses water consumptions have been calculated using Equation (21); the results are reported in Table 44.

$$W_{eu}^{f} = f_{eu} * W_{y,c} \tag{21}$$

Table 44. Commercial end uses water consumptions

End uses water consumptions W^{f}_{eu} [m^3]	
Hotel	
Cooking	2.58E+4
Dish washing	6.07E+3
Bathroom (utility drain/shower)	8.20E+4
Washing clothes	1.82E+4
Swimming pool	3.04E+3
Gardening	9.11E+3
Heating	7.59E+3
Restaurant	
Cooking	8.03E+4
Dish washing	2.62E+4
Bathroom (utility drain/shower)	4.79E+4
Hospital	
Cooking	8.94E+2
Dish washing	8.94E+2
Bathroom (utility drain/shower)	1.64E+4
Washing clothes	2.30E+3
Heating	5.11E+3
Other	
Other	100

Agricultural

As previously mentioned in detail in Chapter 2, dry farming (aridoculture) is practiced on Pantelleria. The aridoculture is a water-saving method that allows the plantation to live on spontaneous irrigation alone [25]. To represent non-irrigated cultivation within the model, it was imposed that the demand of the agriculture sector is met by rainwater, i.e. imposing the rainwater as an input commodity to the technology representing irrigation. However, considering the droughts, the possibility of providing artificial irrigation has also been implemented in TEMOA-Pantelleria. So, in extreme cases, water from the aqueduct system could meet the irrigation water demand.

To take into account the annual cycle of plants, the demand has been divided between two periods of the year, those roughly identified as 'growing' periods. The annual water demand for irrigation purpose is 7.50E+4 m^3 and Table 45 below shows the demand distribution assumption through the year. In this case, f_{eu} is equal to 1, therefore the yearly water requirement is equal to the end use agriculture water consumption (irrigation).

Table 45. Irrigation water demand specific distribution throughout the year

Demand Specific distribution [%]	
Spring	50
Summer	50
Fall	0
Winter	0

4.4 Future prospects

As mentioned before and represented in Figure 23, future projections within the model are divided into two historical period (in case of TEMOA-Pantelleria from 2013 to 2022) and evolution of the system in future years (2023 to 2050).

To develop future prospects within the model, it is necessary to define a scenario, by drivers, constraints and new technologies. Once all these factors are defined, the model will develop results based on economic optimization criteria.

For the individual RWS, two simple scenarios have been assumed: the first one, keeps the in-situ water production capacity unchanged, namely the WPUC; the second giving to the desalination plants the possibility to increase their capacities IWPC, so that the system will be able to choose between importation and in-situ desalination.

4.4.1 Upstream and water production

Past RWS evolution

In order to calibrate the RWS until 2022 based on the two above mentioned scenarios within TEMOA constraints were imposed on the upstream and water production.

In 2015, Pantelleria water supply system improved significantly. Indeed, the EDR and MC desalination technologies were replaced by the Reverse Osmosis (RO). Additionally, the desalination plants capacity has been increased with five moduli with a potential of 1300 m^3/d each.

The introduction of RO technology has advantages both in terms of significant energy savings (for the MC plant) and in economic terms [52]. Table 46 shows the comparison between plants before upgrading technologies and RO.

Table 46. Comparison between the base year desalination technologies and Reverse Osmosis

Technologies	**Water production costs [€/m³]** [52]	**Energy consumption [kWh/m³]**
Electrodialysis reversal (EDR)	0.87	3.3
Mechanical steam Compression (MC)	1.42	19
Reverse Osmosis (RO)	0.77	3.5

As a result of this technological substitution, water production since 2015 at the Sataria (MC technology substituted with RO) plant has had an 80% energy consumption reduction. The total water treatment rated capacity of the plants has been reported in Table 47.

Table 47. Pantelleria desalination plants rated capacity in 2015

Desalination plants rated capacity [m^3]	
Sataria plant	3.54E+6
Maggiuluvedi plant	3.29E+5
Total	3.87E+6

Within the TEMOA environment, the introduction of the desalination using RO has been modeled by a new technology. The main parameters characterizing the new RO plant are reported and descripted in Table 48.

Table 48. New reverse osmosis plant technology main parameters

Reverse Osmosis plants parameters		
Parameter	*Description*	*Value*
Efficiency	Plant efficiency is defined in terms of energy per cubic meter. Within the database it is reported in terms of m3/kWh as it must meet a water demand.	3.5 [kWh/m3]
Investment cost	Since a plant has not been rebuilt from scratch, but the technology has been changed, the defined investment cost is that of membrane replacement. [53]	0.031 [€/m3]
Fixed cost	Fixed costs represent the costs per m3 required to produce water from electricity from the distribution grid.	0.77 [€/m3]
First year of availability	It represents the first working year.	2015
Lifetime	It refers to the life cycle of membranes before they need to be replaced.	5 years

Future RWS evolution

As already mentioned, in Pantelleria, the total water grid losses are about the 50% [47], more than Italian average (36,2% in 2020 [54]). However, in 2016, the Pantelleria Municipality has developed a plan for the water network losses reduction [41] and also in the PNRR framework (Piano Nazionale di Ripresa e Resilienza) water system leakage measures have been introduced [55].

Therefore, for both implemented scenarios in the individual water system, a decrease in physical losses of the water system was assumed from 50% to 30%. A leakage reduction of 20% by 2050 have been assumed considering the limited extension of the island grid, but also the launch and consolidation of specific remote control and monitoring systems and the modernization of the infrastructure [47].

To model this, an improvement in the efficiency of the water distribution grid is implemented.

- WPUC scenario

The first scenario has been developed considering the desalination plants capacity unchanged through the years. In this case, the only water vector that the system can use is the imported water. As previously explained, the Pantelleria water demand increases significantly during the summer months. Therefore, the import commodity increases during this period.

To recreate the scenario in the TEMOA-environment, the constraints are set on the maximum capacity (see Table 49) of the desalination technologies. On the other hand, no limits have been imposed on imports.

Table 49. Max capacity desalination plants, RWS- first scenario

Max Capacity [m3/a]	
Sataria Plant	3.54E+6
Maggiuluvedi Plant	3.29E+5
Total	3.87E+6

- IWPC scenario

The second scenario has been constructed by eliminating the constraint on maximum capacity of the desalination plants. Now, the system is free to choose between importing and producing water. The system will choose the most cost-effective situation. The prices associated with water production and import are shown in Table 50.

To quantify the price of imported water, it has been assumed divided into several parts: Transport cost and the sale price of the Sicilian company 'SiciliaAcque' [45].

Table 50. Prices of water per vector

Water prices					
Water vector	Transport cost [44] [€/m3]	Sicilian region cost of sale [53] [€/m3]	Transportation authorization cost [56] [€/2y]	Water production cost [52] [€/m3]	Investment cost [53] [€/m3/5y]
Desalinated	-	-	-	0.77	0.031
Imported	1.59	0.61	2500	-	-

Demand

To allow the model to perform future projections, the drivers and the elasticity values have been associated to the end-uses demand. The drivers are as same as the RES (Figure 21), while the elasticities have been set equal to 1 because demand projections are associated only with driver behavior. Indeed, because the demand has been modeled by considering specific water needs according to the subsector, a constant specific requirement has been assumed in future year.

Chapter 5

Integrated water and energy system model

5.2 Integrated system features

The study of individual RES or RWS involves neglecting important aspects that could affect the whole system. Indeed, modeling one system alone means disregarding aspects of the other one which could cause consequences that are crucial. For example, considering the isolated energy system, it is not possible to take into account the temporal evolution of water demand and supply and its consequence on energy requirement.

After the development and analysis of the two individual reference systems, an integrated water-energy system has been developed. In particular, the integrated model is divided into two layers (namely the water and the energy one) that communicate through links and connection points. A representation of the Pantelleria integrated energy and water system is provided in Figure 29.

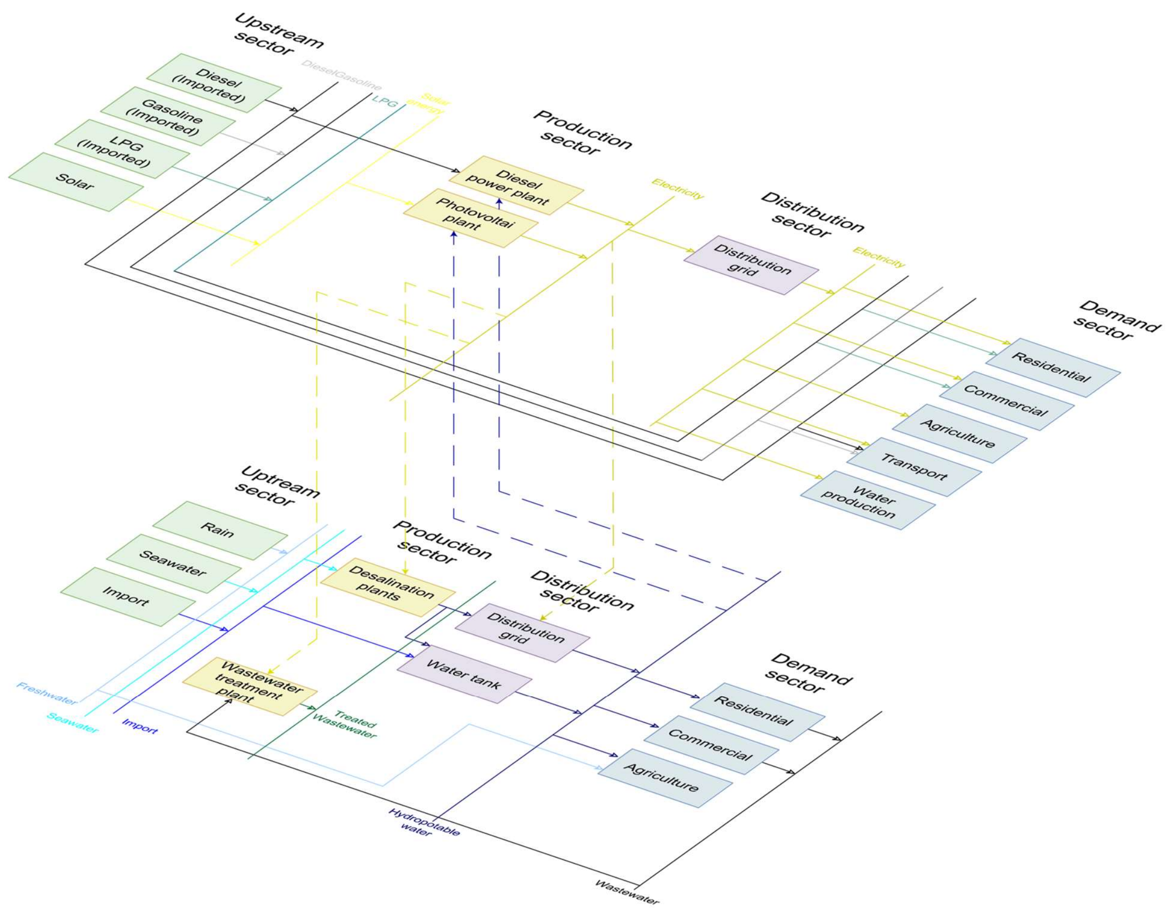


Figure 29. Integrated energy-water system (base year)

Integrated modeling has been performed analyzing the sectors that involve both water and energy. In a simple and isolated case like Pantelleria, mostly water-energy connections are related to the water production sector. Indeed, the desalination plants and the pumping system represent a high percentage of energy consumption on the island.

Also, the wastewater treatment plant of the island needs energy to treat the input water. Other connections present in the system are related to energy production: the diesel motors of S.MED.E plants need water for colling, while in photovoltaic panels it is necessary for cleaning. However, most of these links must be considered negligible due to the very low use of the resource (i.e., water or energy).

Actually, the installed base year solar capacity requires very low water quantities that are not quantified in the water demand [41]; the cooling water for the diesel plant, as mentioned in technical reports of the company [57], is directly pumped by the system; the energy required by wastewater treatment plant has not been counted in the energy consumption analysis of the island [31]. Therefore, the water-energy interactions modelled at this stage of the integrated TEMOA-Pantelleria are the direct relation between the production and distribution of water and the energy consumption.

Practically, in the integrated database, the link between the two systems has been built through the commodities: the produced electricity from the energy supply-side sector, is used in part to satisfy the demand of the water production sector, that, in turn, becomes a water supply-side commodity (Figure 30).

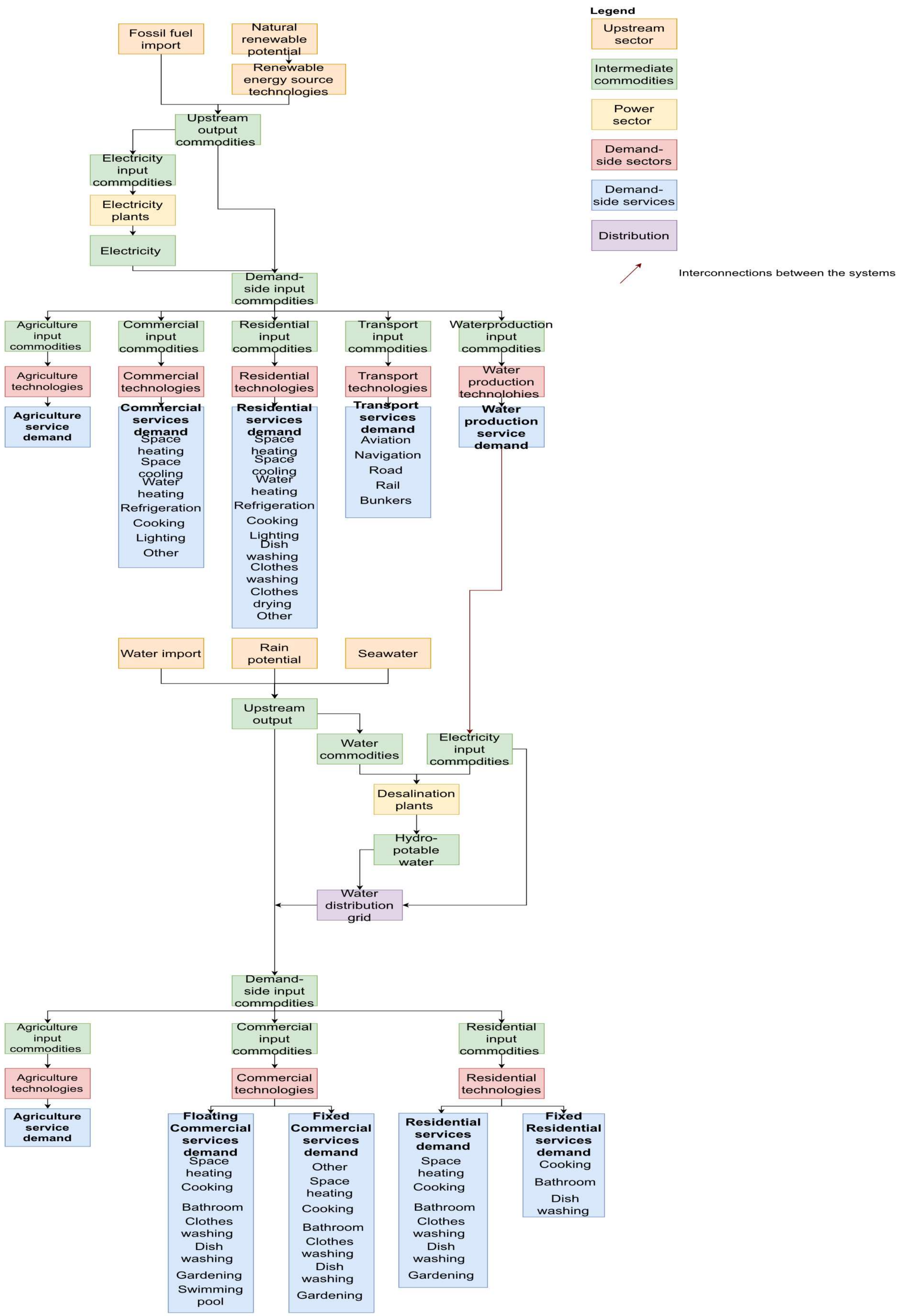


Figure 30. Pantelleria Reference Energy-Water System Structure

Once the system has been created in the TEMOA framework, two simple scenarios have been implemented for testing purposes.

5.3 Scenarios description

As already mentioned, the main linkages between the energy and the water resources in Pantelleria are related to the water production and distribution sectors. Therefore, implementing the scenarios affecting these two sectors, using the integrated model, should result in relevant consequences for both energy and water resources.

Specifically, two scenarios relative to the water distribution network have been implemented:

a. The Losses Decreasing scenario (LD): in the LD scenario, the same hypothesis of water grid improvement considered in the individual water scenarios has been assumed, therefore the water grid efficiency increases from 50% to 70% by 2050, starting from 2025 (Section 4.4.1).
b. The Losses Increasing scenario (LI): in the LI, considering reasonable water grid aging trends similar to those that have occurred in Italy [47], a 10% decrease in efficiency has been imposed between 2025 and 2050.

It has been decided to focus on the water network because this sector influences water production and has direct consequences (related to its energy needs) and indirect consequences (related to the energy needs of desalination) on electricity. It is important to point out that the assumption of electricity mix transition and possibility of increased capacity for onsite water production has been adopted as the foundation for both scenarios.

Chapter 6

Results

In this section, the results obtained from the individual energy and water systems have been analyzed and compared with those of the integrated model. Analyses of the results demonstrate the importance of multisystem analysis to avoid overlooking relevant interconnections between different resources (namely, water and energy) that would lead to a non-exhaustive assessment of future scenarios.

6.1 Reference energy system

For the energy system, as already explained in Section 3.4, since the renewable sources penetration in the electricity production is one of the main goals of the energy transition agenda [19] developed for the island, two scenarios focused on the electricity mix have been developed (Table 51).

Therefore, the first scenario (EMT) has been implemented with constraints on fossil sources utilization in electricity production, while in the second one (NEMT), no restrictions on the power sector have been imposed. The scenarios details are reported in the following.

Table 51. Individual RES scenarios

Scenario name	Scenario features	Main constraints
EMT	Renewables sources penetration on the electricity mix	maximum 20% fossil fuel in the electricity mix by 2030
NEMT	Unchanged constraints on the electricity generation by fossil fuel	Free optimization

6.1.1 Scenarios common results

As already explained in Sections 3.4.1 and 3.4.2, the two scenarios have the same level of electrification. In particular, by 2030 the substitution of LPG cookers by electric ones and a total electrification of the transport road vehicles have been imposed to meet the C4EUI Agenda targets [17] and for consistency with the OSeMOSYS model [19].

The results of the LPG constraints are showed in Figure 35 and Figure 36, the consequence of LPG phasing out is fuel changes to meet residential demand. As figures show, the LPG is replaced by electricity. The same trend occurred in the commercial sector.

As example of fuel transport evolution, the cars technologies trend through the years has been reported (Figure 31). The other types of road vehicles assume the same behavior.

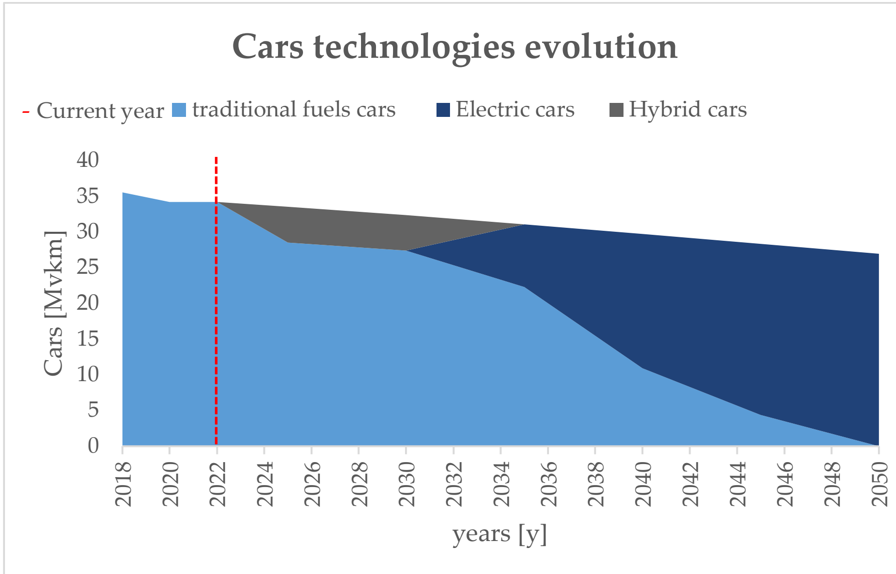


Figure 31. Cars Technologies evolution

In Figure 31 a decrease in energy consumption of cars technologies is shown, common in both scenarios, due to the population decreasing. Since the system is not constrained, it prefers the use of less expensive traditional fuel cars or more efficient electric vehicles, limiting the use of hybrid technologies for a restricted period. Indeed, the model forecasts the use of hybrid cars only when electric cars are not yet widely used (from 2022 to 2035).

6.1.2 Scenarios comparison

In the first energy system scenario, namely the Electricity Mix Transition (EMT), a gradual decrease in the production of electricity from diesel plant has been imposed, supporting the penetration of renewable sources in the electricity mix, up to the minimum share of electricity produced from dispatchable technologies in 2030. As already explained in Section 3.4.1, the minimum share from dispatchable plants have been set equal to about 20% of the electricity mix [17], [36].

In the second RES scenario, no constraints have been imposed on the electricity mix, therefore the model is completely free to choose the most convenient technologies in the optimization process.

In Figure 32 and Figure 33, the two energy mix results by scenario have been shown.

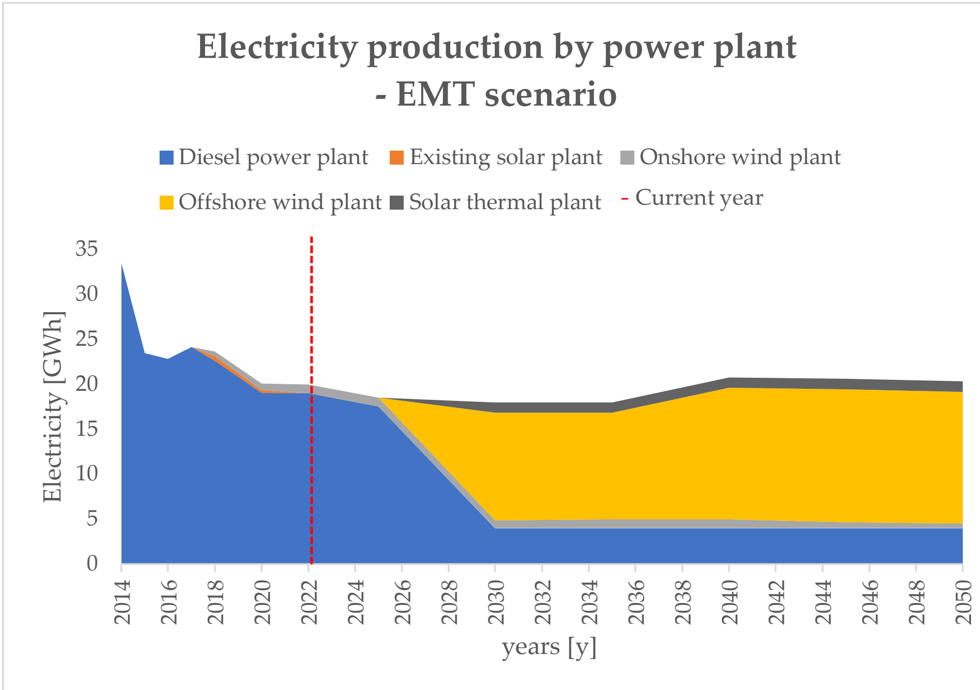


Figure 32. Electricity production by power plant - electricity mix transition scenario

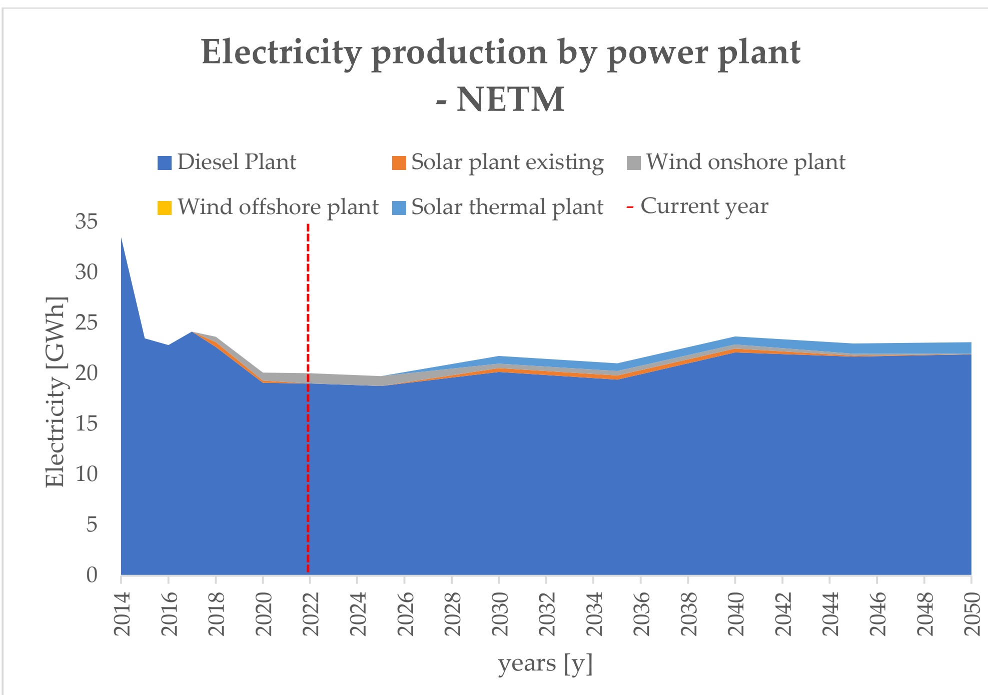


Figure 33. Electricity production by power plant - no electricity mix scenario

Concerning the past-future years, (namely, the years up to 2022), the two scenarios have the same behaviors as the model follows the historical data. Regarding the historical period, it is appropriate to focus on the significant decrease in electricity production between 2014 and 2016. This is due to the total replacement, in 2015, of the desalination technologies with energy-efficient ones (Section 4.4.1).

On the other hand, focusing on future years, the result of the EMT scenario (Figure 32) show a high share of electricity produced by offshore wind, followed by solar thermal and onshore wind, as well as the restricted share of electricity produced by diesel (dispatchable source). In the second scenario (Figure 33), clearly, the system develops the most economically viable alternative, which is the production of electricity by the diesel plant.

From the study of the individual RES, it is inferred that compared to the second scenario (i.e., NETM), by implementing EMT scenario, the savings of electricity generated from fossil sources in 2050 is about 18 GWh.

The total energy mix in two scenarios have been also compared for a historical year (2018) and a future year (2050).

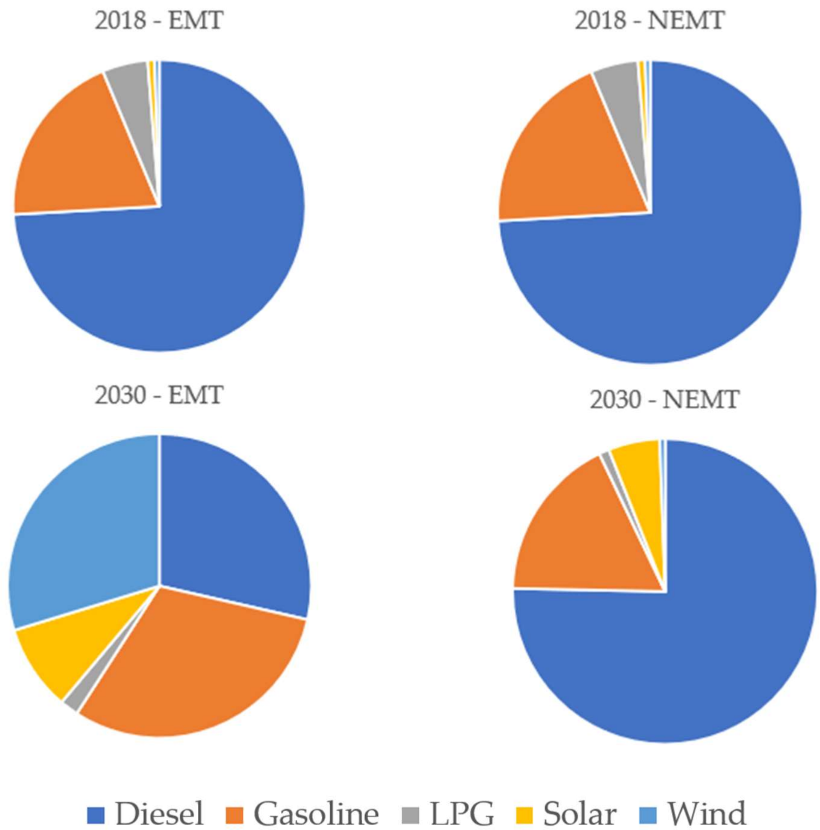


Figure 34. Energy mix comparison - RES individual scenarios comparison

As it was expected and is shown in Figure 34, the historical year is properly the same for both scenarios, while the energy mix is quite different in 2030. Indeed, in the EMT scenario, the percentage of diesel is much lower than the NEMT scenario due to the production of electricity from wind and solar power. The quite high proportion of diesel and gasoline in the first scenario is due to the still high penetration of fossil fuel in transportation in 2030 (shown in Figure 31).

It is interesting to note that even in the NEMT scenario there is a non-negligible percentage of solar in the energy mix. In fact, although there is no constraint about that, the model chooses to meet the heat demand in residential and commercial sectors using solar thermal technology, as being more affordable and with greater availability. Indeed, the fuels used to satisfy the demands of the buildings sector are almost identical between the two scenarios. As an example, the fuels consumed to meet the residential demand in the two scenarios have been reported in Figure 35 and Figure 36.

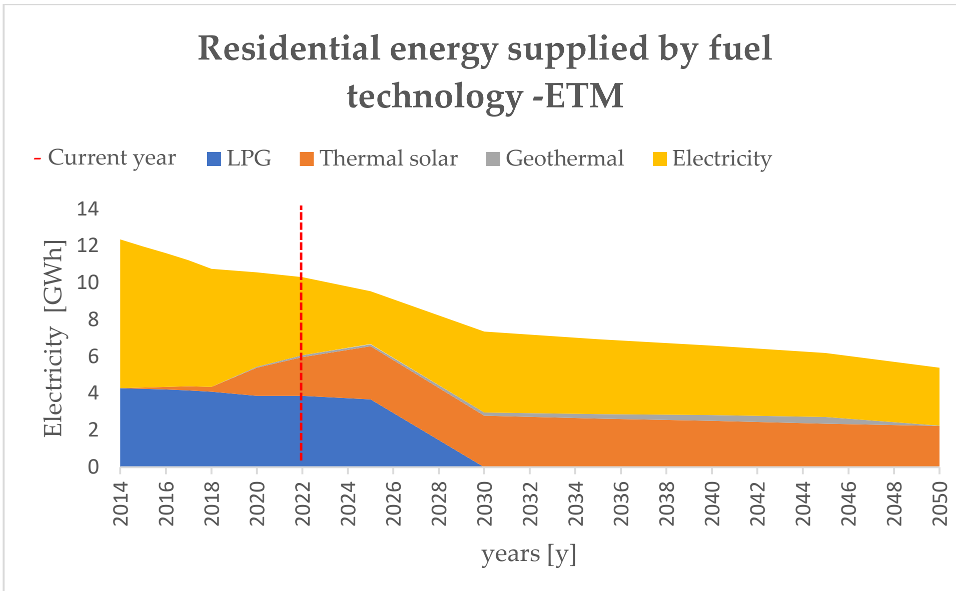


Figure 35. Residential energy supplied by fuel - ETM scenario

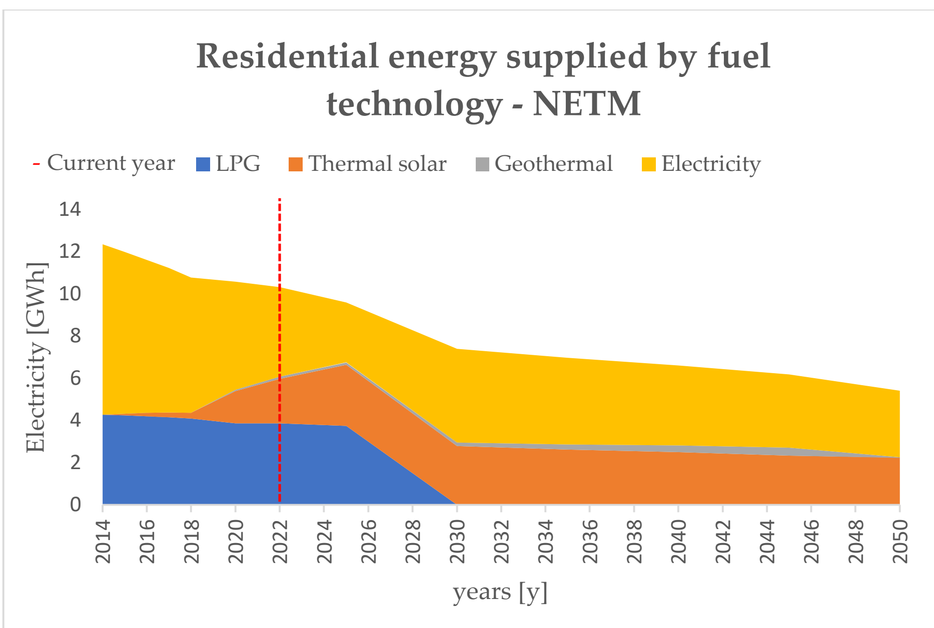


Figure 36. Residential energy supplied by fuel - NETM scenario

6.1.3 Comparison between TEMOA and OSeMOSYS Pantelleria models

As already mentioned in Section 1.3, an energy system modeling attempt for the Pantelleria island has been already performed by the Energy Center Lab of Politecnico di Torino [17]. This study has been considered in the thesis framework to validate the results of the TEMOA-Pantelleria energy system (ETM scenario) and to calibrate, wherever possible, the results of historical years.

The two models have similar basic assumptions, namely the target level of electrification of transport sector, the LPG cooking substitution, and the energy mix transition.

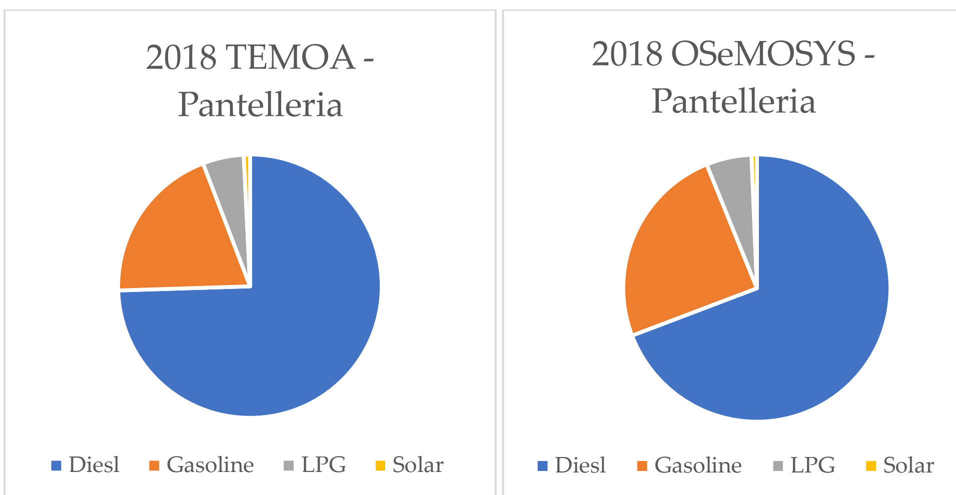
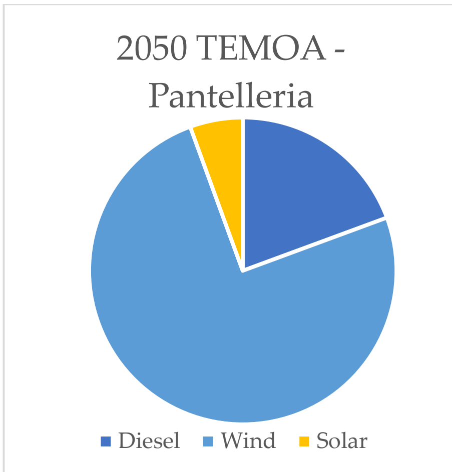


Figure 37. Optimal TEMOA-Pantelleria energy mix in 2018 versus OSeMOSYS result [17]

The first comparison between the two models has been made between the base year of the OSeMOSYS-Pantelleria, 2018, which in the TEMOA framework is a past-future milestone year. As shown in Figure 37, the only notable difference between the two models is the percentage of gasoline and diesel. In the TEMOA model, gasoline and diesel represents respectivley 20%

and 74% of the energy mix , while in OSeMOSYS-Pantelleria the corresponding percentages are 25% and 69%. The gasoline and disel for transport purpose are the same in the two models, therefore the 5% difference between the two energy mix must be due to the plant at the diesel power plant efficiency.



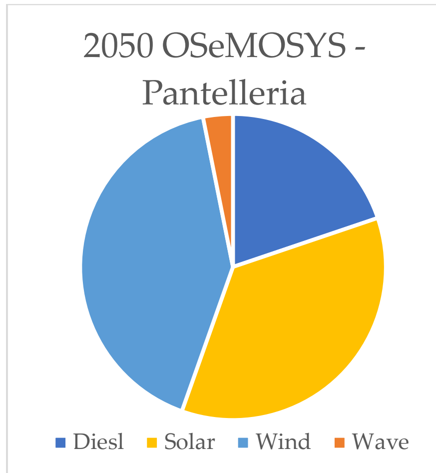


Figure 38. 2050 Pantelleria ELECTRICITY MIX - TEMOA versus OSeMOSYS [2] results

The second comparison has been made between the projection of electricity mixes in 2050 performed by the two models (Figure 38). The results are very different, except the penetration of diesel in the mix, which, in the case of TEMOA-Pantelleria, was set equal to that of OSeMOSYS model (Section 3.4.1).

The only constraint imposed on the TEMOA model electricity mix, other than diesel penetration, is the maximum rated capacity of renewable sources (Section 3.4.1). Thus, TEMOA-Pantelleria, free to optimize the remaining 80% of the electricity generation mix share, finds that offshore wind power is the most cost-effective solution.

The percentage of solar is low because, as seen in Figure 38, the model prefers to use this resource to meet the heat demand (solar thermal). In TEMOA model, the wave energy resource has also been included, but the model, unless forced, does not consider the technology economically convenient to use.

The different energy mix resulting from the two models is due to the different techno-economic characterization, which was inherited from TEMOA-Italy in the case of TEMOA-Pantelleria.

6.2 Reference water system

About the water system, two scenarios focused on the island's future water supply have been implemented (Table 52). Taking into account the water scarcity, analyzing possible alternatives for water supply on the island in the near and remote future is of paramount importance. Indeed, it is necessary to quantify the water volumes that will be required and the alternatives to satisfy the demand.

In the first scenario, namely the Increasing Water Production Capacity (IWPC) scenario, the model is free to install more capacity to produce water on site; while in the second one, e.g., Water Production Unchanged Capacity (WPCU) scenario, no expansions are planned in desalination plants. Scenario characterizations have been reported in the following.

Table 52. Individual RWS scenarios

Scenario name	**Scenario features**	**Main constraints**
IWPC	Increasing of water capacity on site	Free optimization
WPCU	Unchanged water production capacity	Unchanged desalination plants rated capacity

Considering the requalification plan for Pantelleria water distribution system proposed in 2016 by Municipality [46], in both scenarios a decreasing of physical losses in the aqueduct system has been assumed. More details are given in Section 6.2.1.

6.2.1 Scenarios common results

In Pantelleria, the total water grid losses are about the 50% [47], more than Italian average (36,2% in 2020 [54]). Water grid losses can be due to the extent of the network, the number of connections, their density, and operating pressure, but also due to breaks in the pipelines, unauthorized consumption and withdrawals from the network, and meter measurement errors [47]. Head losses have not been explicitly modeled within TEMOA-Pantelleria because they are already considered in sizing the pumping system and in the electricity demand of the water system.

As already mentioned, the Pantelleria Municipality has developed a plan for the water network losses reduction [41]. Also in Italy, in the framework of the PNRR (Piano Nazionale di Ripresa e Resilienza), an investment has been arranged to reduce losses in water distribution networks, including digitization and monitoring of networks [55].

For these reasons, for both scenarios, an improvement of the water network has been imposed: within the model, an increase of the aqueduct system efficiency has been set. A 70% water network efficiency target in 2050 has been imposed, considering the launch and consolidation of specific remote control and monitoring systems and the modernization of the infrastructure. In addition, the reduced length of distribution networks will allow to contain the losses of the water resource in the phase of supply to end users [47].

Annual water losses from 2025 to 2050 for both scenarios are shown in Figure 39. Increasing the efficiency of the water system by 20% saves about 0.6 Mm3 of water (difference between water losses in 2025 and 2050).

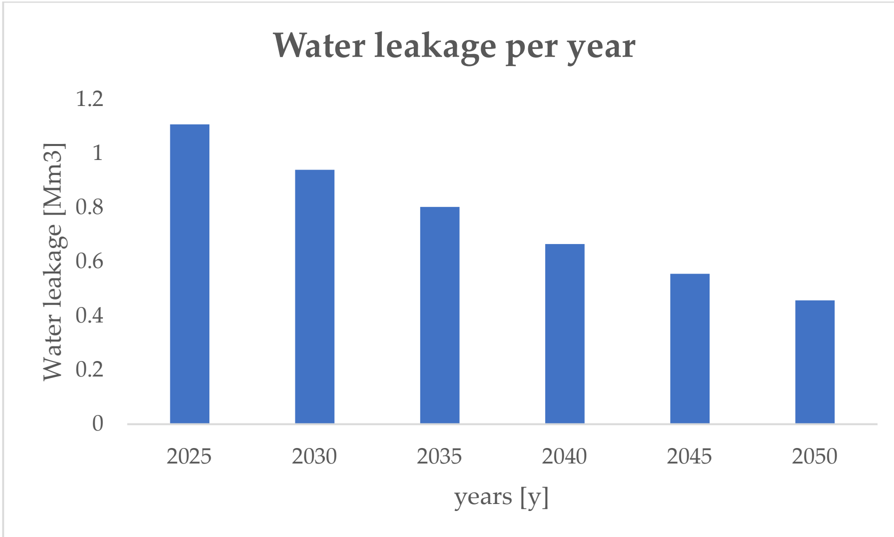


Figure 39. Water leakage through the years

6.2.2 Scenarios comparison

In the first RWS scenario, namely the Increasing Water Production Capacity (IWPC) scenario, the model has been left to choose how to meet water demand: either by continuing to import water or by producing it on-site. To model this scenario, no constraint on the desalination plant capacity has been imposed. The results of the water supplied in the IWPC scenario are shown in Figure 40.

In the second individual RWS scenario, namely the Water Production Capacity Unchanged (WPCU), a constraint on the desalination plants has been imposed. In particular, a production maximum capacity equal to the actual installed capacity of the plant has been imposed. Therefore, the model is forced to import (Figure 41).

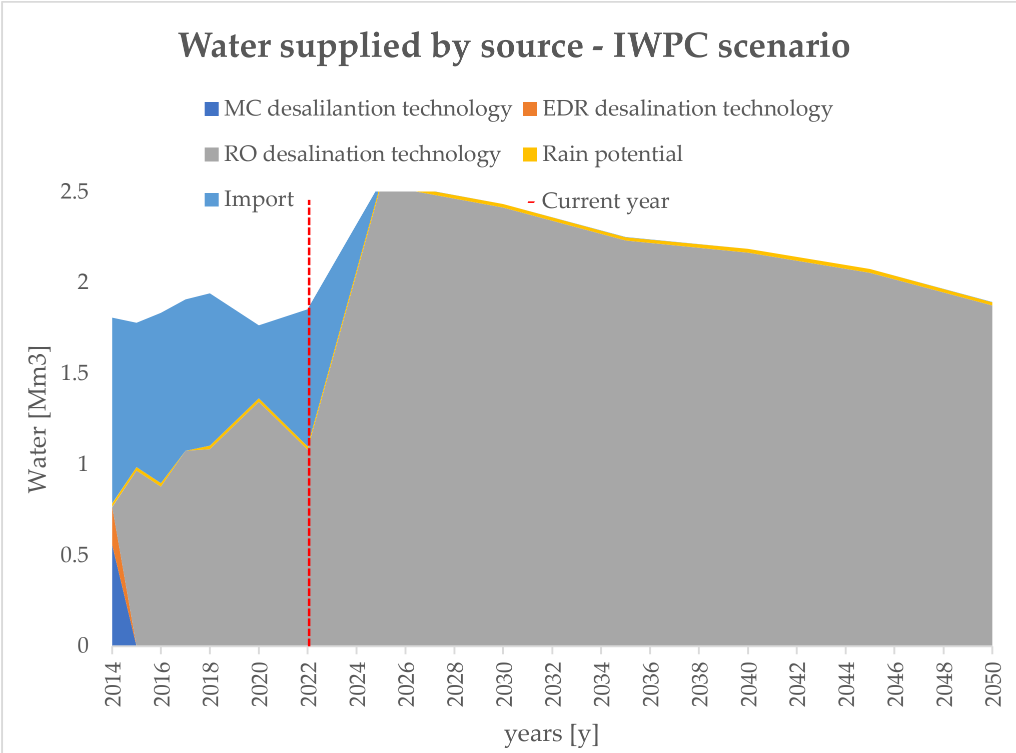


Figure 40. Water supplied by source in IWPC scenario

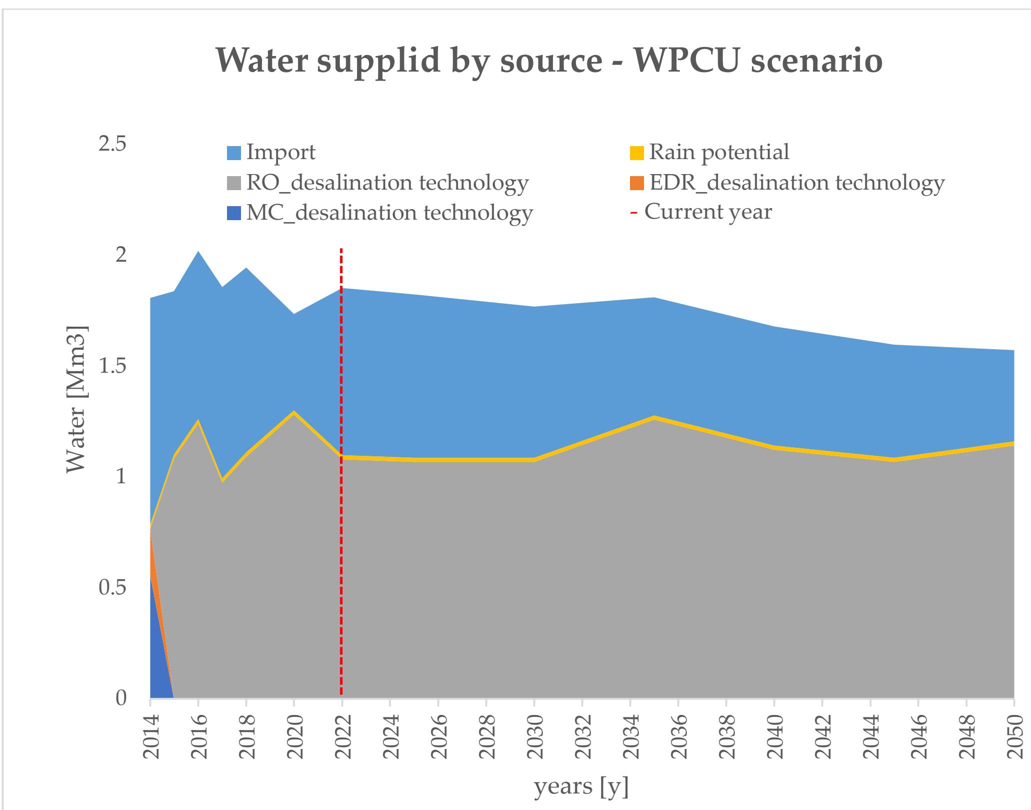


Figure 41. Water supplied by source in WPUC scenario

As is shown in Figure 40, the model optimization results demonstrate that the economically sustainable alternative is to increase water production, i.e., the capacity of desalination plants.

However, comparing Figure 40 and Figure 41, it is possible to see that the increase in water supplied between 2022 and 2025 in IWPC scenario is due to water network leakages. Indeed, the two scenarios have the same water demand, and it has been assumed that imported water is subject to negligible network losses. Therefore, increasing on-site production involves water producing about twice as much as would alternatively have been imported: in the WPCU scenario, in 2025 the import is about 0.7 Mm^3, while in the IWPC scenario the surplus of production is about 1.4 Mm^3.

The assumption that imports are not subject to high leakage is valid since water is stored in tanker ships and then distributed in populated neighborhoods by water tanker trucks [41].

6.2.3 Water consumption projections

The water consumption projections for the reference water system have been modeled in the same way for both scenarios since drivers and elasticities remained unchanged. The figures below show the future projection of water demands for residential and commercial sectors, divided into subsectors associated with the requirements of the resident population and those associated with the seasonal one, as already explained in Section 4.3.2.

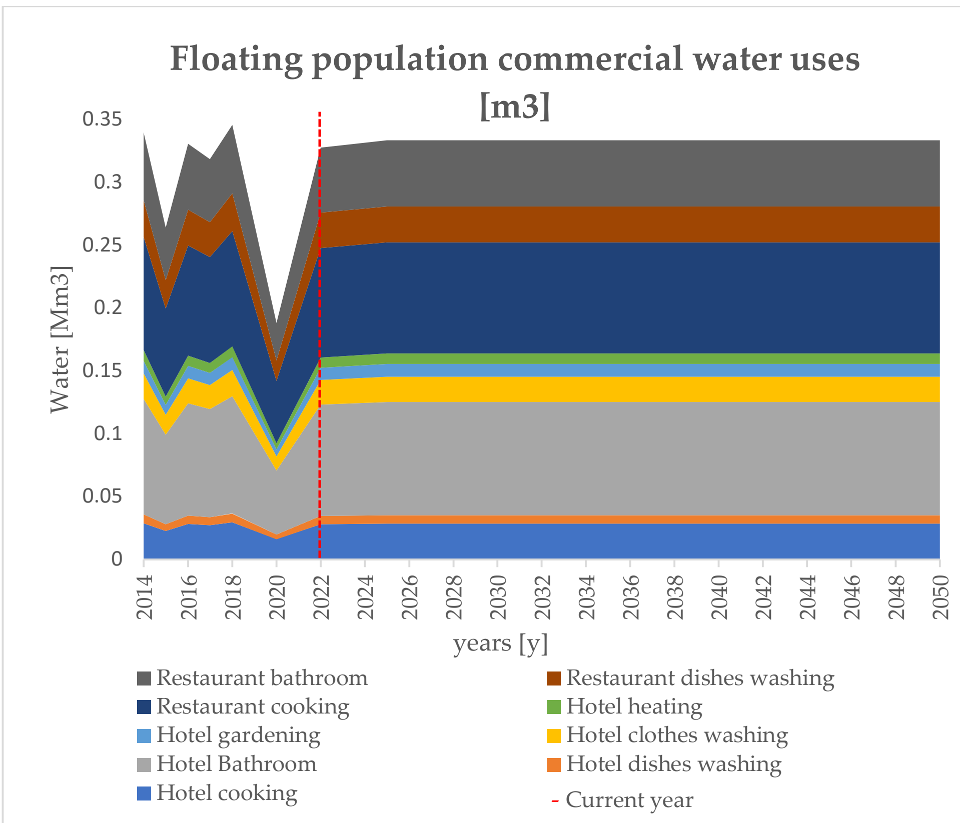


Figure 42. Demand projections for commercial uses associated to seasonal population

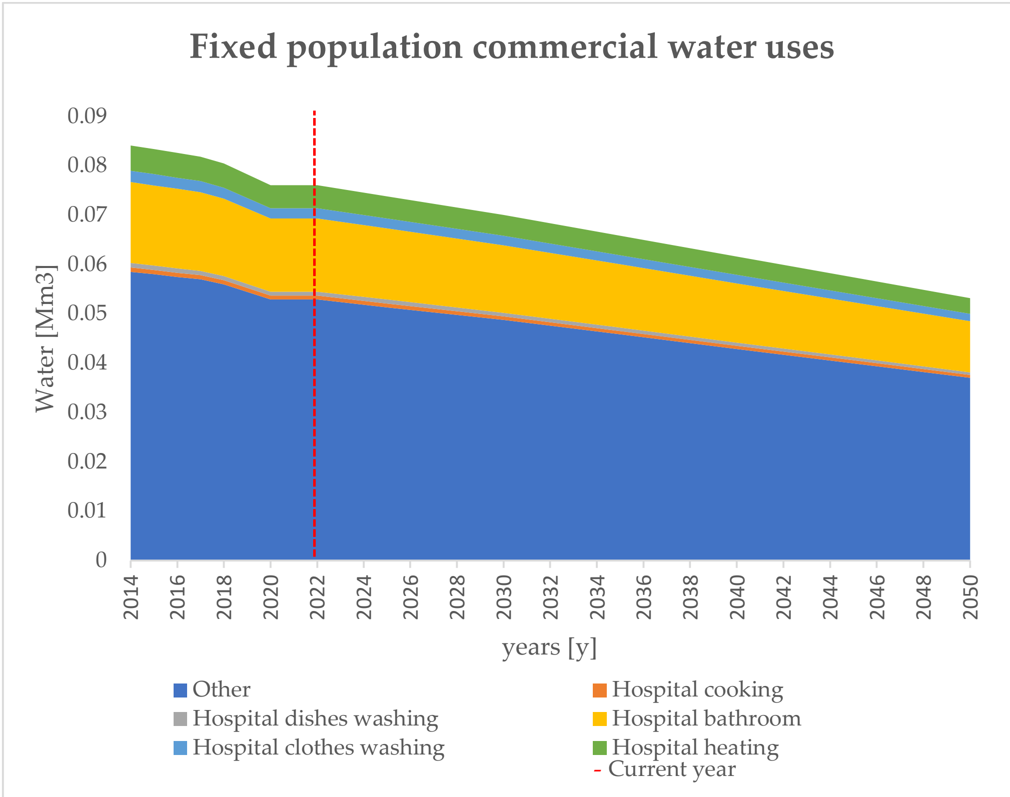


Figure 43. Demand projections for commercial uses associated to resident population

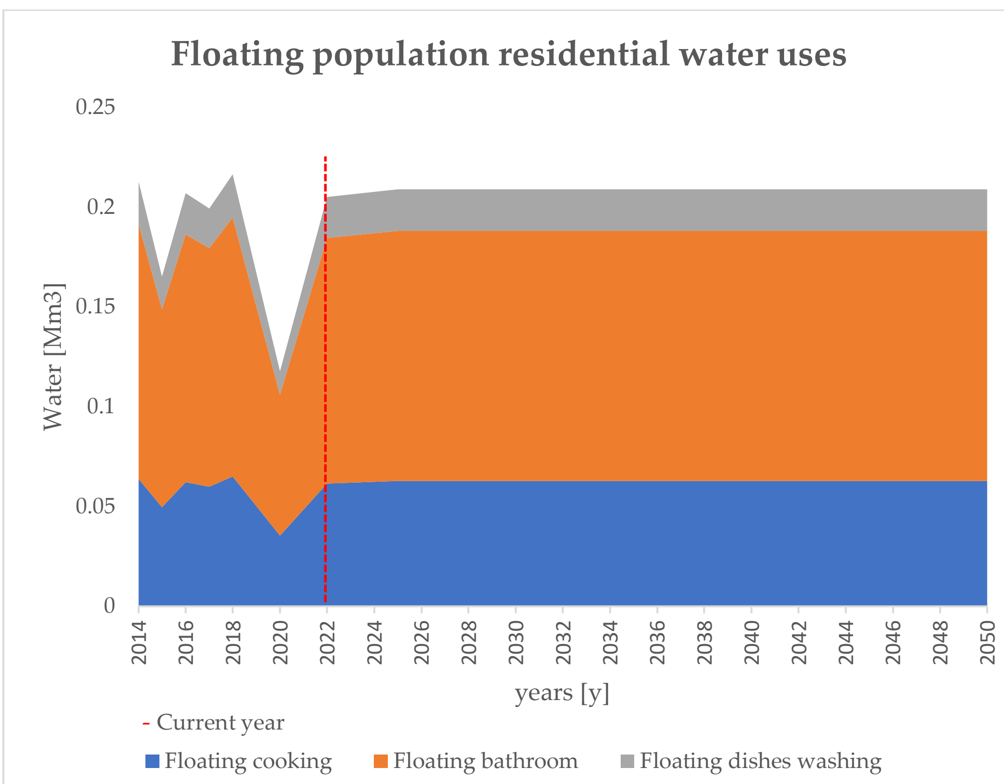


Figure 44. Demand projections for residential uses associated to seasonal population

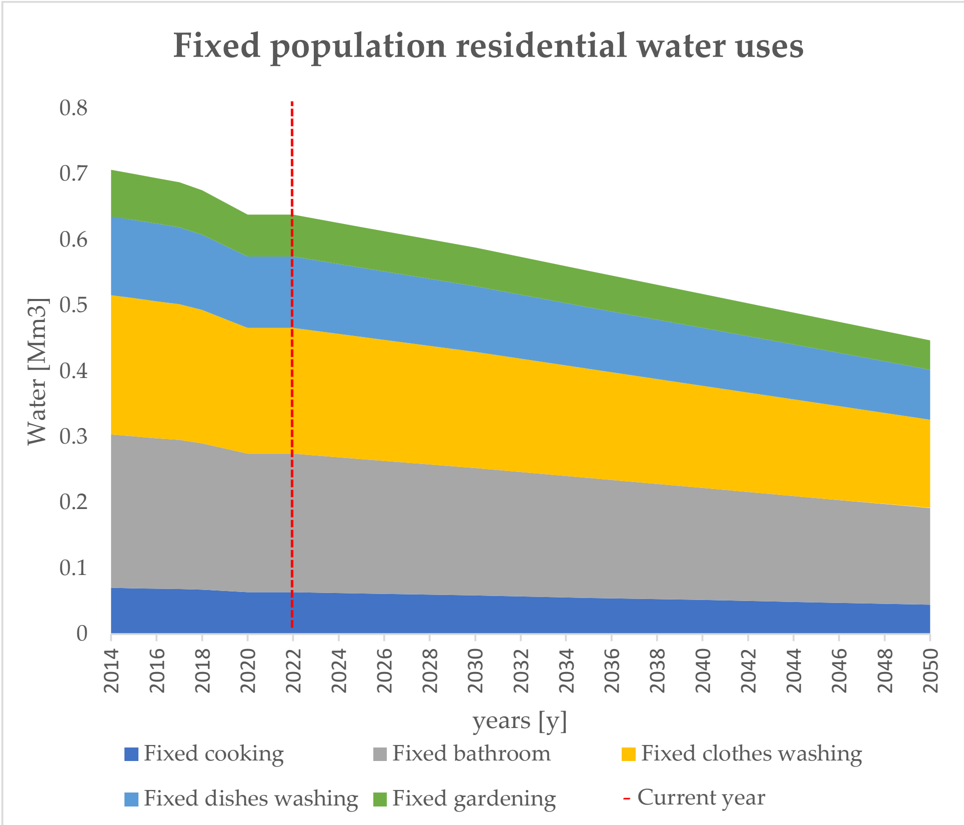


Figure 45. Demand projections for residential uses associated to resident population

For commercial sector, as is possible to see in Figure 42 and Figure 43, the overall water consumption associated with tourism is much higher than that of fixed population end-uses. Specifically, the commercial consumption of the seasonal population is about 0.35 Mm^3 in 2014 and remains quite constant throughout the analyzed historical period, the fixed commercial as of 2014 consumed about 0.085 Mm^3 per year, reaching about 0.05 Mm^3 by 2050.

The trends of fixed and seasonal consumption are different as they are associated with different drivers (Section 4.3.2). A decrease in fixed consumption is expected due to the shrinking resident population [58], while seasonal consumption will tend to remain constant considering an unchanged tourist flow through the years [29]. In addition, it is notable that the model has well represented the historical data, in fact while in 2020 fixed population consumption has not particularly changed, tourism consumption is greatly affected by pandemic effects (minimum value in 2020).

Because floating residential water demand is associated to the tourism population driver , as same as the floating commercial, and fixed residential and commercial demands are associated to the stable population, , fixed and floating residential water consumptions follow the same trends (Figure 44 and Figure 45) as the commercial ones just analyzed, depending on whether the end-uses are related to the permanent population or to tourism (Figure 42 and Figure 43) .

It is worth noting, however, that the consumption associated with vacation rentals is much lower than the consumption of the permanent population (in 2013, respectively about 0.2 Mm^3 and about 0.7 Mm^3 the second one). This is explained as the demand has been evaluated by considering the daily water consumption per person [41]. Therefore, it depends on the time of use and the number of people: the accommodations in vacation homes are about 80000 and are considered to be populated for only 90 days/year, while the resident population is about 7700 people, but the consumption is associated to the entire year.

6.3 Integrated reference water and energy system

6.3.1 Scenarios comparison

The scenarios that have been developed in the integrated framework have the main objective of studying how resources (namely, water and energy) interact and affect each other. Therefore, as already explained in the previous section, the scenarios' constraints affect the water production and distribution sector.

In particular, scenarios have been modeled representing the consequences on the island's water and energy systems, considering possible improvement or deterioration of the water distribution network.

Therefore, the following scenarios have been developed: a scenario with a water distribution grid improvement, i.e., the Losses Decreasing scenario (DL scenario); a scenario considering the hypothesis of the deterioration of the water distribution system, i.e., the Losses Increasing scenario (LI scenario).

The same conditions on the electric mix and water supply have been set at the basis of these two scenarios. Specifically, an electricity mix transition and the possibility of increasing on-site water production have been assumed to be implemented in the integrated system.

Within the model, starting from the milestone year 2025, the improvement or deterioration of water grid conditions have been imposed by changes in the efficiency of the technology associated with the aqueduct system. In detail, in the first scenario, the grid efficiency rises from a value of about 50% to a valued of about 70% (as explained in Section 6.2.2); while in the second case the efficiency decreases to 10% in 2050 considering values in agreement with the deterioration trend in Italy [47].

The model results demonstrate how being constraint to guarantee the same output (i.e. the water demand of the island) in two scenarios (Figure 46), due to the losses increasing, the system needs more incoming water to compensate the leakage (Figure 47) and consequently more electricity to pump it (Figure 48).

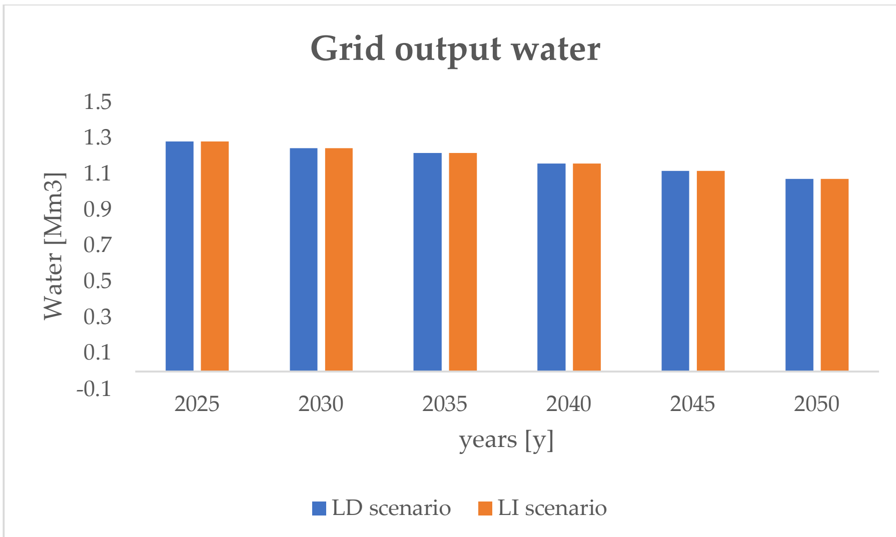


Figure 46. Output water from the distribution grid – LD and LI scenarios comparison

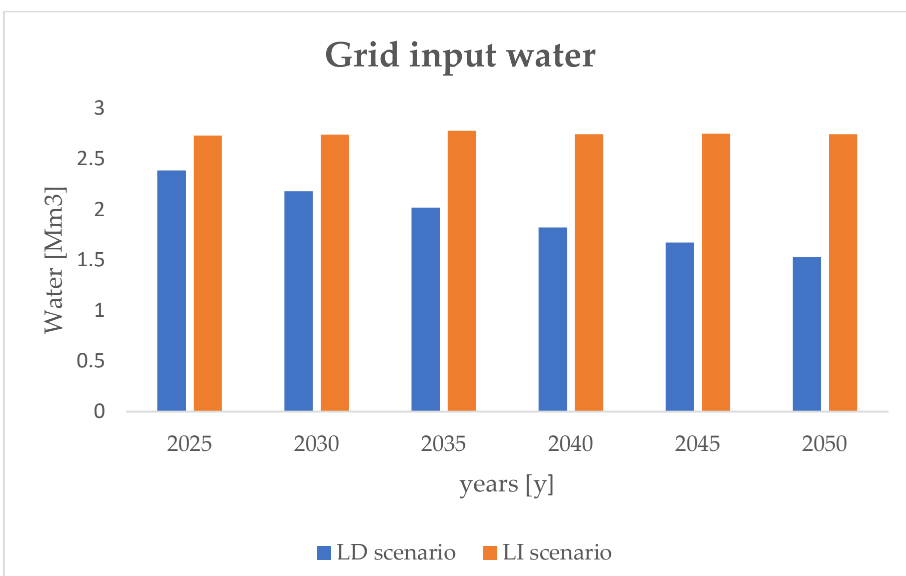


Figure 47. Input water to the distribution grid – LD and LI scenarios comparison

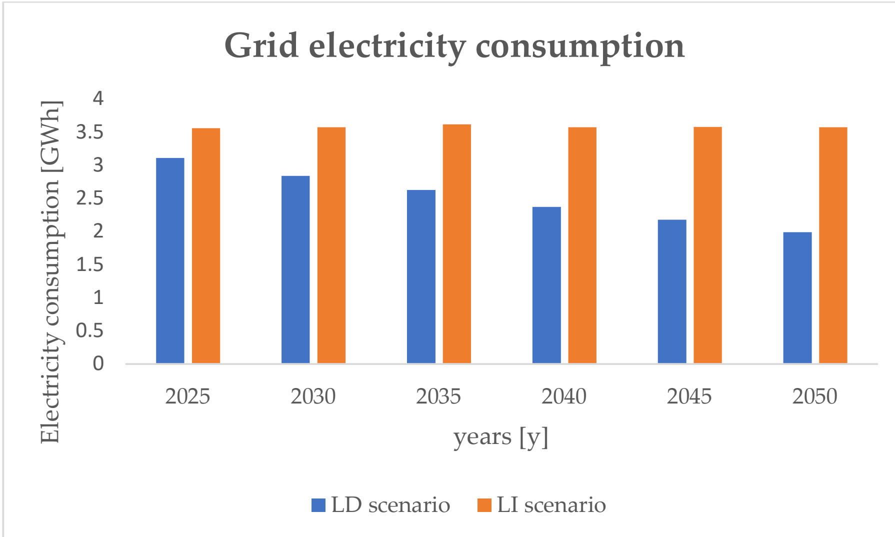


Figure 48. Electricity consumption by the water distribution grid – LD and LI scenarios comparison

The water network conditions also affect the water production sector and the electricity consumption of the water production and distribution system. Indeed, depending on the state of the grid, the desalination plants have to produce different amounts of water (Figure 49) to meet the same demand (Figure 46). Consequently, the electricity demand associated to the water production sector turns out to be different according to the implemented scenario (Figure 50). In Table 53 the electricity consumed associated with the water produced in the two scenarios has been reported.

Table 53. Electricity consumed by water produced

	Water production [Mm^3]	**Energy consumption [GWh]**
LD scenario	1.5	5.3
LI scenario	2.7	9.6

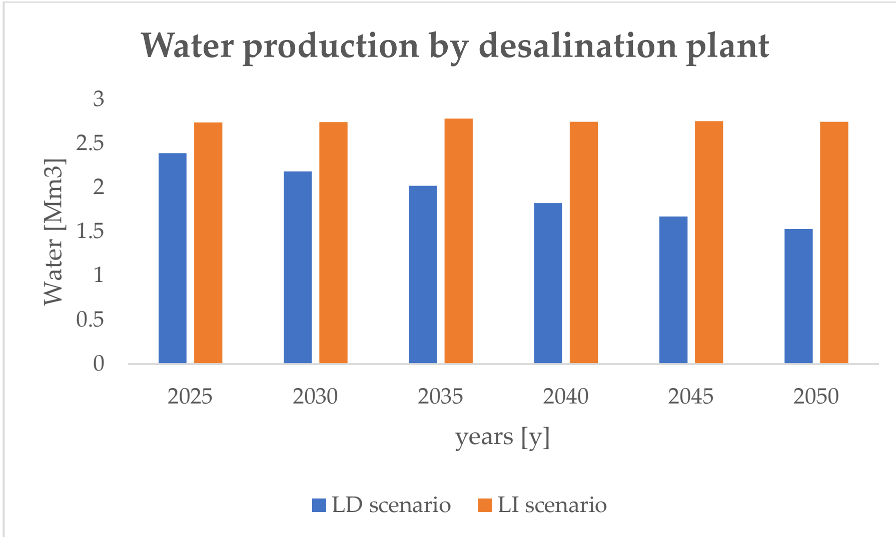


Figure 49. Water produced by desalination plants in the two different scenarios

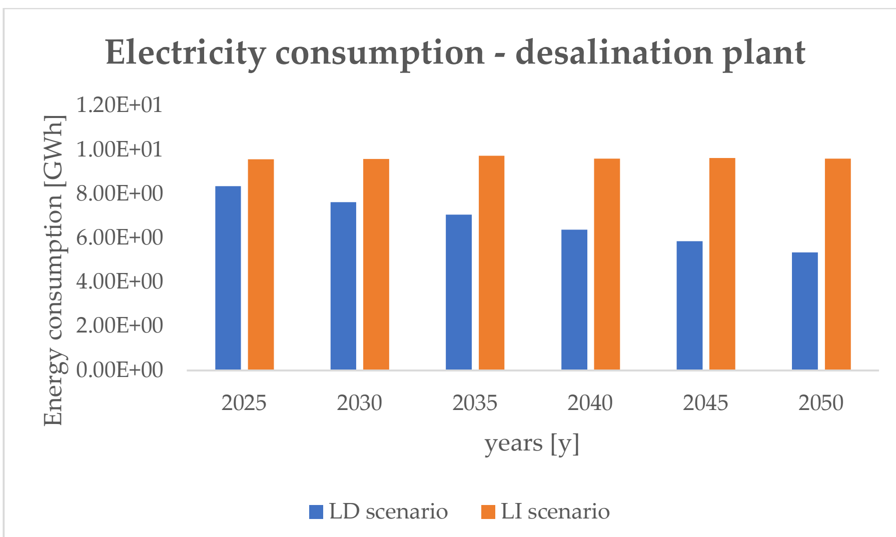


Figure 50. Electricity consumed by desalination plants in the two different scenarios

Analyzing the scenarios on water network conditions, in addition to the assessments on water saving (Figure 51), there is also evidence on electricity consumption saving. In Figure 52 the annually energy saving through the year considering an improvement of water distribution grid have been reported.

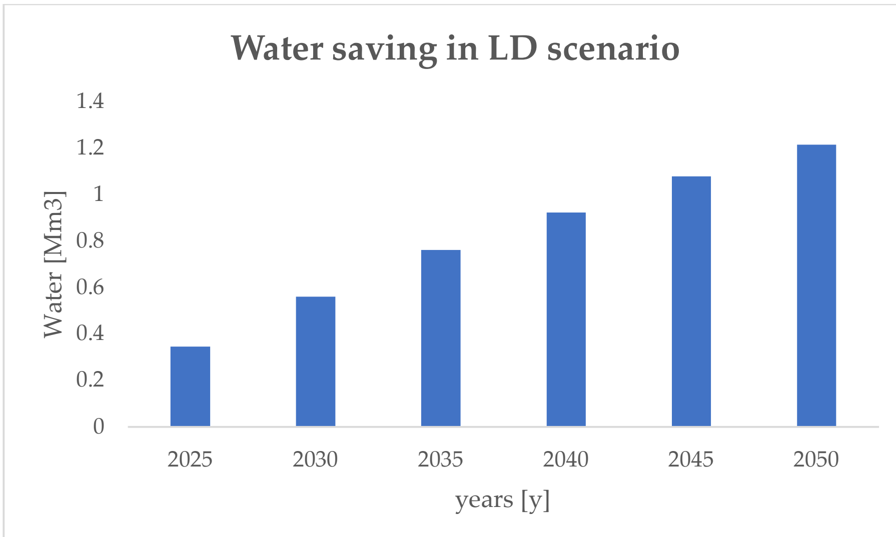


Figure 51. Water saving in LD scenario

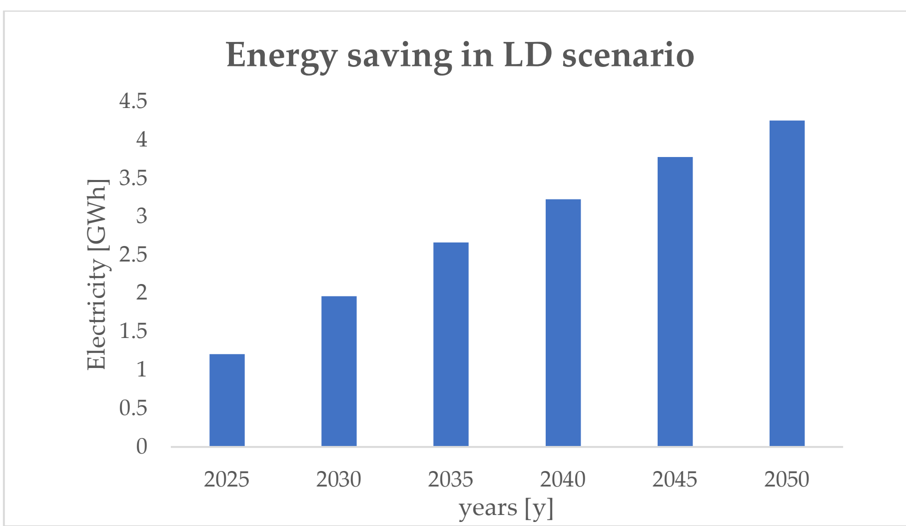


Figure 52. Energy saving in LD scenario

6.2.3 Final comparisons

In this section, to analyze the actual utility of an integrated assessment, the power generation results obtained from the integrated model and the individual energy model have been compared.

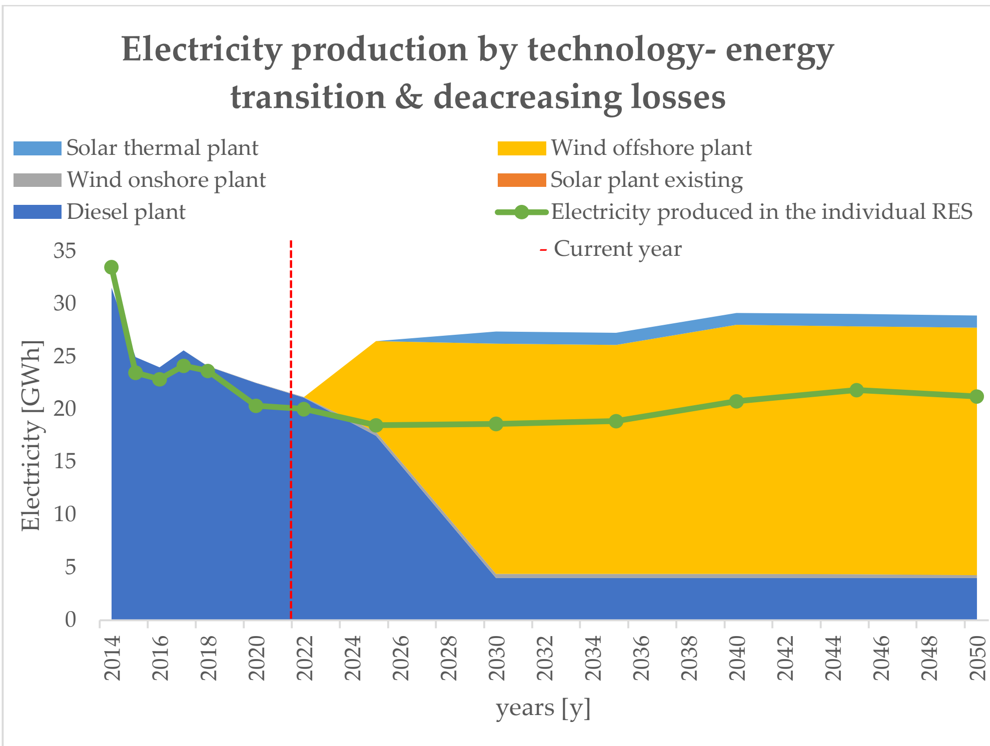


Figure 53. Comparison between electricity produced in the individual RES and in the integrated model - electricity mix transition, DL scenario

In Figure 53, the prospects of future electricity generation resulting from the individual RES model (green line) have been compared with the results of the integrated model, under the hypothesis of electricity mix transition, increased on-site water capacity and decreased losses of water grid.

Considering only the energy system, it is noticeable how the area above the green line would not be considered. Indeed, by studying the energy system alone, assessments related to the possibility of increased water production would have been lost and thus neglected the associated high energy consumption.

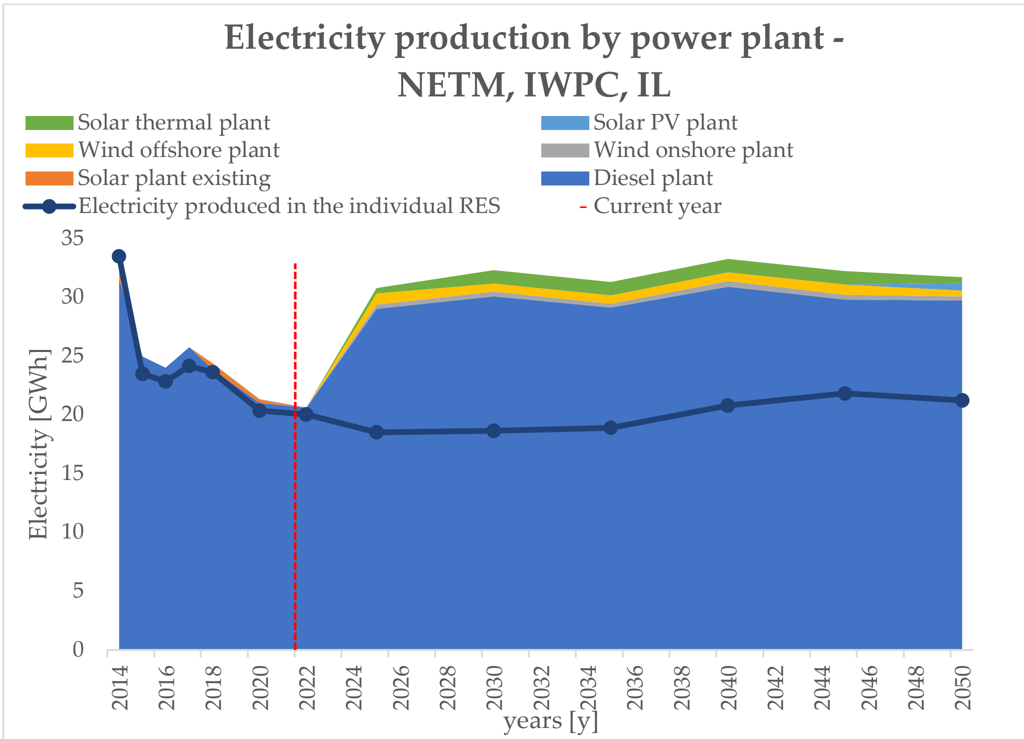


Figure 54. Comparison between electricity produced in the individual RES and in the integrated model – No electricity mix transition, IL scenario

Similarly, in Figure 54, the result of energy system alone and that of the integrated system are compared but considering no electrical transition and an increasing water network leakage. In this case, the energy surplus is higher than Figure 53 and it is mostly produced by fossil sources (namely, diesel power plant). The information lost in this case would have amounted to 10.5 GWh of generated electricity, 94% of which would be from fossil sources.

Chapter 7

Conclusions and perspectives

The TEMOA integrated water-energy model of Pantelleria island gives a more accurate tool for developing sustainable scenarios than analysis of the individual energy or water systems. The multisystem modeling has demonstrated the fundamental role that resources interconnections play in the evaluation of future prospects and the important consequences that measures applied to one system (e.g., water) cause on the other one (i.e., energy) and vice versa: the results of the Pantelleria integrated model quantitatively showed that errors from a single-systemtabek assessment are not at all negligible. Clearly, the integrated Pantelleria model needs to be improved both in the case of water system and energy one, adopting constraints and assumptions that make the modeling more robust and realistic.

At the current stage of the model, the following objectives have been achieved:

a. Based on the TEMOA-Italy, the TEMOA-Pantelleria model instance has been developed and has been compared with the already existing OSeMOSYS-Pantelleria. Two scenarios have been implemented: the first based on an energy transition, consistent with European policies, and the second one without any constraint on fossil-fuel electricity generation.
b. To approach the water scarcity problem of Pantelleria, the water system has been modeled and scenarios relative to water supply alternatives have been studied. In particular, the scenario of increasing on-site water

production and that of keeping the water-supply side unchanged have been evaluated.

c. Energy and water systems have been integrated to obtain a broader view in order to manage the synergies and trade-offs between the two resources, providing an instrument for sustainable development plans. The integrated model has been tested implementing two scenarios simulating different water grid behaviors and their consequences on the energy and water resources. Lastly, the results of the integrated model have been compared with the single system (e.g., energy system).

The most interesting results that have been obtained from the integrated assessment are related to the difference in energy consumption due to an increase of water production on-site, and the consequences that the state of the water network implies not only with respect to the water resource consumption, but also on the energy. Specifically, under the hypothesis of fossil-fuel based electricity mix scenario, increasing of water production on site and water grid losses increasing, in 2050, the integrated model electricity consumption is 10.5 GWh higher than that of individual energy system, where any change in the water production sector have been not evaluated.

The integrated systems modeling has been performed by exploiting an Energy System Optimization approach and adapting it to water system features. Specifically, due to its flexibility, it has been possible to use TEMOA to represent key aspects of the water system. The current integrated model of the island represents a pilot experiment for multisystem modeling. Clearly, the adopted modeling approach for the water system through an ESOM requires simplifications and inaccuracies that need to be improved. The following step could be the evaluation of the water system by exploiting specific tools that take into account all aspects of management and production of the resource, to model the whole system more accurately and derive more detailed and realistic results.

Additionally, the Pantelleria water-energy system is intended to represent the starting point for an integrated assessment that needs to be extended to climate and land-use systems (CLEW Models) with the aim to obtain a comprehensive vision of the overall system to reach a sustainable management of all resources involved.

The ultimate goal of a CLEW model development is to exploit it into larger-scale contexts, expanding it to regional and national levels.

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