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Flexibility Services to Minimize the Electricity Production from Fossil Fuels. A Case Study in a Mediterranean Small Island

Manfredi Crainz, Domenico Curto, Vincenzo Franzitta, Sonia Longo, Francesco Montana, Rossano Musca, Eleonora Riva Sanseverino * and Enrico Telaretti

Dipartimento di Ingegneria, Università degli Studi di Palermo, 90133 Palermo, Italy; manfredi.crainz@gmail.com (M.C.); domenico.curto@unipa.it (D.C.); vincenzo.franzitta@unipa.it (V.F.); sonia.longo@unipa.it (S.L.); francesco.montana@unipa.it (F.M.); rossano.musca@unipa.it (R.M.); enrico.telaretti@unipa.it (E.T.)

* Correspondence: eleonora.rivasanseverino@unipa.it

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Abstract: The design of multi-carrier energy systems (MESs) has become increasingly important in the last decades, due to the need to move towards more efficient, flexible, and reliable power systems. In a MES, electricity, heating, cooling, water, and other resources interact at various levels, in order to get optimized operation. The aim of this study is to identify the optimal combination of components, their optimal sizes, and operating schedule allowing minimizing the annual cost for meeting the energy demand of Pantelleria, a Mediterranean island. Starting from the existing energy system (comprising diesel generators, desalination plant, freshwater storage, heat pumps, and domestic hot water storages) the installation of solar resources (photovoltaic and solar thermal) and electrical storage were considered. In this way, the optimal scheduling of storage units injections, water desalination operation, and domestic hot water production was deduced. An energy hub model was implemented using MATLAB to represent the problem. All equations in the model are linear functions, and variables are real or integer. Thus, a mixed integer linear programming algorithm was used for the solution of the optimization problem. Results prove that the method allows a strong reduction of operating costs of diesel generators also in the existing configuration.

Keywords: multi-carrier energy systems; energy hubs; mixed integer linear programming; optimization; islands energy system

1. Introduction

In the last decades, the electricity system underwent large-scale transformation, and the automation degree of power systems has increased significantly. The steadily increasing energy demand and the growing use of small distributed energy resources (like photovoltaic (PV) and wind energy), called for a rethinking of the management strategies of the power system. The rapid increase of energy demand was accompanied by the transition from “vertically” to “horizontally” integrated energy systems and by the restructuring of monopolistic frameworks towards liberalized markets [1].

The effective integration between generation and load requires a real time balancing of demand and supply, that can also be achieved using electricity storage systems (ESSs), able to store the excess of energy in periods of high generation for later use during peak demand periods. In this way, the use of ESSs also allows a higher integration of renewable energy sources (RESs) in the power system and a reduction of greenhouse gas emissions. ESSs and RESs can efficiently be managed using a smart grid concept, thus ensuring a reliable, affordable, and clean energy system [2]. However, only one third of the final European energy demand comes from electricity [3], thus the concept of a smart electricity needs to be extended, also including other energy carriers, like heating, cooling, water, and so on.

The design of multi-carrier energy systems (MESs) requires electricity, heating, cooling, water, transport, and other infrastructures to be considered as interacting, in order to get the desired objectives. A MES is able to get several benefits compared to a power system operated independently. The multi-energy perspective creates an increased degree of freedom, resulting in the following advantages, both in planning and operational stages:

- Higher efficiency, thanks to the optimal interaction among different power components. For example, a power system with a high wind power penetration, could exploit the excess of wind energy to charge electrical storages such as electric vehicles;
- Higher reliability, thanks to the increased availability of multiple energy sources. The load, indeed, is not dependent from a single source, and can be supplied by the power source with the lowest cost and the highest availability;
- Higher flexibility, thanks to the increased degree of freedom in supplying the loads. An energy carrier that appears polluting or costly can be replaced by a more attractive energy source.

On the other hand, a MES has an intrinsically higher degree of complexity, making it difficult to model. To overcome the problem, a MES can be studied through an energy hub model [4]. Energy hubs can be defined as "entities consuming power at their input ports connected to, e.g., electrical distribution grids and natural gas infrastructures, and provide certain required energy services such as electricity, heating, cooling, compressed air, etc. at the output ports" [5]. Energy hubs can be used to manage energy carriers flows within an energy system, ranging in size from local to national level. An energy hub can be considered as an interface between energy carriers suppliers and consumers through network infrastructures [1]. At the input side, electricity, natural gas, and district heat are demanded from the corresponding infrastructure, converted within the hub, and transferred to the output port, where the electricity, cooling, or heating demand are met. An example of an energy hub is reported in Figure 1.

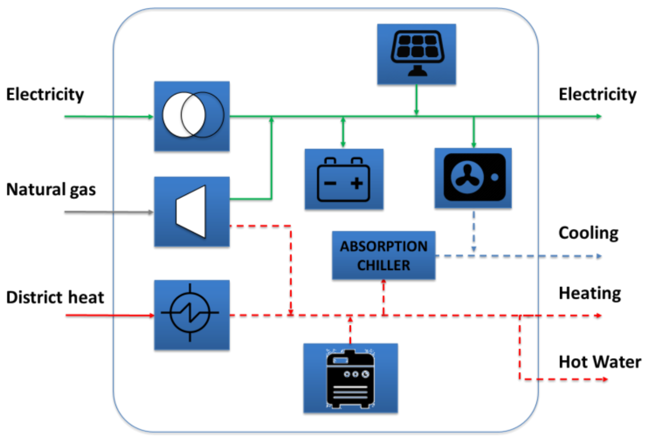

Figure 1. An energy hub containing typical elements.

In this paper, the simultaneous synthesis, design, and operation of the energy system providing electricity and freshwater to a Sicilian island is developed and implemented, using MATLAB as a simulation tool. In this case as compared to the schematic representation depicted in Figure 1, the flexibility of the electrical load is considered, such electricity is devoted to water desalination or water heating.

A mixed integer linear programming (MILP) optimization model was; thus, developed, able to identify the optimal scheduling of RESs, ESSs, and equipment typically installed in small islands, and it was applied to the energy system of a Mediterranean island. The optimization allowed for identifying the minimum annualized cost for meeting the island's demand, also accounting for the flexibility that the desalination unit and the domestic hot water (DHW) storages may provide to reduce partial load operation of electricity generators. The installation of RESs and ESSs was further investigated to perform more ambitious targets posed by the Italian government, aimed at reducing greenhouse gases emissions in small islands.

The original contribution provided by this paper is the inclusion of flexibility services in an energy hub optimization framework, considering both medium and small loads (i.e., freshwater from the desalination unit and DHW storages installed in residential loads, respectively). DHW storages are assumed to be operated as a unique entity through a main controller. The freshwater demand was included in the optimization, representing an innovation with respect to the existing literature. The selected case study is an electric island, as well as a geographical island, and this represents another original aspect of the study. The energy system of Pantelleria was accurately examined before the modeling phase, in order to identify the key points to be addressed. The most significant details on the island energy system are also reported, in order to provide readers with a complete view of the case study for future works. Moreover, the study was divided in two main groups of simulations:

- The first group considers only the desalination unit flexibility service to be integrated with the local diesel generator units;
- The second group accounts also for the installation of new equipment and the flexibility of DHW storages.

The reason behind this separation was to investigate the potential benefit deriving from only new management logics (flexibility of the desalination unit activation) and from the use of new components.

2. Background

2.1. Literature Review on Energy Hubs

Differently from the past, where each energy carrier was operated independently (e.g., electricity [6], natural gas [7], and district heating [8]), recently an increasing number of publications started focusing on MESs, where electricity, heating, cooling, water, transport, and others interact at various levels, in order to get an optimized operation [9].

Moslehi et al. [10] developed a methodology to optimally coordinate the operation of a large industrial cogeneration system, including both electric and thermal systems, with the purpose to minimize the overall costs while satisfying electric and steam constraints. The thermal system is modeled as a linear steady-state model, and the electric system as a standard Newton's power flow model.

Groscurth et al. [11] developed a general model framework aimed at supporting decision-making during the development and realization of regional and municipal energy systems, with the purpose to minimize non-renewable primary energy, air pollutant emissions, and monetary cost. The optimal solution is obtained looking for Pareto-optimal combinations of conventional energy-supply techniques, allowing for an increasing use of RESs and ESSs. The model also includes heat exchangers, cogeneration, heat pumps (HP), demand-side measures and dwelling insulation.

In [12], Bakken et al. presented, among others, a new model designed to analyze complex energy transport systems with multiple energy carriers. The transport system consists of different energy sources (oil, coal, electricity, gas, liquefied natural gas), conversion between different energy carriers, and different energy storages (hydro, liquefied natural gas storage, and gas caverns). The optimization is carried out using MATLAB linear programming algorithms, considering both equality and inequality constraints.

Hecq et al. [13] developed a linear programming model (PRELE), allowing the analysis of combined electricity and gas markets of several interconnected networks, minimizing the total investment and operating system costs.

Bakken et al. [14] outlined a new methodology for analyzing complex energy systems with multiple energy carriers, including technological, economic, and environmental aspects. To better generalize their study, they use a combination of stochastic dynamic programming and deterministic short-term optimization. Available sources are gas (from landfills), biomass (from forestry and farming), and waste (from companies and offices).

In [15], An et al. presented a combined optimal power flow method, considering both electricity and natural gas networks, aiming at maximizing social welfare. First, the electric load flow problem is solved, and the results are used to solve the gas load flow problem.

In [16], Gil et al. developed a single mathematical framework of electricity, gas, coal, and water, using a network flow optimization model. The proposed model, based on the actual US national electricity grid, is able to ensure the economic and physical integrity of the electricity network, taking into account the strong coupling within different energy subsystems.

Nazar and Haghifam [17] developed a three-stage optimization procedure to achieve the optimal expansion planning of a system, minimizing the investment and operational costs and maximizing the system reliability, using the energy hub to take into account the impact of multiple energy carriers. The algorithm allows to determine the optimal allocations, to select optimal capacities and replacement alternatives of system devices, and finally to ensure the optimal restoration in contingency conditions.

Quelhas et al. [18] presented a network flow programming model to evaluate how nodal prices in the electric network are influenced by the dynamics of integrated energy systems and of the various fossil fuel networks (assumed to be similar to that of the USA), with the purpose to find the most economically efficient use of electricity generation, demand, and fuel supply and delivery. The proposed algorithm can be solved by applying the generalized network simplex algorithm.

Soderman and Pettersson [19] proposed a MILP model, with the objective to minimize the overall cost of a distributed energy system, consisting of electricity production and demand, heat production and consumption, power transmission, fuel transport, water transport, and heat storage. The developed algorithm is able to identify the location and the type of production units, heat transport lines, and storages, according to the selected objective function.

In [20,21], Geidl and Andersson presented an approach to manage energy flows in MESs, including gas, electricity, and district heat, based on the idea of energy hubs. In [20], the optimization of energy flows is elaborated using a single entity containing all storages and conversion devices, with a multi-input and multi-output coupling. The problem is defined as a topological optimization, and addressed as a nonlinear constrained optimization problem defined by an objective function under different constraints. In [21], the MES is represented as the sum of several interconnected energy hubs, coupled between them using power conversion devices. A general dispatch rule for linear energy hubs is also derived.

A real case study addressing the energy hub approach was shown by Schulze et al. In [22] the energy hub concept was used to solve optimal power flow problems with a high number of RESs. The objective function is a combination of cost minimization and benefit maximization of each energy hub, considering different energy sources such as natural gas, electricity, fuel oil, and district heating. The model is implemented using MATLAB under linear and non-linear constraints.

Almassalkhi and Hiskens [23] developed a novel method for analyzing interconnected multi-carrier energy hub systems, supporting natural gas, electricity, wind capacity and district heat. The model is implemented using MATLAB and demonstrated on a set of more than 100 hubs, using binary variables to avoid non-linearity.

La Scala et al. [24] analyzed a system composed by several interconnected energy hubs with multiple energy carriers, in order to obtain the optimal energy flow management. The problem is addressed exploiting a non-linear multi-objective optimization procedure, able to minimize several cost functions (technical, economic, and environmental), ensuring a reliable operation of the multi-carrier energy system (electricity and natural gas), also in presence of volatile energy prices and high load demands.

Pazouki et al. [25] proposed an optimal operation method to analyze an energy hub as a super node in an electrical distribution network, where gas, electricity, and wind at the input port cover the required demands in the form of electricity, heat, gas, and water, taking into account storage, direct connections, or demand shifting. A MILP model is used to identify the optimal solution, minimizing the operation cost and maximizing the system reliability in nine different case studies.

Proietto et al. [26] developed a heuristic and non-linear programming-based algorithm in order to get the optimal energy flows dispatch, maximizing the profit for the plant owner. The optimal energy flows dispatch is obtained controlling an energy management system (EMS) as an energy-hub connected to electricity, gas, and hydrogen networks.

Brahman et al. [27] proposed optimal operation methods to analyze a residential energy hub model, where natural gas, electricity, and solar radiation at the input port provide the required demands in the form of electricity, heating, and cooling. The authors also consider demand response (DR) programs, including load curtailment, load shifting, and flexible thermal load of major household appliances, in order to increase the operational flexibility of the model. The results are tested for three different case studies, using both a minimum cost objective function and a multi-objective function, taking also into account pollutant emissions.

Arnone et al. [28] proposed an innovative MES involving both electrical energy and hydrogen power sources. An EMS is able to optimally manage a system composed by a water electrolyzer, a fuel cell, and two different storage systems (INGRID project), exploiting a multi-object optimization algorithm, implemented using MATLAB.

Ma et al. [29] developed an optimal dispatch strategy for a MES, considered as a whole micro energy grid. To enhance the reliability and flexibility of the energy hub, the classic combined cooling, heating, and power (CCHP) is expanded considering a generic energy hub, including RESs, EESs, and CCHP. The generic optimal dispatch model aims to minimize the daily operation cost and the environmental costs, using a MILP optimization algorithm, also considering DR.

Timothée et al. [30] developed an optimal dispatch model of a multi-energy hub, including RESs (PV and wind energy), combined heat and power (CHP), internal combustion generator (ICG), heat, and thermal storages. The optimal dispatch solution is obtained using an evolutionary algorithm, and the flexibility of load demand is obtained using vehicle-to-grid technology.

In Attardo et al. [31], the economic assessment of energy systems aimed at covering electricity and heating demands of an urban district was performed, and comparing results in Italian and Vietnamese scenarios. The study was deepened in [32], where also the cooling demand was evaluated and a multi-objective optimization approach was adopted, considering both economic and environmental objective functions.

As shown in the previous literature works, most of the papers, especially at the beginning, focused on the integration of electric and thermal systems (gas and oil markets) [7,10,13,15]. Only in later years, with the progress of the research, MESs started to focus on other energy sources, such as renewable energies [22,23,25,27,29–32], biomass and waste [14], district heat, energy storages [12,19,20,25,28–32], water transport [16,19,25], district heat [20,22,23,26], demand-side measures [11,25,27,28,30–32], and so on. The optimization is carried out using linear but also non-linear programming methods, with the aim to minimize mainly technological, economic or environmental aspects. Sometimes, a MILP algorithm is used to minimize more than one function at a time [19,25,29].

According to this brief literature analysis, the original contribution of this paper is the employment of the energy hub scheme for the synthesis, design and scheduling of new equipment, taking also into account flexibility services offered by the loads. Both medium and small flexible loads are considered in the analysis, specifically electricity to supply the desalination units and DHW storages installed in residential houses, operated as a unique entity through a main controller.

2.2. Energy Efficiency Measures in Small Islands

With the ratification of the Paris Agreement, 174 Countries (and the European Union) are obliged to introduce specific energy policies in order to limit the CO_2 emissions and, consequently, global warming. As reported in the Second Article of the Paris Agreement, the common goal is the limitation of global warming to "well below 2 °C", in comparison with the preindustrial levels [33]. To achieve this ambitious target, two kinds of solutions can be adopted [34]:

- Replacement of the existing power plants supplied by fossil fuels with new technologies supplied by RESs;
- Improvement of innovative solutions to reduce the energy demand from the final energy consumers, such as the installation of more efficient technologies or the adoption of smart controlling systems.

The application of both techniques is necessary to maximize the environmental benefits, as the different effects produced [35]. In the energy sector, the investments for the installation of RESs have grown in the last decades. It is estimated that all countries invested annually 47 billion USD in 2004 to 286 billion USD in 2015 [36].

Despite the diffusion of plants supplied by RESs, several areas continue to be strongly energy-dependent from fossil fuels. This condition is quite common in the numerous small islands around the world. Some of them are classified as Small Islands Developing States (SIDSs), an acronym introduced in 1994 by the United Nations. The upgraded list of SIDSs is composed by 58 countries, divided in Caribbean (29 countries), Pacific (20 countries), and AIMS (acronym of Africa, Indian Ocean, Mediterranean, and South China Sea, including nine countries) [37].

Considering the energy sector, both SIDSs and small islands belonging to developed countries show several common peculiarities, as [38]:

- Major energy dependence on imported fossil fuels;
- Small-scale generation systems to produce electricity;
- High costs for the energy production, infrastructure, transportation, communication and servicing;
- Under-utilization of the local available RESs;
- In many cases the installation of RESs is an economically feasible solution.

In addition, SIDSs are directly exposed to the international markets of oil, influencing the local economy. Population and local economy show a growing trend. SIDSs are characterized also by a little resilience to natural disasters and a fragile environment [39,40]. It is estimated that about 21 million people live in 2056 small islands, each one having between 1000 and 100,000 inhabitants. These communities require an electrical energy demand equal to 52,690 GWh/y, of which 22,770 GWh/y are concentrated in the Pacific Oceans [41]. In this context, fossil fuel is the main (or in several case the only) source to supply the local energy demand, with Fiji being the only exception. Indeed, thanks to the copious precipitation, this country was able to satisfy 48.74% of the annual energy demand in 2017 [42] through hydro power plants. Small islands usually import fossil fuels from mainland or foreign territories. Papua New Guinea, Trinidad, and Tobago are the only exceptions, as these countries produce and export fossil fuels [43].

About the electrical energy sector, small islands are usually equipped with stand-alone electrical grids, supplied by local diesel power stations [44]. The electrical network is underdeveloped, especially in SIDSs, where it is possible to find small villages disconnected from the main electrical grid. In this case the electricity production is entrusted to very small generators. In case of developed countries, small islands sometimes are interconnected each other or linked to mainland [43,45]. To reduce the dependence from fossil fuels and the emission of greenhouse gases, many islands are adopting specific policies to increase their energy sustainability. As introduced before, two kinds of projects can be implemented: the introduction of RESs and the improvement of energy efficiency for final users. The first approach is quite popular in the literature. As an example, the installation of renewable energy mixes has been proposed in numerous small islands around the world, such as Samsø (Denmark) [46], Faroe Islands [47], Canary Islands (Spain) [48,49], Azores (Portugal) [50], Maldives [51], and Reunion Island (France) [52].

Samsø is a famous example of an islanded community totally powered by RESs. This island is located at the east of Denmark, with a population of 3700 inhabitants. The local electrical network is linked to the mainland one, but the local energy production is enough to cover the local demand, thanks to the utilization of wind turbines and the realization of a heating district network supplied by biomass, produced locally [46]. The case of archipelagos located in remote areas is more complex [53].

As an example, Faroe Islands form an autonomous country (belonging to the Kingdom of Denmark), composed by 18 islands and located in the North Atlantic Ocean between Scotland, Norway, and Iceland. About 50,000 inhabitants live in this archipelago, requiring annually about 335 GWh. The electricity production is entrusted to fossil fuels (49%), hydropower (33%), and wind source (18%) (2017 data) [47]. To reduce the dependence from fossil fuels, Katsaprakakis et al. [47] investigated the possibility to install a wind park to cover 60% of the local energy demand, adding also PV panels and a pumping hydro plant to regularize the electricity production during the year and produce the remaining part of the energy demand.

Canary Islands is a Spanish archipelago located 100 km west from Morocco, in the Atlantic Ocean. About 2.2 million people live in this archipelago, of which 0.85 million live in Gran Canaria and 0.89 million in Tenerife. Gils and Simon [48] investigated the adoption of concentrated solar panels, wind turbines, and pumping hydro plants to improve the RESs share in the islands. The proposed energy scenario suggests also the installation of electrical links to interconnect each other the small islands [48]. To supply the Canary Islands, Rusu investigated also the potential exploitation of sea-wave energy source, considering the current prototypal technologies [49].

Stenzel et al. analyzed the environmental implications of a RESs mix to supply the Graciosa Island, belonging to the Azores, that are a Portuguese archipelago located in the North Atlantic Ocean [50]. The G.R.A.C.I.O.S.A Project suggests the installation of a wind park (4.5 MW), PV panels (1 MW), and the utilization of the existing oil-based power generators to balance the electrical network [50].

Maldives is an autonomous country located to the south of Sri Lanka and India (about 1000 km from Asia) in the Indian Ocean. To supply this archipelago, Liu et al. realized a feasibility study, proposing the installation of a RESs mix based on solar, wind, and biomass sources. The energy balance of the local network could be entrusted to the local desalination and to the diesel power plants, modulating the active units [51].

Selosse et al. investigated different energy scenarios, considering Reunion as a case study. This French island is located in the Indian Ocean, to the east of Madagascar. Several energy sources are considered: biomass, hydropower, wind, solar, geothermal, sea-wave, and the ocean thermal energy conversion (OTEC; i.e., the exploitation of the thermal gradient at different depths of the sea) [52].

As shown in the previous examples, the literature is currently focused on the proposal of renewable energy mixes, considering, normally, wind and solar as energy sources. Geothermal, hydropower and biomass are sometimes taken into account, if they are available. More exotic RESs are occasionally evaluated (sea-wave and OTEC) being this technology at a prototypal stage. An important contribution to the reduction of CO_2 emissions can be given by the improvement of the energy efficiency at final users premises, as introduced by the Kyoto protocol and following environmental agreements [54,55].

In this context, Italy recently published two important decrees to promote the introduction of RESs and the improvement of energy efficiency in small islands. In detail, the decree 14 February 2017 emitted by the Italian Ministry of Economic Development establishes specific targets for 20 small Italian islands, indicating the minimal power to install from RESs (as regards the electricity consumption) and the minimal surface of solar thermal collectors (STCs) to install (as regards the energy demand for DHW) [56]. It is important to underline that the greatest part of Italian small islands is inserted in programs to preserve the natural landscape, so the installation of extensive RES plants (e.g., wind turbines) may not be easily implemented [57].

The decree n. 340 of 14 July 2017 issued by the Italian Ministry of Environment, Land, and Sea provides a funding of 15 million euros to implement specific projects in 21 Italian small islands to improve the energy efficiency at final users premises [58].

Considering the Italian framework and the review of the literature above reported, the authors are interested in investigating the potential energy savings that is achievable in small islands equipped with desalination plants (DESs). Indeed, most of the islands in the Mediterranean Sea is equipped with a DES, including Lampedusa, Linosa, Ustica and Pantelleria [57].

Using a multi-carrier energy hub approach to model small islands, it is possible to modulate the electricity demand from the DES in order to maximize the energy efficiency of the existing power plants, decoupling the freshwater demand thanks to the installation of a water reserve (in most cases already existing). The second step is the modulation of electricity consumption to produce DHW. Indeed, as shown in a recent report produced by RSE (Italian acronym of "Ricerca sul Sistema Energetico", Research on Energy Systems), electric resistance water heaters (ERWHs) are commonly used in Italian small islands to produce DHW [59]. As this technology requires only electricity and it is equipped with a hot water reserve, it is also possible to decouple the DHW demand from the electricity production.

2.3. Grid-Interactive Water Heaters for Energy Storage

As demand response (DR) can push customers to rationalize their energy consumption, playing a vital role in peak-load shifting or load-leveling strategies, more attentions are paid to it nowadays. However, the researches on DR implemented in MESs are rare, and the DR models or strategies are far from full investigation. Customer-side flexibility is the ability of electricity users to reduce their consumption in peak-load hours, shifting part of the load to low-cost hours. The customer-side flexibility has been widely studied by many authors in several works [60–62]. Some of them focus on the heating system models [63,64], others on the estimation of the heating demand [65]. Many of the DR programs aim at minimizing customer energy costs [66–68], while others help to improve the power system operation [69]. Among different solutions to increase flexibility of electricity systems, grid interactive water heaters (GIWHs) can make a significant contribution, against a relatively low cost. As a result, several flexibility programs have already been implemented in the USA, aiming to coordinate several million GIWHs with the electricity network [70,71]. A GIWH can be considered as a thermal storage medium, able to store thermal energy in a tank, in the form of hot water, when the price of electricity is low, while using it during high-price hours, or when a peak in the power diagram occurs. In most cases, the operation of GIWH does not impact on the end-user comfort, due to the large size of the water tanks.

Large-tank electric resistance water heaters (ERWHs) have been identified as the ideal technology to offer DR services to the power network, mainly thanks to the large storage capacity and the high power consumption (able to offset a significant part of the daily power diagram). Furthermore, the ERWH power profiles are often consistent to the utility needs, since the highest consumption occurs during the peak power periods. In terms of cost efficiency, the GIWH is the most cost-effective energy storage technology, being an order of magnitude cheaper than the other technologies [70]. According to the ES-Select Tool of Sandia National Laboratories [72], compared to other storage technologies GIWHs appear the cheapest. GIWHs differ from traditional water heaters since they can be controlled through a bi-directional equipment, able to rapidly turn on/off the GIWH, or increase/decrease the load in just a few seconds. For example, in presence of a capacity shortage in the power network (due to an under-generation condition), GIWHs can be rapidly turned off or partialized. Conversely, in presence of an over-generation condition, GIWHs can be turned-on, to help alleviate the excess of power generation, allowing the load to follow generation. Since the development of the GIWH is quite a mature technology [73], and it provided very profitable results in previous experiences with low installation costs, in this study the possibility of providing flexibility services in Pantelleria from ERWH systems for load modulation is analyzed. Furthermore, since one of the highest electrical loads in

Pantelleria is the DES, this research also investigated the potential benefit deriving from the cooperated scheduling of these loads to reduce the consumption of the local diesel generators.

3. Case Study

Pantelleria is an island located at about 100 km (62 miles) southwest of Sicily and 65 km (37 miles) east of the Tunisia coasts in the Mediterranean Sea. With its 84.5 km^2 of extension, it is the largest between the small islands belonging to Sicily. The volcanic island has a mountainous territory, as shown in Figure 2 [74].

Figure 2. Satellite view of Pantelleria [75].

Since 1999 the greatest part of the island is classified as reserved area, thanks to the establishment of the natural oriented reserve of Pantelleria island. Since 2016 this area is defined as the national park of Pantelleria island [76,77]. In order to preserve the landscape, several restrictions were introduced in the local building regulations [78]. For this reason, the current electricity generation system of the island is mainly based on eight diesel oil generators with a total installed power of about 25 MW. Generators are owned by S.MED.E. Pantelleria S.p.A. (Palermo, Italy) a vertically-integrated company providing electricity production, distribution, and supply, as happens in most of the Italian small islands. Nevertheless, some renewable plants are also installed in the island, whose installation was recently pushed by Ministry Decree 14 February 2017 [56], promoting renewable energies in small islands. The decree established specific targets for each island, equal to 2720 kW of electricity RESs plants and 3130 m^2 of STCs for Pantelleria island. Currently, there are two small wind turbines with a total capacity of 32 kW and many PV plants, covering the local loads of both private users and big loads as the hospital and the airport, with a cumulated peak power equal to 449 kW. The contribution of renewable systems to the island electricity demand is lower than 1%, with a coverage level of 17.68% of the RESs target. Regarding thermal RESs, there are 20.8 m^2 of STCs (0.66% of the target for the thermal energy production by RESs) [57]. Notwithstanding this small penetration, the RESs installation potential in Pantelleria is very high, covering solar, wind, and geothermal energy [79].

The generation system, as in many Italian small islands, is largely oversized compared to the average demand, as the summer peak is equal to about 8 MW, while the minimum yearly demand is about 2 MW. This great oversizing results in a loading factor equal to 0.167, as the yearly energy demand is about 36.5 GWh (2018), with a minimum in middle seasons being 2.5 GWh and a maximum in August being 4.6 GWh [80]. Data on local generation are summarized in Table 1, while Figure 3 shows the diesel oil consumption and generators average specific fuel consumption during 2018.

Table 1. Generation groups in Pantelleria [80].

Generation Units	Rated Power [kW]
Diesel generator 1	1250
Diesel generator 2	5040
Diesel generator 3	3070
Diesel generator 4	2920
Diesel generator 5	3089
Diesel generator 6	2648
Diesel generator 7	1760
Diesel generator 8	5220
TOT Diesel generators	24,997
PV plants	449
Wind turbines	32
TOT Diesel + RES generators	25,478

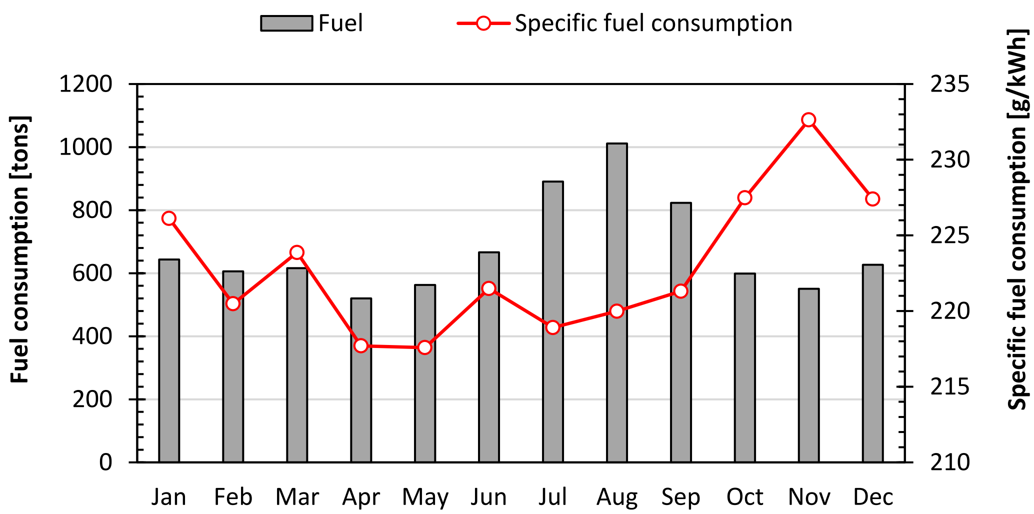

Figure 3. Monthly fuel consumption and average specific fuel consumption, data elaborated by authors taken from [80].

Like in other small islands, the energy production shows a peak during summer, as a consequence of the increase in population due to tourist arrivals. Indeed, energy demand in Pantelleria is strongly influenced by tourism. While the resident population is equal to 7759 inhabitants, about 91.8 people/km^2, tourist numbers can be up to 10,483 (The number of tourists was estimated as the sum of beds in hotels and tourist facilities (1948) and the number of summer houses (2845), assuming three people per house), with an increment of 135% [81].

The Italian government recognizes an incentive to small island production companies, to cover the difference between the national unique price paid by the users and the real production costs faced by the company. This incentive is granted to counteract difficulties that production companies have to face in small islands, as the diesel oil is transferred by ships from the mainland. For Pantelleria, this incentive was equal to 0.2979 €/kWh in 2015, accounting for more than 9,030,840 € [82]. Considering all the Italian small islands, this incentive was equal to 74 million € [83].

Pantelleria is supplied by a 10.5 kV distribution grid, with a specific length of 6.79 km per km^2 of island surface [84]. Due to the low voltage level, distribution losses are quite high, and outages are frequent [85].

Regarding energy demand, as in the other minor islands of the Mediterranean Sea, the total primary energy demand in Pantelleria is covered thanks to fossil fuels [86]. According to the data reported on Pantelleria's Sustainable Energy Action Plan (SEAP) [87], four main energy carriers are employed to satisfy all local needs: electricity, gasoline, diesel, and liquefied petroleum gas (LPG). The gasoline and diesel consumptions are related to the local private and public transport, also including maritime transport. The LPG one is essentially caused by the energy demand for cooking. Differently from the other carriers, the electricity demand steadily increased until 2013, and this energy carrier is produced using almost exclusively diesel oil in the local power plants, since the island is not connected to the main European power grid. This trend was then inverted due to the recent (2014) revamping of the DES.

To have an idea about how energy is used on the island, the energy demand (in terms of primary energy consumption) by sector is reported in Appendix A.

The main energy requirement in the island is electrical energy, as both DHW production and space cooling in summer are provided by electrical equipment, while fossil fuels are employed for cooking [59]. Electricity demand is mainly due to domestic users, representing 30.2% of the total load in 2015 [59], but there are also other big loads, such as the DES, the hospital, and the airport. As the RESs generation in the island is limited, the trend of electricity production from the diesel generators can be considered as an estimation of the island electricity demand. A detailed analysis of electricity demand, reported in the Appendix A, confirms also that a significant share is related to the residential sector. Indeed, the sum of main and secondary residences represents the 37.20% of the local electricity demand in 2016. A further focus on the residential sector is provided in Figure 4. Among the electrical loads in the residential sector in Pantelleria, the production of DHW through ERWH [59] has the main role (31.1% in 2011), corresponding to 3.8 GWh/y. The annual trend of the primary energy demand for DHW production is reported in Figure 5.

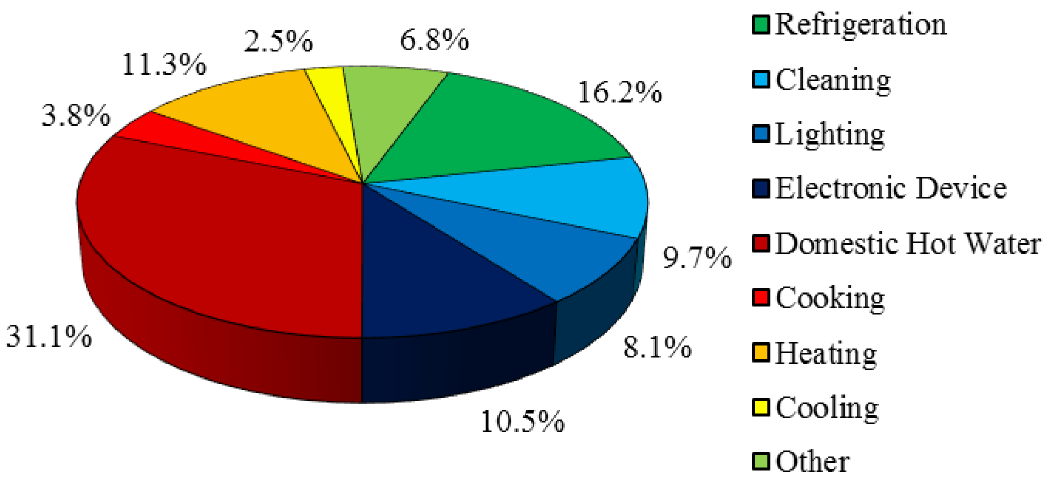

Figure 4. Share of electricity consumption in Pantelleria in the residential sector by main loads, in 2011, figure elaborated by the authors from data provided by SMEDE [87,88].

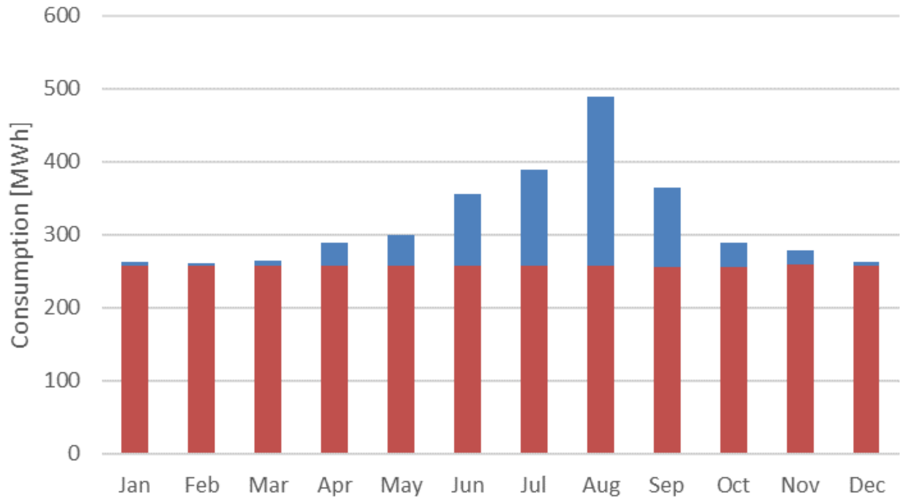

Figure 5. Annual trend of electricity consumption for Domestic Hot Water, DHW in the residential sector in Pantelleria in 2011 (The figure was elaborated by the authors based on data provided by SMEDE [87]).

Among the electrical loads, water desalination plants are often indicated as big consumers for small islands, and this is confirmed by the analyzed case study, where the desalination energy demand was equal to 3300 MWh in 2018 (about 10% of the whole island demand), corresponding to the production of about 870,000 m^3 of freshwater [89].

In detail, Pantelleria is equipped with two DESs, named "Sataria" and "Maggiuluvedi" (by the name of localities where the plants are installed). After the recent replacement of desalination units, both plants are currently based on reverse osmosis (RO) technology units.

Sataria plant is composed by four RO units working in parallel, each one having a rated capacity to produce about 1200 m^3/day of freshwater [89], using sea water as source. From the electrical point of view, each RO unit absorbs up to 200 kW of electric power. Depending on the season, the operation of the DES modules is modulated: The number of active units spread from two (winter) to four (summer), as shown in Figure 6, where the turnover between units for maintenance reasons is also shown. In the same figure, the freshwater productions in 2015 and 2018 are compared. For the 2015, the contribution of each desalination unit is also reported.

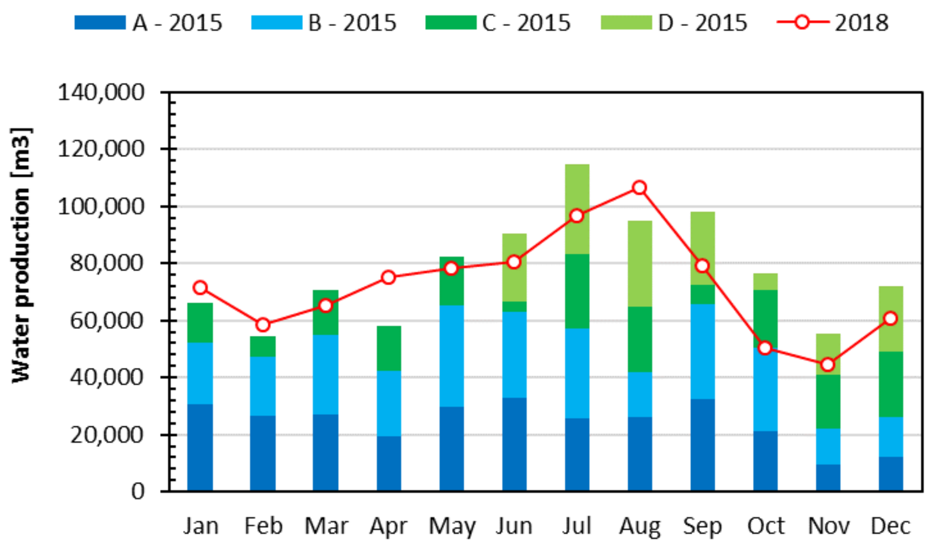

Figure 6. Freshwater production in 2018 in Pantelleria [89,90].

From the DES, freshwater is pumped into Kaffefi and Gelfiser reserves, each one having a capacity of 7000 m^3 and located, respectively, at 262 and 371 m above sea level. In this way, thanks to the gravity effect, freshwater is distributed into several other reserves until the final users.

The other DES is located in Maggiuluvedi. It is currently equipped with a RO unit, supplied with brackish water from the Valenza well. Freshwater is directly distributed to the local water network and the Arenella reserve. In the Appendix A in Table A1, the detail of the island water capacities is reported.

In order to reduce the primary energy consumption of the island, this study analyzed the possibility to exploit DESs operation to enhance flexibility, ensuring a more stable operation of diesel generators. Since the owner of DESs in Pantelleria, SOFIP S.p.A. company (Palermo, Italy) demonstrated its willingness to provide flexibility services only through the Sataria plant, in this study, the presence of the Maggiuluvedi desalination unit was neglected, grouping its energy consumption with the remaining electricity demand and neglecting its freshwater production. Furthermore, during an interview, *SOFIP S.p.A.* stated that the Sataria plant dispatches the freshwater produced to a 5000 m^3 capacity storage, thus this value was adopted for the simulations.

Furthermore, to promote the RES installation in small islands, according to the new Italian regulation, a second optimization problem was formulated, considering also the installation of PV systems, STCs, and ESSs and the flexibility service provided by the ERWHs. The economic feasibility of ESSs was also assessed in a previous study on Pantelleria, where the combination with RESs plants resulted in a payback time lower than 10 years [91].

4. Mathematical Model

4.1. Methodology

The aim of this study is to identify the optimal combination of components (synthesis stage), their optimal sizes (design stage) and their optimal operating schedule (operation stage) that allows minimizing the annual cost for meeting the energy demand in Pantelleria, and more in general, of an islanded microgrid. Starting from the existing system (AS-IS scenario), composed by diesel generators (DG), a desalination plant, DES, a freshwater storage (WSS) and HPs, and DHW storages (Hot Water Storage System, HWSS) distributed over the island, as in Figure 7a, the desalination unit flexibility was considered in the TO-BE scenario 1 (Figure 7b), where the components are the same as the AS-IS scenario, but DES operation is optimized. In the TO-BE scenario 2 (Figure 7c), the optimized installation of PV, STCs, and ESSs was deduced.

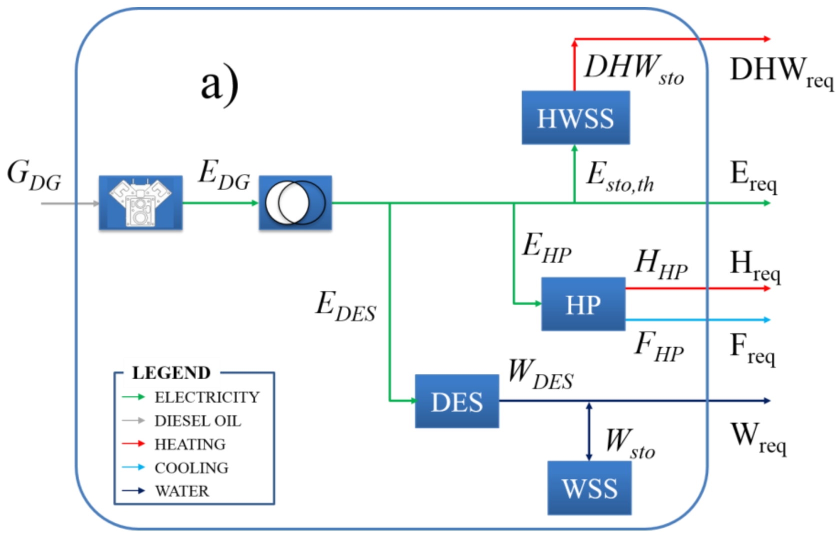

Figure 7. *Cont.*

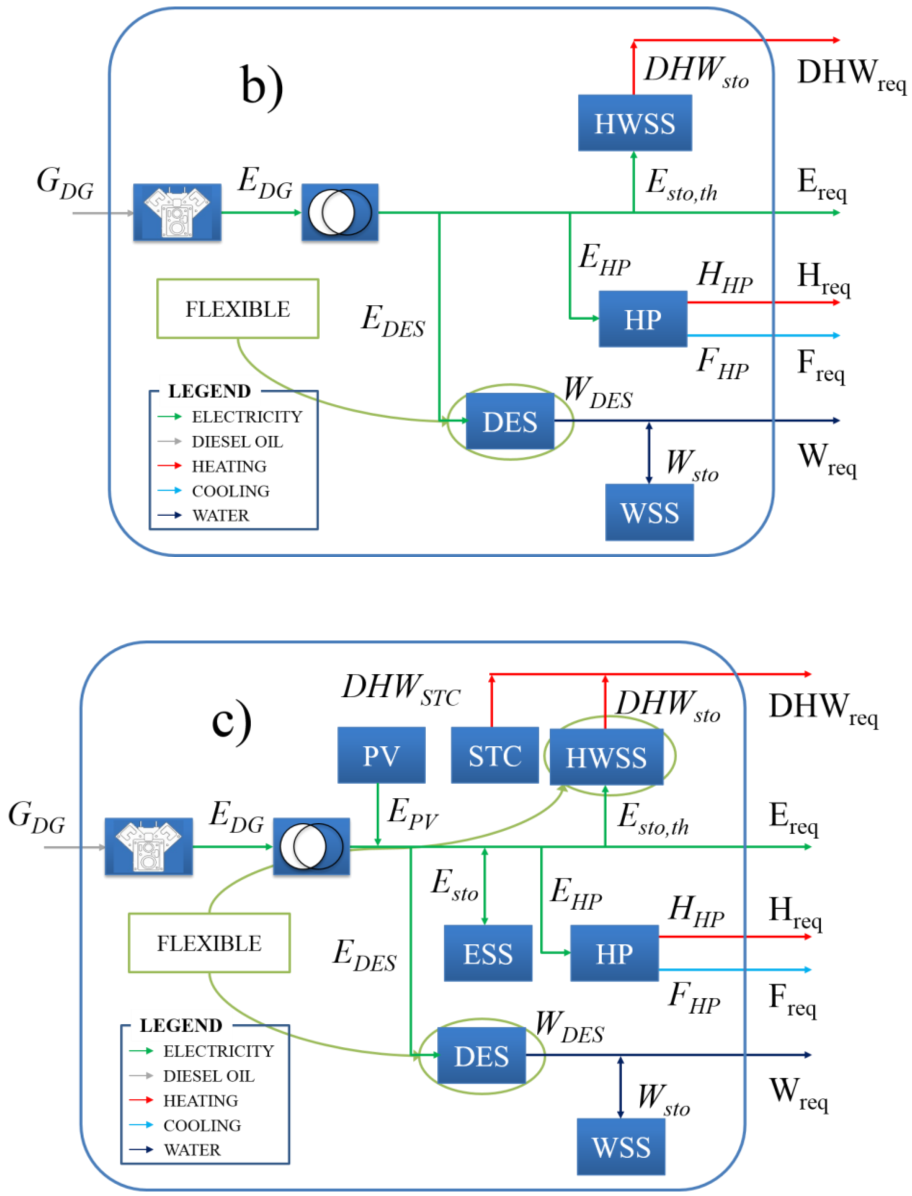

Figure 7. Scheme of the energy system in Pantelleria: (**a**) AS-IS scenario; (**b**) TO-BE scenario 1; (**c**) TO-BE scenario 2.

In the figure, G_{DG} is the diesel oil flow in DG, E_{DG} is the electricity produced by DG, E_{PV} is the electricity produced by PV, E_{DES} is the electricity consumed by DES, E_{STO} is the electricity exchange of ESS, E_{HP} is the electricity consumed by HP, $E_{sto,th}$ is the electricity consumed by HWSS, E_{req} is the island electricity requirement, DHW_{STC} is the DHW flow produced by STC, DHW_{sto} is the DHW flowing out from HWSS, DHW_{req} is the island DHW requirement, H_{HP} is the space heating produced by HP, H_{req} is the island space heating requirement, F_{HP} is the space cooling produced by HP, F_{req} is the island space cooling requirement, W_{DES} is the freshwater produced by DES, W_{sto} is the freshwater exchange of WSS, and W_{req} is the island freshwater requirement.

An energy hub optimization model was implemented in MATLAB [92], allowing the identification of the combination of new and existing equipment that minimizes the annualized installation and operating costs. The model takes into account the various aspects related to the Pantelleria's energy system, which was deeply analyzed before the modeling phase. Indeed, a preliminary analysis of the island allowed neglecting some aspects of the system, as electricity is not imported from the mainland, and natural gas distribution or district heating and cooling systems do not exist. Furthermore, as space heating and cooling demands are mainly met through electricity, the estimation of the corresponding loads appeared to be superfluous, as they are already accounted for in the power demand supplied by diesel generators (data reported in Figure A4). Being these components already installed, their sizing was also neglected. Although both freshwater and DHW are also provided through electricity, a different approach was adopted in order to evaluate the economic feasibility of flexibility services from the desalination system and from final users, respectively. Since both of these services are based on storage systems (municipality water storage and DHW storages), flexibility can be provided without the installation of new components. For these reasons, the total electrical demand of the island was divided into three main components: electricity, freshwater, and DHW. The demand estimation was based on data collected from local companies. In detail, SOFIP S.p.A., the company that owns the DESs, provided electricity demand and water production of each unit, while DHW demand was evaluated as a fraction of the residential electricity demand, as reported in [87]. The cumulated electricity demand was provided by the local generation company, S.MED.E. Pantelleria S.p.A., through monthly standard day trends with an hourly detail. The electricity demand for this study was extrapolated from these trends deducing the amount for desalination units and DHW.

Since renewable technologies are subjected to constraints, due to landscape preservation, the useful solar radiation of Pantelleria was reduced to the available areas. In detail, annual average solar radiation in available zones was estimated in [59] and scaled to a monthly basis using data for the whole island from the European Joint Research Center JRC typical meteorological year [93]. During each day, the solar radiation trend was assumed to follow a sinusoidal path, with sunrise at 06:00 and sunset at 18:00. Since the absolute value of the area was not provided in the referenced study, the upper bound for solar technologies to be installed was estimated taking as a reference the minimum targets imposed by the Ministry Decree 14 February 2017 [56].

Efficiencies of solar technologies were assumed to be constant and based on the values reported from datasheets. In detail, the nominal efficiency of the PV module selected (equal to 17.11%) was reduced by a 95% factor, to take also into account for the inverter losses, while for the solar collector a constant average temperature difference between the collector and the air equal to 30 °C was assumed, providing an efficiency of 69.4%.

4.2. Energy Hub Mathematical Model

The mathematical model of the optimization problem is composed by energy balance equations, for each energy carrier and storage system and by relations describing each component's behavior [31,32]. These equations were employed as equality and inequality constraints in the optimization model. The following assumptions were considered in the development of the mathematical model:

- Objective function and constraints are represented by linear equations;
- Energy balances are evaluated in steady state condition;
- System losses are evaluated only for components, while networks losses are neglected.

The variables of this problem can be categorized as synthesis, design, and operation variables for components and energy flows from grids. Synthesis variables indicate whether a new component is selected or not, and there is one Boolean variable for electricity storage (δ_{ESS}). Four additional design variables were selected to indicate the number of PV and solar thermal collector, STC, units (N_{PV} and N_{STC}), and the size of electricity and water storages (S_{ESS} and S_{WSS}), since the possibility of rising the storage capacity was also investigated. It should be noted that PV and solar collector design variables represent synthesis variables.

Operation variables indicate, for each component and each timestep t, the amount of energy produced (for renewable technologies), the amount of energy absorbed or released (for electricity and DHW storages), the amount of energy or water accumulated in the storages and Boolean variables indicating the state of electricity storage (since it cannot charge and discharge at the same time), and the number of desalination units. Operation variables for diesel generators are related to the load percentage of each of the eight generators. Variables can be identified in the following equations as they are written using bold style.

Although most of components efficiencies were assumed to be constants to keep the linearity of the problem, the efficiency variation of diesel generators at partial load was taken into account, as it is much more sensitive than for other components. In this way the diesel oil consumption, calculated as the ratio between electricity production and efficiency, would require a non-linear formulation. In order to keep a linear formulation, the efficiency trend was modeled through four average constant values depending on the load through a logical formulation. The trend and the average values are shown in Figure 8.

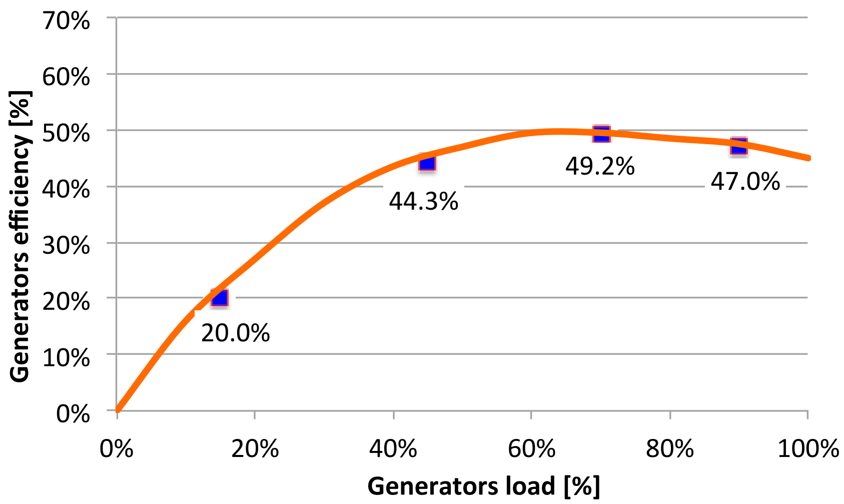

Figure 8. Diesel generators efficiency vs. load estimated trend and piecewise averaging (The figure was elaborated by the authors based on data provided by SMEDE [80]).

Since the whole operating year was simulated assuming 12 monthly standard days, with an hourly detail, the total number of operating hours is equal to 288, with a total number of 12,674 continuous variables and 867 discrete variables. Considering lower and upper bounds of discrete variables, the search space of this problem is composed by 1.3×10^{382} alternative combinations.

Since this search space would lead to an unfeasible computational time, the problem was simplified through the following approach:

- First, twelve monthly optimizations were performed, both for TO-BE scenarios 1 and 2, based on standard day data with hourly detail, obtaining optimal solutions for synthesis, design, and operation of each variable in each month. In this way, variables number was reduced to 1058 continuous variables and 75 discrete variables, with 4.5×10^{38} combinations for each optimization. The results are then extended to the month duration;
- For TO-BE scenario 2, since the simulations involve the design of new equipment, the optimal size of each component assumed different values depending on the monthly demand. For this reason, the obtained results were combined and the highest size of each equipment was selected, obtaining a sub-optimal solution to the problem. Nevertheless, this result is considered to be very close to the optimal solution since the diesel generators operating costs are one order of magnitude higher than investment costs for new components.

The objective function can be expressed as the annualized cost related to the island energy production, given by the sum of operating cost for diesel generators and the investment costs for components (Equation (1)). Investment costs were annualized through the capital recovery factor (*CRF*) of the investment, whose formula is shown in Equation (2).

$$\min\left\{\begin{array}{l} C_{op,DG} \cdot \sum_{t=1}^{24} \sum_{j=1}^{8} \left[\frac{\boldsymbol{E_{DG,j}}(t)}{\eta_{DG,j}(t)}\right] + C_{PV} \cdot \boldsymbol{N_{PV}} \cdot CRF_{PV} + C_{STC} \cdot \boldsymbol{N_{STC}} \cdot CRF_{STC} + \\ +(C_{ESS} \cdot \boldsymbol{S_{ESS}} + C_{ESS,0} \cdot \boldsymbol{\delta_{ESS}}) \cdot CRF_{ESS} + C_{WSS} \cdot (\boldsymbol{S_{WSS}} - S_{WSS,0}) \cdot CRF_{WSS} \end{array}\right\} \quad (1)$$

$$CRF = \frac{i \cdot (1+i)^{UL}}{(1+i)^{UL} - 1}, \quad (2)$$

where $C_{op,DG}$ indicates operating diesel oil supply costs, $E_{DG,j}$ is the rated power of the *j-th* diesel generator, $\eta_{DG,j}$ is the efficiency of the *j-th* diesel generator, C_{PV}, C_{STC}, C_{ESS}, $C_{ESS,0}$, and C_{WSS} are the installation costs for PV, STC, ESS, and freshwater storage, respectively, $S_{WSS,0}$ is the initial water storage capacity, i is the interest rate, and UL is the useful life of each component.

Although these costs may be faced by different actors of the energy system (energy production company, DES owner, final customer), they were coupled in a unique objective function, since all the costs in the energy sector are always reflected in the final users bills.

The average electricity storage price was modeled as a linear function, with the constant term being multiplied by the synthesis variable in order to neglect this term when ESS is not selected in the optimization. Maintenance costs were neglected in this study, as were the financial subsidies to energy efficiency and renewable energies.

To describe the system, balance equations for each energy flow and each timestep have been considered as constraints. Energy balance equations were imposed as equality constraints, referring to the scheme reported in Figure 7, for electrical energy flows, DHW flows, electricity storage, DHW storage, and freshwater storage, where symbols are defined in the nomenclature:

$$\begin{array}{c} \boldsymbol{E_{DG}}(t) \cdot \eta_{TR} + \boldsymbol{E_{PV}}(t) - \boldsymbol{E_{sto,ch}}(t) + \boldsymbol{E_{sto,disch}}(t) - \boldsymbol{E_{sto,th}}(t) + \\ -\boldsymbol{\delta_{DES}}(t) \cdot E_{unit} = E_{req}(t) + H_{req}(t)/COP_{HP} + F_{req}(t)/EER_{HP} \end{array} \quad (3)$$

$$\boldsymbol{DHW_{STC}}(t) + \boldsymbol{DHW_{sto,disch}}(t) - \boldsymbol{DHW_{req,flex}}(t) = 0, \quad (4)$$

$$\boldsymbol{E_{sto}}(t+1) = \boldsymbol{E_{sto}}(t) + \eta_{ESS,ch} \cdot \boldsymbol{E_{sto,ch}}(t+1) - \boldsymbol{E_{sto,disch}}(t+1)/\eta_{ESS,disch}. \quad (5)$$

$$\begin{array}{c} \boldsymbol{DHW_{sto}}(t+1) = \boldsymbol{DHW_{sto}}(t) \cdot (1 - \eta_{HWSS,loss}) + \\ \eta_{HWSS,ch} \cdot \boldsymbol{E_{sto,th}}(t+1) - \frac{\boldsymbol{DHW_{sto,disch}}(t+1)}{\eta_{HWSS,disch}} \end{array} . \quad (6)$$

$$\boldsymbol{W_{sto}}(t+1) = \boldsymbol{W_{sto}}(t) + K_{DES} \cdot \boldsymbol{\delta_{DES}}(t+1) \cdot E_{unit} - \boldsymbol{W_{req,flex}}(t+1). \quad (7)$$

In detail, Equation (3) is the electricity flows balance, Equation (4) the DHW flows balance, Equation (5) the energy balance on the ESS, Equation (6) the energy balance on the HWSS, and Equation (7) the mass balance on the WSS. COP_{HP} and EER_{HP} are the conversion coefficients from electricity to heating and from electricity to cooling, commonly known as coefficient of performance (COP) and energy efficiency ratio (EER), respectively. These parameters are indicated only to show the approach to the study, since the local DSO provided the whole island electricity demand, including, also, consumptions related to air conditioning.

Further equality and inequality constraints, describing the behavior of each component, were imposed. Equations (8) and (9) limit the electricity production of PV and the DHW production of STC up to the energy provided by the solar radiation, reduced by their efficiencies. Equations (10) to (12) impose the repeatability of daily or yearly storage systems cycles. Equations (13) and (14) are the constraints describing the flexibility service for DHW storages and desalination unit, respectively, since they set the sum of these variables flows equal to the daily requirement. Equations (15) to (21) are further constraints for the ESS, avoiding that the component is charged and discharged at the same time, imposing that a minimum amount of energy, known as depth of discharge (*DoD*), is constantly stored in the system, to guarantee a longer useful life, and linking synthesis and design variables. Equation (22) limits the amount of freshwater in the WSS to be up to the storage capacity.

$$\boldsymbol{E_{PV}} \leq \eta_{PV} \cdot \boldsymbol{I_{sun}} \cdot \boldsymbol{N_{PV}} \cdot A_{PV}. \tag{8}$$

$$\boldsymbol{DHW_{STC}} \leq \eta_{STC} \cdot \boldsymbol{I_{sun}} \cdot \boldsymbol{N_{STC}} \cdot A_{STC}. \tag{9}$$

$$\boldsymbol{E_{sto}}(1) = \boldsymbol{E_{sto}}(end). \tag{10}$$

$$\boldsymbol{DHW_{sto}}(1) = \boldsymbol{DHW_{sto}}(end). \tag{11}$$

$$\boldsymbol{W_{sto}}(1) = \boldsymbol{W_{sto}}(end). \tag{12}$$

$$\sum_{t=1}^{24} \boldsymbol{DHW_{req,flex,j}}(t) = DHW_{req}. \tag{13}$$

$$\sum_{t=1}^{24} \boldsymbol{W_{req,flex,j}}(t) = W_{req}. \tag{14}$$

$$\boldsymbol{E_{sto,ch}}(t) \leq \boldsymbol{\delta_{ESS,ch}}(t) \cdot Q_{ESS}. \tag{15}$$

$$\boldsymbol{E_{sto,disch}}(t) \leq \boldsymbol{\delta_{ESS,disch}}(t) \cdot Q_{ESS}. \tag{16}$$

$$\boldsymbol{\delta_{ESS,ch}}(t) + \boldsymbol{\delta_{ESS,disch}}(t) \leq 1. \tag{17}$$

$$DoD \cdot \boldsymbol{S_{ESS}} \leq \boldsymbol{E_{sto}}(t) \leq \boldsymbol{S_{ESS}}. \tag{18}$$

$$\boldsymbol{E_{sto,ch}}(t) \leq \boldsymbol{S_{ESS}} \cdot (1 - DoD). \tag{19}$$

$$\boldsymbol{E_{sto,disch}}(t) \leq \boldsymbol{S_{ESS}} \cdot (1 - DoD). \tag{20}$$

$$\boldsymbol{S_{ESS}} \leq \boldsymbol{\delta_{ESS}} \cdot Q_{ESS}. \tag{21}$$

$$\boldsymbol{W_{sto}}(t) \leq \boldsymbol{S_{WSS}}. \tag{22}$$

The mathematical model depends on real and integer variables, where real variables mainly indicate energy flows and integer variables were employed for the electricity storage, for the DES units and for the solar technologies design variables. All the equations in the model, both objective function and constraints, are linear functions. For this reason, a MILP algorithm was adopted for the solution of the optimization problem.

The linear formulation was preferred to a non-linear model since it always allows for the identification of an absolute optimum solution, if it exists, although it requires the neglection of some aspects of the system's behavior. It is worth to mention that, in this study, the costs optimization is also oriented to the reduction of greenhouse gas emissions during the running phase of the system, since every action aims at reducing the diesel gas consumption. Indeed, the flexibility of DES and DHW storages, as well as the installation of an ESS, fill the valleys in the load diagram ensuring a smoother and more efficient operation of generators, while the introduction of renewable systems reduces the energy demand that the diesel generators have to fulfill.

The parameters employed for this study are technical parameters (demands, efficiencies, capacity of existing equipment, average surface occupied by the PV and STC units), economic parameters (installation or operating costs), and environmental parameters (solar radiation and greenhouse gas emissions). Demands, available surface for RESs, and environmental parameters were derived from available literature or data provided by local companies, while economic parameters were obtained through linear regression on market reports.

These parameters are reported in Appendix A, Tables A2–A5. The rated power of the diesel generators are reported in Table 1.

5. Optimization Results

5.1. Case Study 1: TO-BE Scenario 1—Desalination Unit Flexibility

In this section, only the improvements deriving from the flexibility provided by the DES was assessed. Thus, it is assumed that the DES produces the same amount of freshwater that it would have produced, but the hourly operation schedule is changed, according to the MILP algorithm results. More specifically, since the eight diesel generators have higher efficiencies when the power output is between 60% and 80% of their rated powers, the optimization identifies, hour-by-hour, the optimal number of desalination units whose load, added to the non-flexible load of the island, allows the maximum possible generator efficiency. This is the most interesting case for the existing situation, since it does not involve the installation of new components. In order to evaluate this case, the variables related to PV, STCs, ESSs, and HWSSs were set equal to zero in the model. The standard day trends of electricity consumption in May (minimum load), January (average load), and August (maximum load) are provided in Figures 9–11, where only the optimization variables are reported, neglecting the fixed electrical load. From the graphs it is possible to see that the optimization identifies, as optimal solution, a variable production rather than a smooth operation for the generators, since in this way the generators operate with the maximum efficiency. The desalination units' operation is quite smooth, although in some hours of the day the plant has to be turned off.

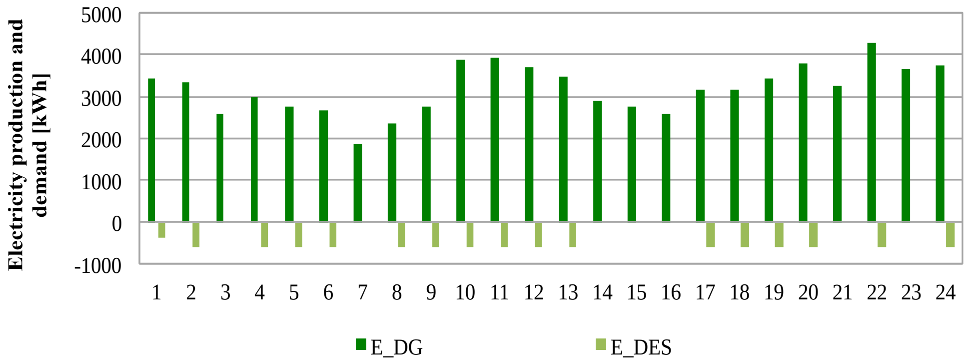

Figure 9. Optimal daily schedule of diesel generators and desalination units in May (minimum load month) in the TO-BE scenario 1. In this figure E_DG is the variable E_{DG} and E_DES is the variable E_{DES}.

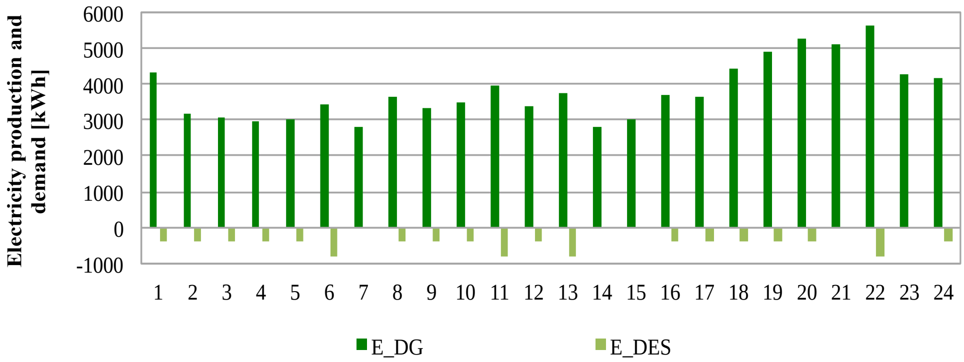

Figure 10. Optimal daily schedule of diesel generators and desalination units in January (average load month) in the TO-BE scenario 1. In this figure E_DG is the variable E_{DG} and E_DES is the variable E_{DES}.

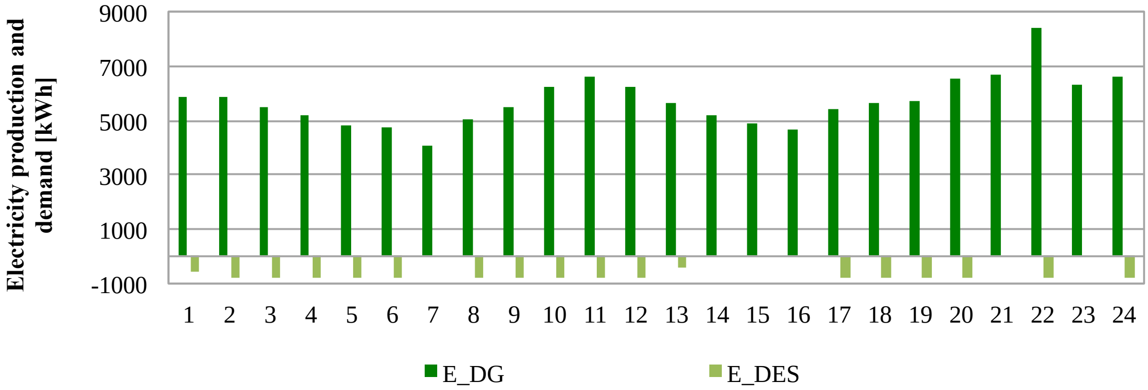

Figure 11. Optimal daily schedule of diesel generators and desalination units in August (maximum load month) in the TO-BE scenario 1. In this figure E_DG is the variable E_{DG} and E_DES is the variable E_{DES}.

The optimization allowed for the identification of a highly efficient schedule, with 97% of annual operating hours working with maximum efficiency, see Figure 12.

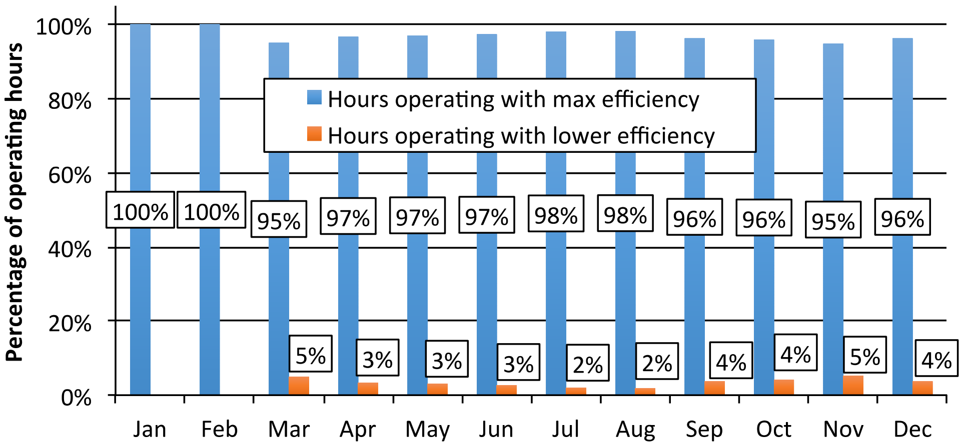

Figure 12. Percentage of diesel generators operating hours inside and outside maximum efficiency region, in the TO-BE scenario 1.

Since there are many possible generators combinations, a post-processing phase was performed, aimed at refining the operating times of the generators, since this is one of the operating criteria adopted by the company, preferring the use of the newer ones. The number of operating hours per diesel generator, DG, after the optimization in the TO-BE scenario 1 is reported in Table 2.

Table 2. Operating hours of diesel generators in the TO-BE scenario 1.

Parameters and Optimized Number of Operating Hours of DGs	DG_1	DG_2	DG_3	DG_4	DG_5	DG_6	DG_7	DG_8
Rated power [kW]	1250	5040	3070	2920	3089	2648	1760	5220
Installation year	1976	2002	1990	1998	1981	1985	2009	2007
Operating hours [#]	1324	1832	1565	1825	1643	1758	2716	2974

In Table 2, DGi is the i-th diesel generator. Regarding the desalination units flexibility, the most important parameter to show is the amount of electricity that was deferred through the exploitation of the freshwater storage, that is reported in Figure 13. This is the amount of electricity consumption related to the desalination of the water that was stored instead of being sent to the local distribution network. At annual level, about 274 MWh of electricity consumption was deferred, corresponding to 68,500 m^3 of freshwater stored.

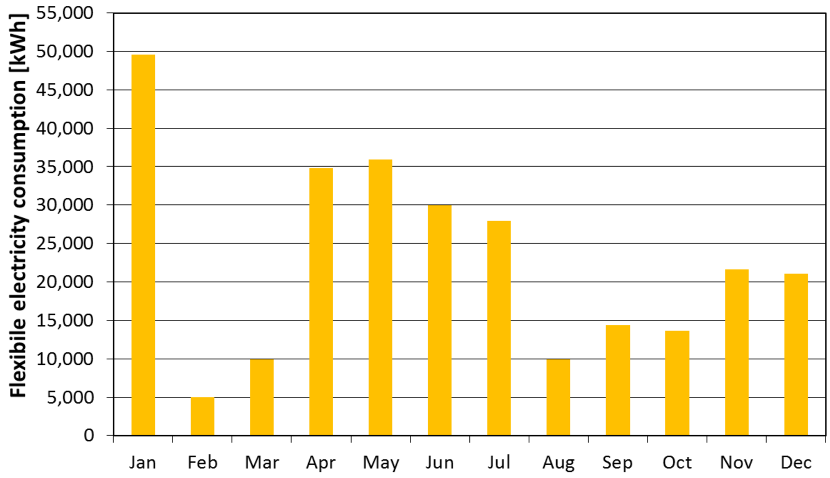

Figure 13. Monthly DES flexible consumption in the TO-BE scenario 1.

In this first case study, the cooperated scheduling of electricity generators and desalination units allowed to reach an annual economic saving equal to 1360 k€ related to the diesel oil supply reduction, deriving from a very efficient operation of the generators. This value corresponds to more than the 20% of the yearly operating costs of the electrical plant related to the fuel supply. Although part of this saving would be given to the owner of the DES as a reward for the flexibility service, this value represents a promising result. In this way, the diesel oil consumption can be reduced from about 8100 to about 6300 tons/year. Considering an average emission of 0.267 CO_2 tons/MWh [87], the consequent avoided emissions is equal to 5385 ktons. Monthly economic and emissions reductions are provided in Figure 14.

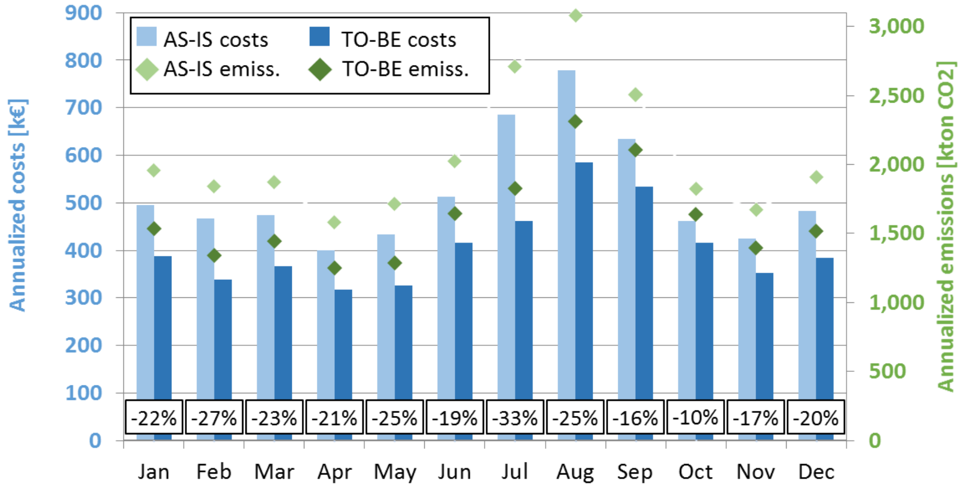

Figure 14. Monthly economic and emission saving in the TO-BE scenario 1 compared to the AS-IS scenario.

5.2. Case Study 2: TO-BE Scenario 2—Desalination Unit and DHW Storages Flexibility + Equipment Installation

In this section, the economic feasibility of the DES flexibility was assessed in a scenario where also renewable solar technologies and ESSs were installed, pushed by the Ministry Decree 14 February 2017 [53]. Furthermore, since the existing literature showed that the GIWH technology can provide very profitable results with a limited investment, the flexibility of water heaters was also evaluated in this case study. The optimization results showed that the PV plant is almost always profitable, since its size corresponds to the upper limit (16,000 m^2, corresponding to 9775 kW) in every monthly optimization except for January, when no PV plant is considered in the optimum, due to the combination of low solar radiation and medium electricity load. On the opposite, Solar Thermal Collector, STC, installation is optimal in every month and considered more convenient than GIWHs, that are rarely employed and only in November, December, and January (92 h during the year with a total energy produced of about 4000 kWh). It is important to remark that GIWH intervention is required in these months only because the STC size has reached its upper limit. The optimal number of STCs (N_{STC}) to install is highly influenced by two factors: the average monthly solar radiation I_{sun} and the DHW requirement (DHW_{req}), as qualitatively shown in Figure 15.

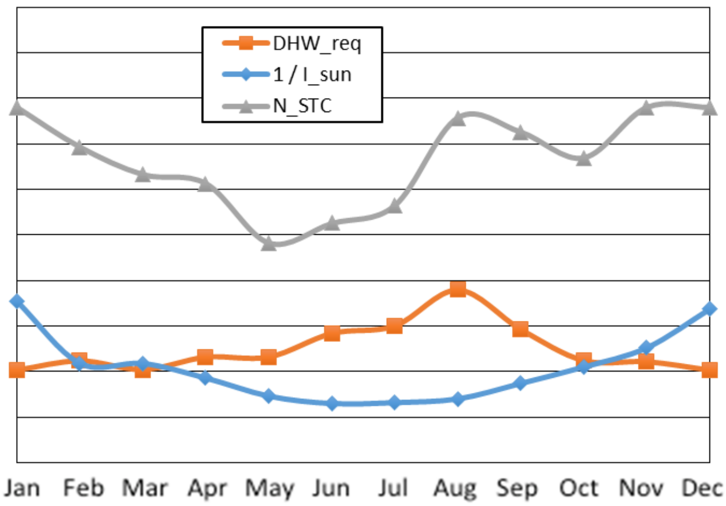

Figure 15. Solar thermal collectors STC size influence in monthly optimizations in the TO-BE scenario 2. In this figure DHW_req is the variable DHW_{req},, I_sun is the solar radiation and N_STC is the variable N_{STC}.

Indeed, the surface needed to produce a unit amount of energy (proportional to the inverse of the solar radiation, blue trend), is lower in summer and higher in winter, while the DHW demand follows the touristic trend, with higher values in summer (orange trend). The combination of these two factors determines a variation in the optimal STC size, with the minimum value occurring in May (2170 m^2) and the maximum in November, December, and January (3500 m^2, equal to the upper bound), while in August the optimal size is 3400 m^2 due to the high DHW demand. These results corroborate the economic convenience of the installation of RESs in small islands, since they help to reduce the price of energy bills as well as "greening" the power system. The results also suggest that higher sizes would be profitable, but the landscape constraints in the island may conflict with this aspect. Given that the energy production of the PV system is low, if compared with the diesel generators contribution, the ESS is never selected by the optimizer, also because of the high installation cost.

The standard day trends of electricity consumption in May (minimum load), January (average load), and August (maximum load) are provided in Figures 16–18. Comparing these trends with those related to the TO-BE scenario 1, it is possible to see that, in general terms, the electricity load is slightly lower, thanks to the DHW that is almost totally supplied by the STC and the PV plant that contribute, when available, to the reduction of the load covered by diesel generators. Furthermore, the DES operation is more discontinuous but with a higher number of units turned on at the same time. Furthermore, comparing the same day between TO-BE scenarios 1 and 2:

- In May, a high fraction of the low energy demand is covered by the PV during the central hours of the day, while the two trends are similar in the rest of the day;
- In January, the electricity production from diesel generators is very similar, since it is the unique month when the optimization does not select the PV installation;
- The yearly peak, occurring at 20:00 in August, that is also the true yearly peak, as shown in Figure A4, was reduced from 8398 to 7732 kW, also allowing minor power flow on the power grid, although this was not the aim of the optimization.

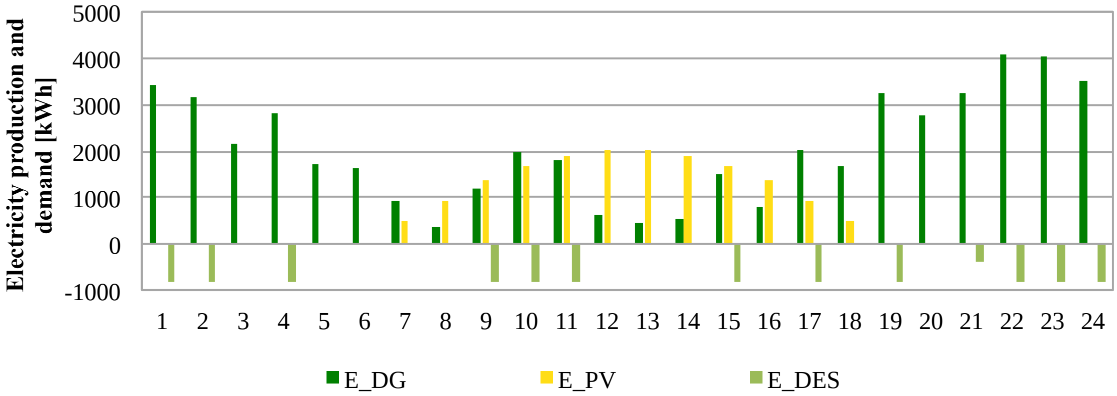

Figure 16. Optimal daily schedule of diesel generators and desalination units in May (minimum load month) in the TO-BE scenario 2. In this figure E_DG is the variable E_{DG}, E_PV is the variable E_{PV} and E_DES is the variable $E_{DES.}$

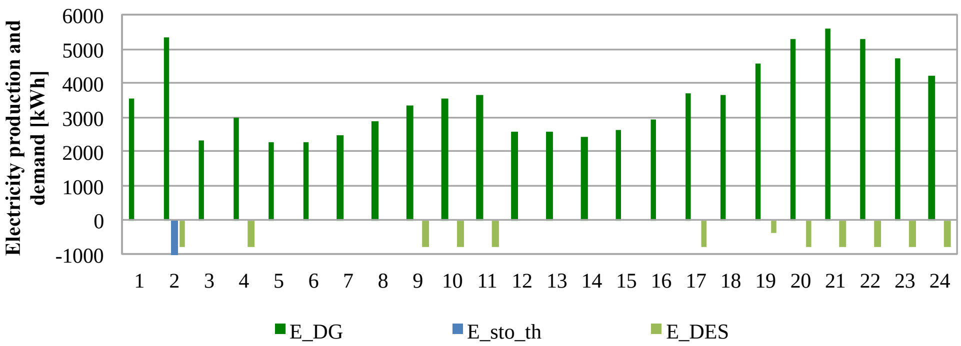

Figure 17. Optimal daily schedule of diesel generators and desalination units in January (average load month) in the TO-BE scenario 2. In this figure E_DG is the variable E_{DG}, E_sto_th is the variable $E_{sto,th}$ and E_DES is the variable $E_{DES.}$

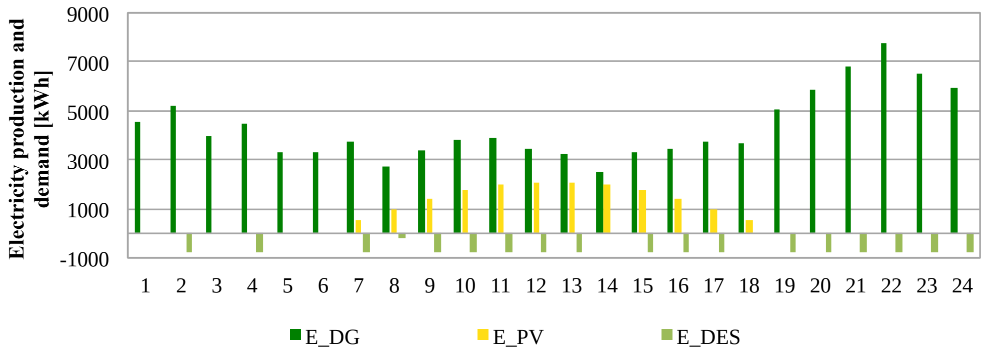

Figure 18. Optimal daily schedule of diesel generators and desalination units in August (maximum load month) in the TO-BE scenario 2. In this figure E_DG is the variable E_{DG}, E_PV is the variable E_{PV} and E_DES is the variable $E_{DES.}$

The generators daily schedule results are also very efficient, although less than in the previous scenario, with 95.8% of annual operating hours working with maximum efficiency. The monthly detail is reported in Figure 19, while Table 3 shows the operation hours of the diesel generators during the year.

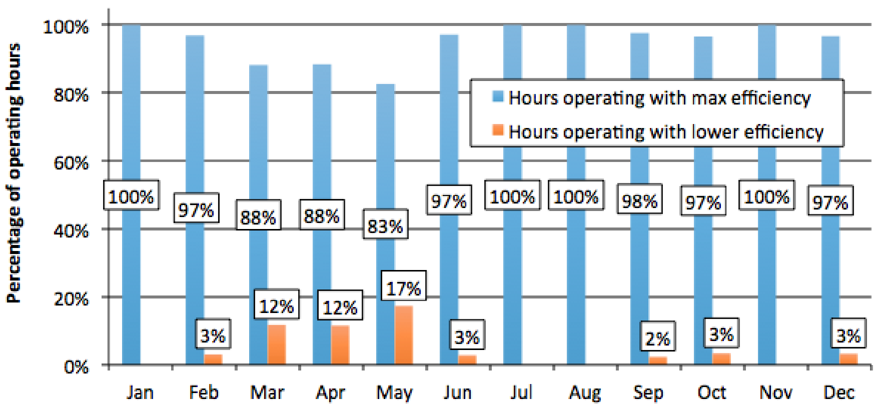

Figure 19. Percentage of diesel generators' operating hours inside and outside the maximum efficiency region in the TO-BE scenario 2.

Table 3. Operating hours of diesel generators in the TO-BE scenario 2.

Parameters and Optimized Number of Operating Hours of DGs	DG1	DG2	DG3	DG4	DG5	DG6	DG7	DG8
Rated power [kW]	1250	5040	3070	2920	3089	2648	1760	5220
Installation year	1976	2002	1990	1998	1981	1985	2009	2007
Operating hours [#]	1645	1497	1004	1075	1020	1393	2160	2618

Regarding the RESs plants, since twelve monthly optimizations were performed, sizes change every month, as reported in Table 4.

Table 4. PV and STC in twelve monthly optimizations.

Month	A_{PV} [m^2]	A_{STC} [m^2]
Jan	0	3500
Feb	16,000	3111
Mar	16,000	2841
Apr	16,000	2753
May	16,000	2170
Jun	16,000	2362
Jul	16,000	2539
Aug	16,000	3399
Sep	16,000	3258
Oct	16,000	3005
Nov	16,000	3500
Dec	16,000	3500

Referring to the twelve monthly optimizations, the combined effect of the installation of RESs plants and DES flexibility allows for the reduction of about 25% of the annual electricity load covered by the diesel generators and of about 40% of the annual diesel oil consumption. Since these values are related to the optimization results, where different RESs sizes were selected in every month, the energy and environmental saving would be higher by installing the maximum possible size of PV and STC.

Monthly detail of costs and environmental savings is provided in Figure 20.

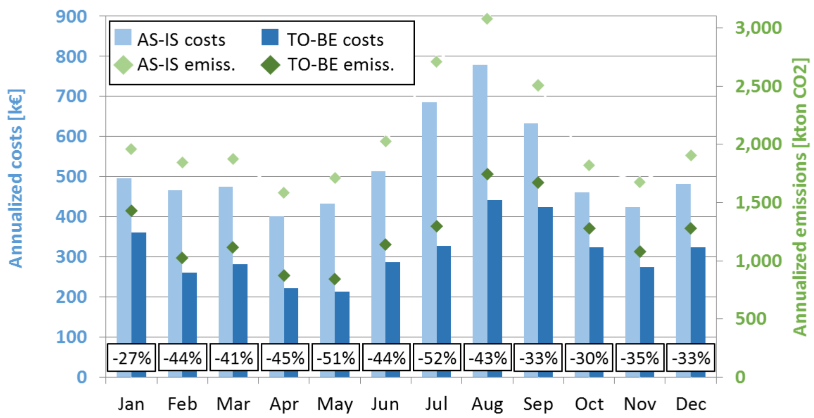

Figure 20. Monthly economic and emission saving in the TO-BE scenario 2 compared to the AS-IS scenario.

In order to identify the most convenient size of PV and STC from an economical point of view, a comparison between cost terms was performed. In detail, considering the results of the twelve optimizations, the operating saving due to the diesel oil supply reduction obtained with variable components sizes is equal to 2506 k€/year. On the other hand, assuming the installation of the maximum sizes obtained by the monthly optimizations (16,000 m^2 of PV and 3500 m^2 of STC), the annualized installation cost would be equal to 453 k€/year (366 k€/year for PV and 87 k€/year for STC, respectively). Thus, assuming the installation of the maximum size of PV and STC, obtained by the twelve simulations equal to the upper bounds of the variables, would cause an investment cost that is about 5.5 times lower than the operating cost saving, providing a very profitable investment. Moreover, since PV would produce electricity also in January, this energy would cause an additional operating reduction in terms of diesel oil saving, while the higher STC surface would not cause additional savings, since in the months between February and October it is already able to cover the whole monthly demand.

6. Discussion and Conclusions

In this study, the optimal combination of components (synthesis stage), their optimal sizes (design stage), and their optimal operating schedule (operation stage) has been identified, for the energy demand fulfillment and optimization in the island of Pantelleria (Mediterranean sea).

Starting from the existing energy system (AS-IS scenario), composed by diesel generators, a DES, a freshwater storage, HPs, and DHW storages, distributed over the island, different strategies were considered to reduce costs and emissions.

An energy hub optimization model was developed and implemented using the MATLAB simulation tool. All the equations implemented in the model are linear functions, and selected variables are real or integer. For this reason, a MILP algorithm was adopted for the solution of the optimization problem minimizing the annualized installation and operating costs. With reference to the efficiency variation of diesel generators at partial load, an efficient strategy for linearizing the problem was considered: Four different average values were considered in the different operating ranges, in order to be able to operate diesel generators at their maximum efficiencies.

In view of limiting the investment to reduce the primary energy demand, an important solution was the modulation of not privileged loads, temporarily shifting the energy demand in order to maximize the energy efficiency of the local power plant. In detail, considering the features of small islands, two solutions were considered: Modulation of freshwater production by local DESs (adding a freshwater reserve) or improvement of the energy efficiency for the DHW production in domestic uses. Both approaches were investigated in the paper.

The study was divided in two main groups of simulations:

- The first group considers only the desalination unit flexibility service to be integrated with the local diesel generator units;
- The second group accounts also for the installation of new equipment and the flexibility of DHW storages.

The RES minimum installation limits imposed by Ministry Decree 14 February 2017 for Pantelleria, adopted as upper bounds in this study, were proved to be cost-optimal, since almost each optimization selected the maximum PV size, while the STC size proved to be almost sufficient to fulfill the island DHW requirement, although this technology can be used also for low temperature space heating and also for space cooling, if combined with an absorption chiller. Furthermore, the cost-optimality was achieved by adopting cost values related to domestic plant sizes and neglecting subsidies to renewable energies, confirming the validity of the result, since the economic feasibility of RESs without subsidies is usually hard to achieve.

According to the simulations, the optimized load profile for desalination can produce an annual economic saving equal to 1360 k€, due to the avoided diesel combustion (about 8100 tons/year) related to the improving of the energy efficiency of the local power plant. Furthermore, in terms of environmental benefit, this approach can avoid the emission of 6300 tons of CO_2 per year. Another interesting result concerns the non-utilization of ESSs, which appears too costly as compared to other "non-strictly electrical" storage technologies.

Additional benefits may be achieved if the DHW production is also optimized. As the greatest part of small islands in the Mediterranean Sea are equipped with electrical heaters, the paper investigated the potential benefits deriving from a flexible DHW production, even though in this case study the DHW solar production resulted to be more economically profitable, as well as environmentally preferable. It is worth to underline that the thermal storage, a necessary component for the STC systems, is assumed to be already available exploiting the existing electrical boilers.

A further improvement was proposed considering the installation of solar technologies for electricity and DHW production and an electrical storage. The simulations suggest that the installation of RESs by the final users is to be preferred as much as possible, since in most of the cases the optimization selected a PV plant with upper bound size and STC plant able to cover the whole DHW demand. This result suggests that the constraint of the maximum installable size is a more limiting criterion than the economic feasibility. Considering the installation of 16,000 m^2 of PV and 3500 m^2 of STC, the authors estimated an annual economic saving equal to 2506 k€/year, due to the avoided fuel consumption, that is about 5.5 times greater than the annualized installation cost for the equipment (453 k€/y).

The method and the model employed for this study can be applied to almost each small island in the Mediterranean Sea, but also to every island not linked to the main power grid, since the production of electricity and freshwater is usually local. A few exceptions may be related to tropical islands, where the abundant rains may render unnecessary the employment of desalination plants. Since some small islands employ sustainable electrical mobility, the flexibility from the vehicles charging may be also taken into account.

In the light of the above results, in future works the optimization study will be repeated using more reliable and accurate data provided by both companies, and the plants sizes and schedules obtained from the optimization will be exploited to develop a detailed annual simulation model of the Pantelleria's energy system, in order to accurately evaluate the potential benefit deriving from the installation of RESs and from the flexibility provided by the DES.

Author Contributions: Conceptualization, methodology, software: M.C., D.C., V.F, S.L., F.M., R.M., E.R.S. and E.T.; validation, formal analysis: M.C., F.M. and E.T.; investigation: M.C., D.C., V.F., S.L., F.M., R.M., E.R.S. and E.T.; resources, data curation: D.C., F.M. and E.R.S.; writing—original draft preparation, writing—review and editing, visualization: M.C., D.C., F.M. and E.T. supervision project administration, funding acquisition: V.F., S.L., E.R.S. and E.T.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

AIMS	Africa, Indian Ocean, Mediterranean, and South China Sea
CHP	Combined Heat and Power
CoM	Covenant of Mayors
COP	Coefficient of Performance
CRF	Capital Recovery Factor
DES	Desalination Plant
DHW	Domestic Hot Water
DR	Demand Response
DSO	Distribution System Operator
EER	Energy Efficiency Ratio
ERWH	Electric Resistance Water Heater
ESS	Electricity Storage System
GIWH	Grid Interactive Water Heater
HP	Heat Pump
HPWH	Heat Pump Water Heater
HWSS	Hot Water Storage System
ICG	Internal Combustion Generator
LPG	Liquefied Petroleum Gas
MES	Multi-Carrier Energy System
MILP	Mixed Integer Linear Programming
OTEC	Ocean Thermal Energy Conversion
PV	Photovoltaic
RES	Renewable Energy Source
RO	Reverse Osmosis

RSE	Ricerca sul Sistema Energetico
SEAP	Sustainable Energy Action Plan
SIDSs	Small Islands Developing States
STC	Solar Thermal Collector
WSS	Water Storage System

Symbols and Abbreviations

A_{PV}	Surface occupied by a PV unit
A_{STC}	Surface occupied by a STC unit
C_{ESS}	ESS first order investment cost
$C_{ESS,0}$	ESS zero-th order investment cost
$C_{op,DG}$	DG operating cost (diesel oil supply cost)
C_{PV}	PV system investment cost
C_{STC}	STC investment cost
C_{WSS}	WSS investment cost
COP	Coefficient of performance
CRF_{ESS}	ESS capital recovery factor
CRF_{PV}	PV system capital recovery factor
CRF_{STC}	STC capital recovery factor
CRF_{WSS}	WSS capital recovery factor
DHW_{req}	DHW daily requirement
$DHW_{req,flex}\ (t)$	Flexible DHW flow
$DHW_{STC}\ (t)$	DHW produced by STC
$DHW_{sto}\ (t)$	DHW amount in the DHW storage
$DHW_{sto,disch}\ (t)$	DHW flowing out from the DHW storage
DoD	Electricity storage depth of discharge
$E_{DES}\ (t)$	Electricity consumed by desalination units
$E_{DG}\ (t)$	Cumulated electricity produced by diesel generators
$E_{PV}\ (t)$	Electricity produced by PV
$E_{req}\ (t)$	Electricity requirement
$E_{sto}\ (t)$	Electricity amount in the electricity storage
$E_{sto,ch}\ (t)$	Electricity flowing into the electricity storage
$E_{sto,disch}\ (t)$	Electricity flowing out from the electricity storage
$E_{sto,th}\ (t)$	Electricity flowing into the DHW storage
E_{unit}	Electricity consumption per each desalination unit
EER	Energy efficiency ratio
$F_{req}\ (t)$	Space cooling requirement
$G_{DG}\ (t)$	Diesel oil consumed by diesel generators
$H_{req}\ (t)$	Space heating requirement
HP	Heat pump
I_{sun}	Average solar radiation
i	Interest rate in energy sector
K_{DES}	Electricity consumption per the production of each cube meter of freshwater
N_{PV}	PV design variable
N_{STC}	STC design variable
Q_{ESS}	Electricity storage upper bound size
S_{ESS}	Electricity storage capacity
S_{WSS}	Freshwater storage capacity
$S_{WSS,0}$	Freshwater storage available capacity
UL	Useful life of components
W_{req}	Freshwater daily requirement
$W_{req,flex}\ (t)$	Flexible freshwater flow
$W_{sto}\ (t)$	Freshwater amount in the freshwater storage
$\delta_{DES}\ (t)$	Number of active desalination units
δ_{ESS}	ESS synthesis variable

$\delta_{ESS,ch}\ (t)$	Boolean variable indicating when electricity storage is charging
$\delta_{ESS,disch}\ (t)$	Boolean variable indicating when electricity storage is discharging
η_{DG}	Diesel generators efficiency
$\eta_{ESS,ch}$	Electricity storage charging efficiency
$\eta_{ESS,disch}$	Electricity storage discharging efficiency
$\eta_{HWSS,ch}$	DHW storage charging efficiency
$\eta_{HWSS,disch}$	DHW storage discharging efficiency
$\eta_{HWSS,loss}$	DHW storage self-discharge rate (thermal losses)
η_{PV}	PV system efficiency
η_{STC}	Solar collector average efficiency
η_{TR}	Transformer efficiency

Appendix A

Considering the equivalent primary energy demand, the trend of the share of the energy carriers in the island of Pantelleria is reported in Figure A1. All figures A1 to A5 have been created by the authors based on data provided by SMEDE.

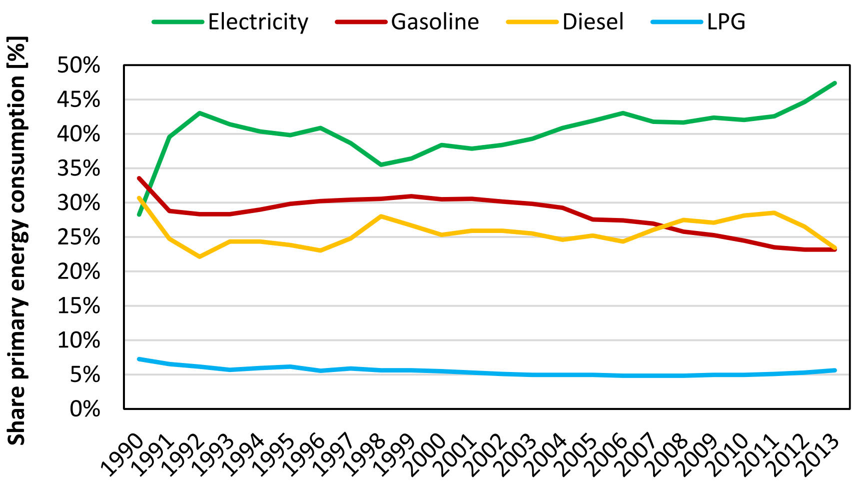


Figure A1. Share of energy carriers in primary energy consumption [87].

The transport sector is responsible for the gasoline and diesel consumption shown in the previous Figure A1. The LPG is related essentially to the residential sector, while electricity is consumed by residential, services, and industrial sectors, see Figure A2.

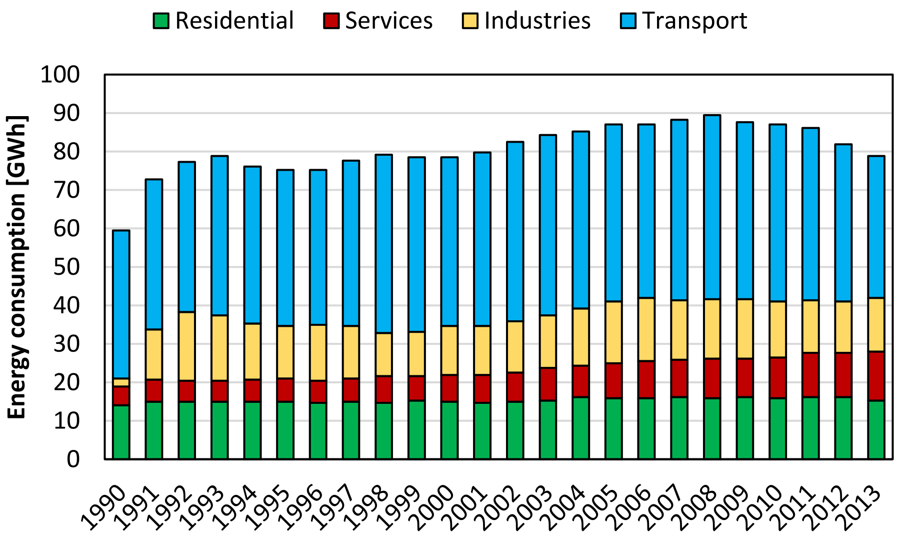


Figure A2. Primary energy consumption by sector in Pantelleria [87].

Figure A3 shows monthly production of diesel generators in 2014, 2016, and 2018. The comparison reveals a significant reduction of the local energy production in the last years. This aspect is essentially related to the recent revamping of the DES, thanks to the installation of new units at the end of 2014.

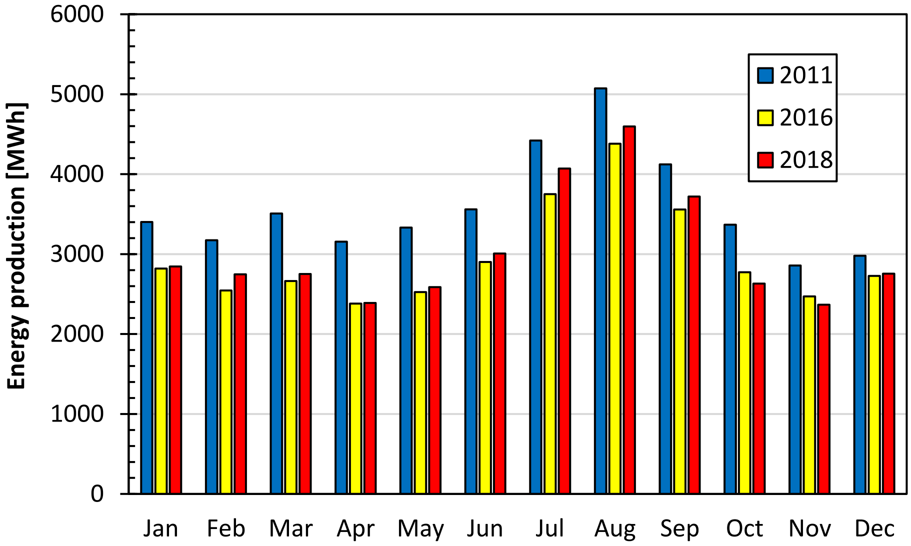


Figure A3. Comparison of monthly electricity production in 2011, 2016, and 2018 [80,87].

Further detail is provided in Figure A4, where the hourly trend of electricity demand is reported for each monthly typical day. As stated in the paper, the maximum power demand is in August, because of the massive presence of tourists, while the month with minimum demand is May, as tourists' presence is not relevant and there is no need of air conditioning.

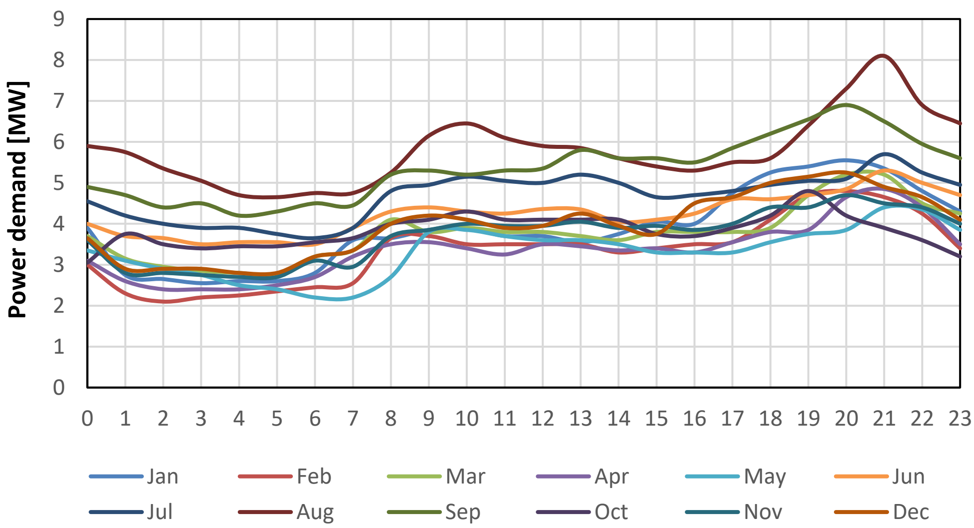
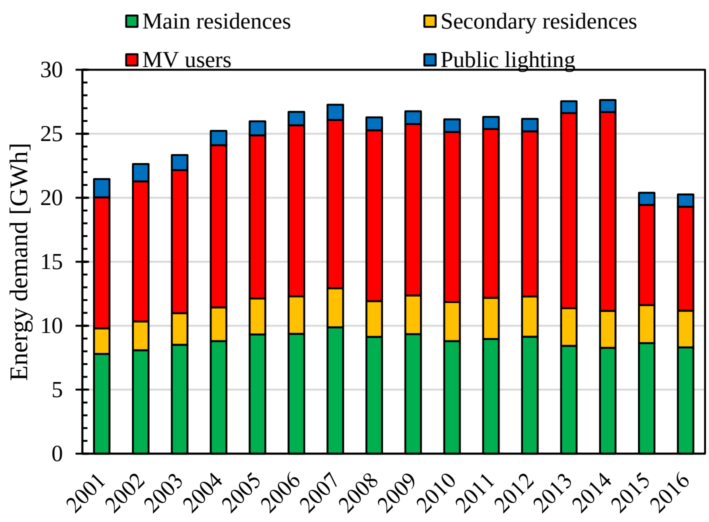
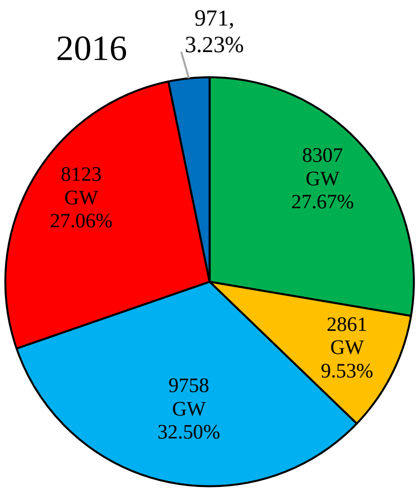


Figure A4. Hourly electricity demand in monthly typical days in 2016 [80].

The yearly trend of the electricity demand by users is reported in Figure A5a, while the 2016 share is reported in Figure A5b. As shown in the graph, a significant share is related to the residential sector. Indeed, the sum of main and secondary residences represents 37.20% of the local electricity demand in 2016. The item "Other Low Voltage users" is related to services, offices, hotels, and non-residential buildings. This term represents 32.5% of the energy demand. As regards to the "Medium Voltages users", this term (27.06%) is essentially related to the local DES and to the airport. Finally, the public lighting has a marginal role, representing only 3.23% of the electricity demand in 2016. As anticipated previously, the graph emphasizes the significant reduction of the energy consumption for desalination, after the revamping at the end of 2014.



(**a**)



(**b**)

Figure A5. Electricity consumptions by users: (**a**) Yearly trend; (**b**) 2016 share [80].

Below, in Table A1, the reservoirs serving the desalination plants are detailed.

Table A1. Characteristic of water reserves in Pantelleria network [90].

Locality	Altitude [m a.s.l.]	Capacity [m^3]
Kaffefi	262.0	7000
Gelfiser	371.5	7000
Zinedi	230.1	300
Sant'Elmo	117.8	850
Kuddia Bruciata	109.3	300
Lago	249.2	300
Russo	294.6	850
Runcuni di Pigna	267.2	300
Ex Vedetta	290.7	850
Arenella Vecchio	20.0	200
Arenella Nuovo	10.0	3500
Scauri	20.0	3500

Table A2. Electricity demand in monthly standard days in Pantelleria [80].

	Electricity Demand [kWh]											
Hour	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
00:00	3532	2598	2783	2094	2573	2954	3274	4509	4038	2647	2853	2710
01:00	2382	1895	2213	1597	2321	2641	2961	4344	3834	3347	2069	1960
02:00	2281	1696	2014	1299	2131	2601	2879	3944	3533	3098	2055	1952
03:00	2182	1796	1920	1264	1972	2449	2784	3662	3640	2997	2001	1970
04:00	2232	1846	1871	1279	1722	2499	2716	3293	3328	3047	1965	1854
05:00	2231	1946	1819	1352	1631	2489	2476	3248	3433	3047	1973	1862
06:00	2432	2046	2264	1561	1418	2453	2375	3399	3632	3147	2349	2264
07:00	2840	2146	2426	2150	1322	2854	2625	3502	3470	2953	2196	2406
08:00	2532	3248	3175	2496	1746	3255	3536	3969	4023	3218	2795	3015
09:00	2718	3296	2861	2545	2819	3386	3690	4751	4185	3495	2896	3256
10:00	2790	2986	2963	2966	2864	3269	3901	5064	4010	3697	2951	3150
11:00	2575	3038	2871	2604	2653	3176	3910	4693	4234	3498	2854	2935
12:00	2561	3098	2870	2555	2438	3314	3819	4496	4285	3496	2854	2999
13:00	2415	3096	2784	2519	2439	3285	3926	4462	4735	3593	2951	3305
14:00	2615	2791	2658	2394	2338	2986	3740	4207	4685	3693	2801	3009
15:00	2925	2769	2605	2416	2153	3050	3390	3993	4733	3343	2849	2804
16:00	2865	2920	2639	2292	2141	3191	3451	3894	4634	3292	2776	3552
17:00	3635	3096	2681	2545	2147	3543	3546	4111	4974	3493	3158	3709
18:00	4120	3696	2783	2651	2414	3558	3673	4193	5337	3793	3813	4059
19:00	4438	4298	3639	2696	2742	3716	3775	4997	5533	4393	3835	4239
20:00	4723	4398	4440	3517	2838	3988	3828	5927	5837	3793	4135	4511
21:00	4421	4248	4469	3696	3249	4441	4428	6854	5438	3493	3928	4145
22:00	3871	3846	3769	3254	3204	4141	3981	5622	4888	3193	3834	3906
23:00	3375	2998	3529	2480	2689	3841	3696	5051	4533	2793	3431	3349

Table A3. Domestic hot water DHW and freshwater demands in monthly standard days in Pantelleria.

Month	DHW Demand [kWh] (Authors Elaborations on [87])	Freshwater Demand [m^3] [89]
January	8470	2300
February	9325	2100
March	8515	2100
April	9661	2500
May	9677	2500
June	11,849	2700
July	12,537	3100
August	15,827	3450
September	12,203	2650
October	9342	1600
November	9239	1500
December	8463	1950

Table A4. Economic parameters.

Parameter	Value
Operating cost of diesel generators (diesel oil supply cost)	650 €/m^3 [80]
Investment cost of PV system	527 €/unit [94]
Investment cost of STC	650 €/unit [95]
First order investment cost of electrical storage	165 €/kWh [94,95]
Zero-th order investment cost of electrical storage	2974 € [94,95]
Investment cost of water storage	450 €/m^3 [96]
Interest rate in energy sector	5% [97]

Table A4. *Cont.*

Parameter	Value
Useful life of PV system	25 years [94]
Useful life of STC	15 years [98]
Useful life of electrical storage	7 years [99]
Useful life of water storage	25 years
Capital recovery factor of PV system	0.071
Capital recovery factor of STC	0.096
Capital recovery factor of electrical storage	0.173
Capital recovery factor of water storage	0.071

Table A5. Technical and environmental parameters.

Parameter	Value
Diesel generators efficiency at part load between 0% and 30%	20.0% [80]
Diesel generators efficiency at part load between 30% and 60%	44.3% [80]
Diesel generators efficiency at part load between 60% and 80%	49.2% [80]
Diesel generators efficiency at part load between 80% and 100%	47.0% [80]
Freshwater storage initial available capacity	5000 m^3 [89]
Lower heating value of diesel oil	41.025 MJ/kg
Transformer efficiency	99%
Electricity consumption for the production of each cube meter of freshwater	4 kWh/m^3 [89]
PV system efficiency	16.25% [94]
PV occupied area per unit	1.6368 m^2 [94]
PV maximum available area	16,000 m^2 [56]
Solar collector zero-loss efficiency	79.7% [94]
Solar collector first order heat loss coefficient	3.18 W/(m^2 K) [94]
Solar collector second order heat loss coefficient	0.008 W/(m^2 K^2) [94]
Solar collector average efficiency	69.4% (with 30 °C temperature difference)
Solar collector occupied area per unit	2.5235 m^2 [94]
Solar collector maximum available area	3500 m^2 [56]
Electricity storage charging efficiency	97%
Electricity storage discharging efficiency	97%
Electricity storage depth of discharge	20%
Electricity storage upper bound size	100,000 kWh
DHW storage charging efficiency	95%
DHW storage discharging efficiency	100%
DHW storage self-discharge rate (thermal losses)	1%/h
Annual average solar radiation	5.02 kWh/m^2 [59]
Average CO_2 emission for electricity production	0.267 tons/MWh [87]

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