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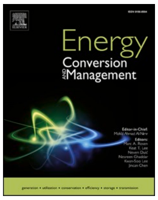

# Optimal planning of energy and water systems of a small island with a hourly OSeMOSYS model

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ABSTRACT

Islands all over the world face common challenges connected to energy costs and greenhouse gas emissions. Thus, islands have been identified as perfect sites for implementing and testing innovative solutions to boost the green energy transition towards a sustainable and clean energy system. The supply of clean water is a major issue that affects small islands, and desalination, particularly Reverse Osmosis, represents a valid solution to this challenge. In this research, an energy system model is used to analyse long-term water and energy supply strategies of the tourist island of Favignana, Italy. The model is built with the Open Source long-term energy modelling tool OSeMOSYS at an hourly resolution. It considers both the potential synergies offered by Reverse Osmosis Desalination and the use of water storage to store the excess electricity when needed. The indirect emissions for the maritime transportation of goods and fuels (i.e., water and diesel) to the island are also accounted for. Different energy policies are compared to understand how a carbon tax, a limit on emissions and no policy would impact the long-term energy strategy of the island. The results show that a carbon tax that covers also the maritime transportation sector would lead to the lowest overall cumulative emissions. They additionally reveal that the contribution of emissions for maritime transportation of goods and fuels is relevant and cannot be neglected if a full decarbonisation has to be achieved. On the technological side, investment in a desalination plant is the most viable option in all cases. Finally, for the first time, OSeMOSYS is applied with hourly resolution and the results are compared with those obtained with lower time resolution showing that inaccuracies are found both for overall values and for the dispatching strategies.

## 1. Introduction

Islands represent territories and ecosystems that are particularly vulnerable to climate change [1]. Despite that, most islands rely heavily on fossil fuels for purposes such as energy supply [2] and the different uses in the maritime transport such as fishing, passenger transportation, and delivery of goods and services, [3] thus leading to high greenhouse gas (GHG) emissions. Moreover, there are several technical requirements such as the high seasonal variations, the low system inertia, and the increased cost of fuels and materials for their delivery to the island from the mainland that make the insular, off-grid, energy systems much more expensive than the one on the mainland [4]. Therefore, despite the high motivation for islands to undertake a transition towards cleaner energy systems, their technical cases are particularly challenging. This is why islands have been identified as frontrunners for the energy transition within the Clean Energy for EU Islands Initiative [5]. Thus, it is very relevant from a scientific and technical point of view to analyse island energy systems while also offering higher economic saving potential given the much higher current cost of energy.

Within the framework of the transition to sustainable systems, the supply of clean water is a major issue that particularly affects small islands [6]. Desalination presents a common solution to this challenge. Desalination is defined as the purification of water through the complete removal or reduction below a certain threshold of salt from the water. All the possible technologies to purify water are energy intensive [7]. In general, different technologies adopt phase change membranes (such processes are also called thermal because they use a thermal energy source) or semi-permeable membranes (in this process electricity is

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supplied to separate solvent and solutes) [8]. Most of the desalination plants around the world are based on Reverse Osmosis (RO) technology which represents 65 % of all desalination plants installed worldwide [9]. It is important to consider desalination plants at the system planning level since they have significant investment costs [10] and they might also represent one of the highest load on the island. This is especially true for small islands, since most of the time the industrial sector is not very much developed in insular contexts and thus desalination would cover a high share of the overall energy demand [11]. Furthermore, desalination plants can also offer interesting flexibility potential thus enabling to better manage variable and non-dispatchable renewable energy supply [12]. For these reasons, the flexibility potential of RO desalination plants has been widely studied [13].

Carta et al. [14] proved that an RO desalination plant working intermittently can still produce quality water maintaining the same efficiency and without experiencing additional deterioration to the machinery. Also, Meschede et al. [15] analysed the flexibility potential of a RO plant in La Gomera, Gran Canary, Spain highlighting a potential contribution of the magnitude of GWh and also pinpointing that a limited number of stakeholders need to be involved thus making the realisation of such solution easier to apply. Furthermore, Torabi et al. in two studies, [16] and [17], tested an RO plant in Porto Santo, Portugal, as a deferrable load proving the benefit it would bring in terms of $CO_2$ emissions reduction and peak shaving potential. Also, Liu and Mater [18] proved the flexibility potential of such technology. Karaca et al. [19] analysed the energy system of Antigua and Barbuda integrating photovoltaic, RO desalination plant and a compressed air energy storage unit obtaining a 88 % overall emission savings. Additionally, also other desalination technologies are studied in integration with the energy system such as the humidification dehumidification (HDH) desalination plant anlysed by Zhao et al. [20] in a standalone hybrid system on the island of Xiaowanshan.

The possibility to produce fresh water on the island would bring a twofold benefit since by producing fresh water on the island would lead to social benefits since the water production would not be affected by the weather conditions, which often isolate islands limiting the possibility of transportation. Additionally, it also reduce the emission and energy consumption for water delivery which is also extremely expensive [21]. Particularly, the emissions due to the transportation of water to the island, as well as the transportation of fossil fuels, are never considered when planning the island's future energy systems [22]. Such lack leads to underestimating the benefits of Renewable Energy Source (RES) and RO desalination since the additional savings, both in energy and environmental terms, for the avoided transportation of fossil fuel and drinkable water, respectively, are not accounted for.

In this context, this research aims at studying the water-energy nexus on a small island taking into consideration both the flexibility potential offered by the RO technology and the twofold benefits of avoided maritime transportation for the delivery of water and fossil fuels. A long-term optimisation approach is applied to contextualise the research in the island's clean energy transition to answer the following research questions:

- What are the benefits and trade-offs of different time resolutions in the analysis of desalination options for islands?
- Does considering the emissions of the maritime transport of goods (i.e. water and diesel for power generation) impact the optimal solution?
- Does the optimal transition pathway change if an emission constraint of zero emissions in 2050 is used instead of a carbon tax
- What would be the economically optimal solution with no carbon tax and no emission threshold?

To study the water sector and at the same time also the importance of the maritime transport of goods (i.e. water and fossil fuel) the "OSeMOSYS - Open Source Energy MOdelling SYStem" framework has been used because of its modularity and flexibility, as well as the possibility to analyse a long-term energy strategy to create a so-called transition pathway.

OSeMOSYS was first presented in 2008 and it represents one of the first open-source, long-term energy models [23]. It aims at providing the least cost optimisation for an investment and an energy dispatching problem while coupling different energy-consuming sectors. Being a bottom-up, technology-rich model generator, it enables the user to use varying time resolutions in order to manage the computational effort and thus running time that is extremely important for long term analysis. One of the major issues of OSeMOSYS, and similar energy systems models, is that in order to reduce the computational burden, the time resolution is reduced in common applications. In this study, a model with an hourly resolution has been developed in order to study the effects of the different timesteps on the results.

OSeMOSYS has been widely tested in different contexts and at different scales [24] such as Country level in Brasil [25], USA [26], and China [27], Continental level such as the study of the European energy system of Henke et al. [28], the model of South America – SAMBA used to study the future role of Brazil [29] and the Bolivian one [30] and also the TEMBA model that models the whole African Continent [31]. OSeMOSYS has also been used at a global scale with the name of GLUCOSE [32]. Nevertheless, the model can also be used at a smaller scale as proved by the analysis made at city level in Austin, Texas [33] but also the one in Chocò, Colombia [34]. The model has also been applied at island level both at Country level on the island of Cyprus [35] and at small island scale on the island of Pantelleria [36].

OSeMOSYS has also been used to analyse the water-energy nexus. For instance in [37], Sridharan et al. study the Eastern African context and the impact of climate change on the hydropower availability and how this would affect the energy sector and the optimal water management approach. The water-energy nexus has also been expanded to include the land issue in [38]. Additionally, Ramirez et al. focused on the reuse of agricultural wastewater and its connection and potential synergies with the energy sector [39]. The OSeMOSYS framework has also been applied to systems that include water desalination and the management of wastewater plants [40].

The novelties of this research are multiple and can be connected to the above research questions and are listed here below:

- the first novelty lies in the analysis of the impact of different time slices on the obtained results both in overall terms and in the resulting transition pathway. This goal is achieved by modelling for the first time an 8760-timeslice model in OSeMOSYS;
- the second novelty consists in considering, for the first time, the emissions connected to the delivery of water and diesel to the island within the optimisation of the energy system itself to consider the twofold benefits of self-sufficiency both in terms of clean energy and clean water production;
- the last novelty consists in the analysis of different energy policies at the island scale since this kind of study is usually confined to wider scales (e.g. National or Continental).

The paper is organised as follows, Section 2 describes the methods, Section 3 describes the case study, Section 4 presents the results and discussion and finally, Section 5 summarises the main conclusions.

## 2. Materials and methods

This section describes the modelling tool and the data used to build the model. A brief description of the modelling tool is presented first and then a detailed explanation of the specific energy model and assumptions made for this research are explained in the later part of the section.

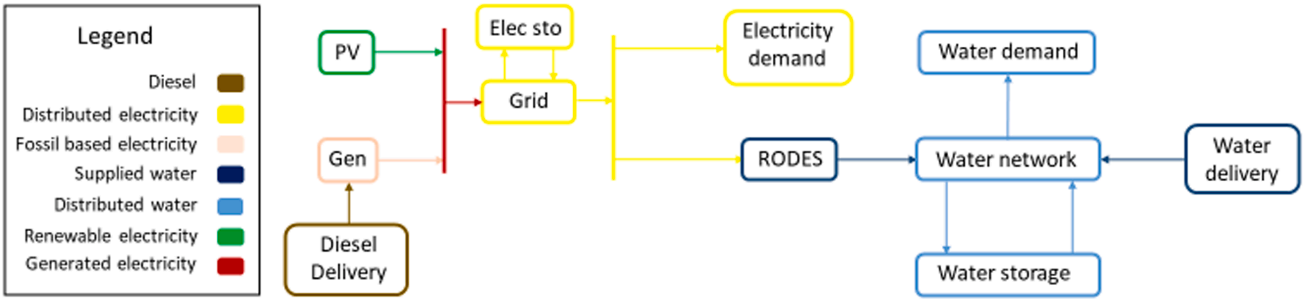

**Fig. 1.** Flowchart of the analysed energy system.

### 2.1. Modelling tool – OSeMOSYS

The model built in the study has been developed using the long-term open-source energy system optimization tool OSeMOSYS. OSeMOSYS was first presented in 2008 and it represents one of the first open-source, long-term energy models for medium to long-term energy planning [23]. It is based on Linear Program (LP) based algorithm to solve a least-cost optimisation for an investment and an energy dispatching problem while coupling different energy-consuming sectors. It is a bottom-up, technology-rich model generator and it enables the user to use varying time resolutions depending on several factors such as the number of analysed technologies, simulated years and more generally the computational effort and thus simulation time. One of the major issues of OSeMOSYS, and in general several energy systems models, is that in order to reduce the computational burden, the time resolution is reduced [41]. In this study, for the first time, a model with the hourly resolution has been developed. This has been done to prove if reducing the timesteps affects or not the solution.

OSeMOSYS has been formulated in several different languages. The python version of OSeMOSYS developed in the python-based optimisation-modelling package PULP has been used for this study [42,43].

OSeMOSYS is structured into different blocks of functionality, which represent different parts of an energy system model such as costs, storage, capacity adequacy, energy balance, constraints and emissions [23]. These blocks can be plugged into the model when needed based on the modelled case. OSeMOSYS considers a least-cost optimization method. Hence, the model computes the investments and dispatching strategies corresponding to the lowest total costs of the energy system.

In OSeMOSYS, conversion technologies in the energy system are represented as different blocks with energy vectors flowing between them. The representation of a model in OSeMOSYS can be seen in Fig. 1. The blocks represent the different technologies or storages in the model, while the vectors represent the different fuels or commodities moving between the technologies. These vectors are used to connect the different technologies to form a chain of production from resource to demand [23].

Further, as represented by the different blocks, OSeMOSYS also considers a range of different constraints in the model, such as capacity and availability constraints, energy generation and resource availability constraints, and emission accounting through emission penalties and limits. The model also considers a discount rate and a salvage value for investments. Thus, it computes the discounted total investment costs for all the technologies. The cost component in OSeMOSYS is shown in Equation (1)). The *Totalcost* shown in Equation (1) indicates the objective function of the model. The model minimises the Total cost of the system while respecting other constraints.

$$\begin{aligned} Totalcost = \sum_{Year}\{ \sum_{Technology} & (Discountedtechnologyinvestmentcosts \\ & - TechnologySalvagevalue \\ & + Discountedtechnologyoperatingcosts \\ & + Discountedtechnologyemissionpenalties) \\ & + \sum_{Storage}(Discountedstorageinvestmentcosts \\ & - Storagesalvagevalue)\} \end{aligned} \tag{1}$$

The two main operational constraints for the model, capacity adequacy and energy balance are described below. The capacity adequacy constraint which ensures that the models invest in the required capacity for all technologies is shown in Equation (2)).

$$TotalCapacity(t,y) \times CapacityFactor(t,l,y) \geq Production(t,l,y) \tag{2}$$

Here, t is technology, l is timestep and y is year.

The energy balance constraint which ensures that the supply is equal to or greater than the demand in every timestep is represented in Equation (3)).

$$\begin{aligned} Production(t,l,y) \geq Demand(l,f,y) + Use(l,f,y) + (Trade(l,f,y) \\ \times TradeRoute\ ) \end{aligned} \tag{3}$$

Here, f represents a fuel or a commodity for which there is either a demand or is being used by another technology in the model. Equations of OSeMOSYS have been explained in detail in Howells et al. [23] and the details of the modelling tool are further documented online [44].

### 2.2. Specific assumptions and scenarios

In this section the analysed scenarios are explained.

As a secondary objective, the research uses an hourly resolution in an OSeMOSYS model. This is the first application of OSeMOSYS at an hourly resolution to the best knowledge of the authors. Specifically, this research wants to test the impact of using different timesteps(hourly resolution and lower resolutions that are required to reduce computational burden, especially in large models) on the final solution. To test the impact of using different timesteps on the results. four timesteps are analysed, namely:

- 1248: the load profile is composed of 52 typical days of 24 h, each day representing the typical daily profile of one week of the year. Indeed, every hour of each day of the profile is obtained by the sum of the same hour of each day of the week (i.e. the first hour of the first day of the profile is built with the sum of the first hours of the first 7 days of the full year). The solar potential is built in the same way but with the average instead of the sum;

- 2184: profiles are composed of 91 days of 24 h. Typical days are built like the previous case with the sum/average of 4 consecutive days;
- 4392: profiles are composed of 184 days of 24 h. Typical days are built considering 2 consecutive days;
- 8760: 365 days are considered with an hourly resolution (i.e. no sum nor average is required).

Also, four scenarios analysing different energy policies have been created, namely:

- PEN_MAR: This scenario takes into consideration emissions due to the delivery, via boat, of diesel for the diesel generator and drinkable water. Furthermore, this scenario considers an increasing carbon tax, thus a penalty hence the name of the scenario (PEN) covering both diesel generators and maritime transport;
- PEN: this scenario considers an increasing carbon tax that covers only diesel generators. The emissions of the maritime transport sector are not considered.
- LIMIT: This scenario takes into consideration emissions due to the transport, via boat, of diesel for the diesel generator and drinkable water. In addition, this scenario has a limit of total emissions that slowly brings the system to zero-emission in 2050.
- MARKET: This scenario takes into consideration emissions due to the transport, via boat, of diesel for the diesel generator and drinkable water. Also, this scenario does not consider any limit on emissions or carbon tax thus it obtains the purely economic optimum.

A summary of the scenarios and their key assumptions is shown in Table 1.

In scenarios with taxation on $CO_2$ emissions, an increasing tax has been considered as this is the clear intention of the European Union (EU) as analysed in previous studies [45,46]. These studies present taxes that increase up to more than 200 €/t$CO_2$. Lower taxes have been assumed in this study to be conservative. However, the results show that higher carbon taxes would not lead to different results since a 100 % RES share is reached before 2050. Namely, a cost of 51 €/t$CO_2$ has been considered in 2020, a cost of 75 €/t$CO_2$ in 2025, 90 €/t$CO_2$ in 2030, 110 €/t$CO_2$ in 2035, 120 €/t$CO_2$ in 2040, 130 €/t$CO_2$ in 2045 and 140 €/t$CO_2$ in 2050.

Firstly, the impact of the different time resolutions is analysed, using the PEN_MAR scenario. The model was developed in OSeMOSYS, and it can be represented by the reference energy system shown in Fig. 1. In Fig. 1, “RODES” refers to the RO Desalination plant while “Gen” refers to the diesel generators and “Elec sto” refers to the battery electricity storage.

As shown in Fig. 1, the research focuses on the electricity and water sectors while also considering the part of the maritime transportation sector connected to diesel and water delivery. The heating and terrestrial transportation sectors are not directly considered in this research since the electrification of these sectors are assumed by increasing the electricity demand as previously explained.

The model analyses the island’s energy system from the year 2020 up to the year 2050. To reduce the computational burden, not all years are simulated. Instead, a multi-year approach is adopted and reference years with a step of 5 years are considered (i.e. 2020–2025-2030–2035-2040–2045-2050) thus implicitly assuming that all years in between can be assimilated to the closest simulated ones. Due to a large time resolution, the model needs to be run on a computing system with large memory and high performance. A desktop computer with 256 GB memory and a processor with the specification 3.50 GHz, 3492 MHz, 4 Core(s), and 8 Logical Processor(s) is used to run the models. The open-source solver Coin-or branch and cut (CBC) is used to solve these models.

**Table 1**
Overview of analysed scenarios.

| SCENARIO | Annual Emission Limit | Emission Penalty | Emissions for DELIVERIES |
|---|---|---|---|
| PEN_MAR | OFF | ON | ON |
| LIMIT | ON | OFF | ON |
| MARKET | OFF | OFF | ON |
| PEN | OFF | ON | OFF |

## 3. Case study: Favignana island

The Favignana island is the biggest island of the Aegadian archipelago (i.e. 19.8 $km^2$) in the Western coast of Sicily (Italy) and has a stable population of 3400. As most small, not interconnected islands, its power system is fully dependent on diesel, particularly on 7 diesel generators of 12 MW nominal power. The only RES generators are residential Photovoltaic (PV) for a total installed power of 170 $kW_p$. The described generators cover the whole power demand of 12.56 GWh/y.

The transport sector accounts for about 60 % of the final energy consumption. Particularly, the maritime has the highest consumption with 57.23 GWh/year used to supply ferries from and to the mainland and to connect Favignana with the other islands of the archipelago, i.e. Marettimo and Levanzo [48]. Such value has been evaluated considering the 100 % of consumption in routes between Favignana, Marettimo and Levanzo and 50 % of the consumption for routes between the 3 aforementioned islands and the mainland as done in [48]. The high consumption is mostly due to the tourism sector which is the most important economic sector for the island of Favignana and the archipelago. The high number of daily travellers also adds to energy consumption. The terrestrial transportation consumption is much lower with a diesel demand of 3.8 GWh/year, and a gasoline demand of 5.5 GWh/year. However, these will not be considered in this study. The demand in the heating sector is mostly due to electric boilers and radiators, and as such, it is considered within the electricity demand. An additional consumption due to the use of Liquefied Petroleum Gas (LPG) for heating and cooking purposes is equal to 3410.5 MWh/y. The share of primary energy consumption of each sector is shown in Fig. 2.

The consumption profiles have seasonal variations with higher peaks in summer due to the tourist season. For instance, the electricity load in summer can be three times higher than one in winter, as seen in Fig. 3.

The electricity load data refers to a single year and have been obtained from the Distribution System Operator (DSO) in Favignana, SEA S.p.A.. This electricity demand profile is used for all simulated years. The annual electricity consumption is considered to increase by 1 % each year starting from 12.53 GWh in 2020 (data provided by SEA S.p.A) and reaching a value of 14.56 GWh/y in 2050. The increase accounts for the further electrification of the transport and heating sectors. The demand growth rate is lower than the national demand growth rate the population on the island is not considered to increase and closed communities such as the insular ones usually show slower uptake of new technologies

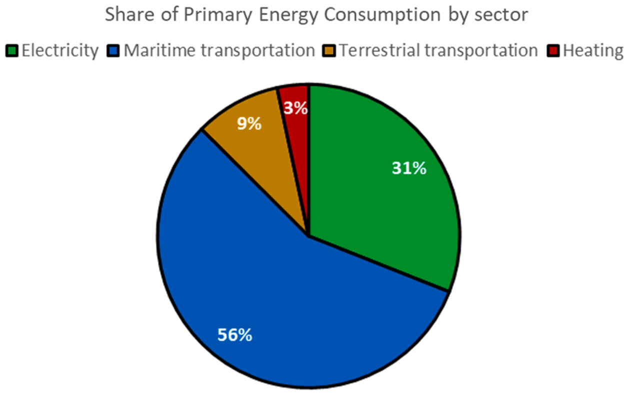

**Fig. 2.** Share of Primary Energy Consumption in Favignana by sector.

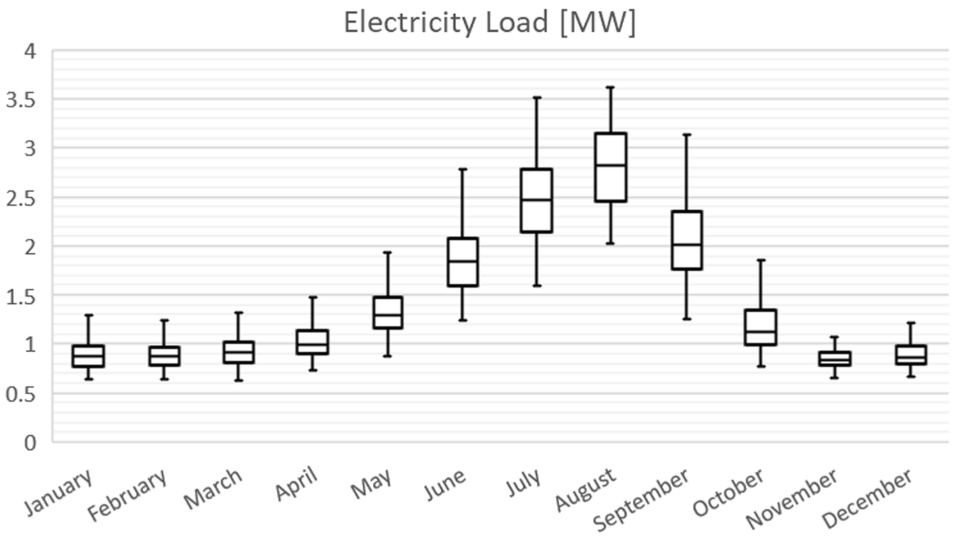

**Fig. 3.** Monthly electricity load in Favignana.

such as electric Vehicles. In contrast to the electricity demand, water consumption has been considered to remain steady over the years and equal to 291310 m$^3$/year since neither the population nor the tourist fluxes are considered to change noticeably. The annual water consumption has been evaluated considering the monthly presence of both residents (stable) and tourists on the island, using data obtained from the island Sustainable Energy and Climate Action Plant (SECAP) [48]. The water consumption per person has been assumed to be 200 L/day per capita [49]. The water consumption profile has then been built based on the electricity demand profile as both demands have similar profiles [50].

This study considers the installation of renewables on the island and the corresponding technical potential. The study only considers the installation of Solar PV technologies since the installation of wind turbines is not allowed on the island. The PV production potential as well as the hourly profile have been obtained by renewables.ninja online tool [51].

The main economic parameters are shown in Table 2 and Table 3.

The water delivery cost can range between 7 €/m$^3$ [58] and 13 €/m$^3$ [59], as also recorded in Italy [49]. Thus an average cost of 10 €/m$^3$ which has been previously used in other research studies [57,49], is chosen. The $CO_2$ emissions connected to maritime transport have been evaluated following the methods explained in [60,61]. The method consists of evaluating the energy consumption in each phase of the trip is divided into Manoeuvring, Acceleration, Crossing, Retardation, Braking and In Port. This is done by considering the percentage of the engine that is used in each phase and the duration of the phase. The nominal power of the engine has been considered to be 1700 kW considering a typical vessel used for water delivery in Italy [62].

In Table 4, the detail of the fuel consumption per trip is shown.

Thus, the total fuel consumption for a full trip assuming an average engine efficiency of 0.3 was equal to 9214.9 kWh. Assuming that each ship can deliver 2000 m$^3$ of water [62], the specific consumption and the emissions per unit of water delivered are calculated to be 4.6 kWh/m$^3$ and 0.001043 t$CO_2$/m$^3$ respectively, based on an emission factor per unit of energy of 0.2264 t$CO_2$/MWh.

**Table 3**
Economic parameters of the analysed technologies.

| Technology | Unit | Fixed O&M (k€/unit) | Variable O&M (€/unit) | Lifetime | $CO_2$ Emissions |
|---|---|---|---|---|---|
| PV | MW | 5 [52] | – | 20 [52] | – |
| Gen | MW | 8.8 [52] | – | 25 [52] | 266.4 |
| RODES | m$^3$/h | 0.2 [57,49] | – | 35 [57,49] | – |
| Water Delivery | m$^3$ | – | 10 [57,49] | 100 | 0.0031 |
| Diesel Delivery | MWh | – | 5320 | 100 | 0.31 |

By applying the same method of calculation for diesel delivery, the specific consumption and emissions were evaluated per unit of transported MWh of diesel assuming a lower calorific value of 11.86 kWh/kg, an emission factor of 3.2 $tCO_2/t_{fuel}$ and a density of 850 kg/m$^3$. The emission factor obtained was 0.1 t$CO_2$/GWh.

The efficiency of the diesel generators has been assumed to be constant and equal to 0.38 as communicated by SEA S.p.a. The Water Network was considered to have an efficiency of 0.47 [63] while the electricity grid is assumed to have no losses. The specific electricity requirement of the RODES plant has been considered to be 3.5 kWh/m$^3$ as an average value between the commonly indicated range of 2–6 kWh/m$^3$ [64,65].

Furthermore, the residual capacity of diesel generators is assumed to decrease over the years. The installed capacity was considered to remain at 12 MW until 2030, then decreases to 6 MW in 2040 and then drop to 0 in 2045 and 2050. The installed capacity of PV in the year 2020 was equal to 0.17 MW while the one of water storage was 3200 m$^3$ [48].

A maximum installable capacity of PV has been set equal to 18 MW

**Table 2**
Investment cost within the analysed period.

| Technology | Unit | Investment cost | | | | | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | ***2020*** | ***2025*** | ***2030*** | ***2035*** | ***2040*** | ***2045*** | ***2050*** | |
| PV | k€/MW | 750 | 750 | 500 | 500 | 350 | 350 | 250 | [52] |
| Gen | k€/MW | 350 | 350 | 350 | 350 | 350 | 350 | 350 | [52] |
| RODES | k€/m$^3$/h | 20 | 20 | 20 | 20 | 20 | 20 | 20 | [53,54] |
| Electricity Storage | k€/MWh | 1042 | 1042 | 622 | 622 | 394 | 394 | 255 | [55] |
| Water tank | k€/m$^3$ | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | [56] |

**Table 4**

Evaluation of maritime transport energy consumption per sub-phase.

| Technology | Manoeuvring | Acceleration | Crossing | Retardation | Braking | In Port |
|---|---|---|---|---|---|---|
| Time (s) | 45 | 90 | 6466.67 | 185 | 90 | 300 |
| Power output (%) | 75 | 80 | 42 | 7 | 56 | 14 |
| Energy Consumption | 15.94 | 34 | 1282.56 | 6.12 | 23.8 | 19.83 |

considering the whole rooftop availability as well as the possibility to install more in parking lots or other available locations as previously analysed in [66].

## 4. Results and discussion

The results section has been divided into two sections focusing on:

- The impact of time resolution
- The impact of policy

In the first sub-section, the results of models with 8760, 4392, 2184 and 1248 time slices are compared and discussed. In the second sub-section, the different scenarios, carbon tax (PEN and PEN_MAR), a limit on emissions (LIMIT) and no policy restrictions (MARKET) are analysed.

### *4.1. The impact of time resolution*

Fig. 4 shows the different installed PV capacities in the PEN_MAR scenario with different timesteps.

There are significant differences in the results as shown in Fig. 4. This is true both in terms of transition pathways and in terms of overall installed capacity in the horizon year (i.e. 2050). Precisely, the overall cumulative installed PV capacity ranges between 12.8 MW with 1248 timesteps and 13.6 MW in the 8760 model with the other two models 4392 and 2184 with an installed capacity of 13.53 MW and 13.49 MW, respectively. The difference in investments occurs in the years 2045 and 2050 while the rest of the pathway is the same in all models. It can be noticed that a lower timestep leads to an underestimation of PV capacity (about −6% in the 1248 model compared to the reference one, i.e. 8760) and this is especially true for a system with high-RES share as is the case for the last years of the simulation (i.e. 2045 and 2050).

Representative days created by using the average of the solar potential of the same hours of different days could smoothen out the variations between consecutive hours as well as maximum and minimum values. This creates more regular profiles and thus decreases the need for flexibility and consequently for storage which is used to manage mismatches between demand and supply. Thus, variation in timesteps could impact the accuracy of the determined storage capacity. Nevertheless, the results show that such a problem is not encountered. On the contrary, the results with a lower timestep end up having a slightly higher size of storage. Fig. 5 shows the results in terms of newly installed storage capacity in MWh.

In the case of storage, the relative error is much higher than in the case of PV capacity. In terms of cumulative installed capacity, the results can be seen in Table 5.

There is a significant error also in the case of 4392-time resolution and the relative error increases to 42 % in the lower time resolution model. Some differences can be found from the year 2030 to 2040 when most of the storage capacity is installed. Considering that the differences in terms of PV installed capacity happen to be in the years 2045 and 2050, it can be assumed that the different storage capacity impacts such errors in RES capacity.

In the water sector and the installation of a Reverse Osmosis (RO) Desalination plant (results in the model are called RODES), the results are almost not impacted at all by the time resolution, as shown in Fig. 6.

Indeed, the investment is extremely advantageous and the whole water demand is covered entirely by the RO plant starting by the year 2025 (i.e. the first year in which investments are enabled, indeed the year 2020 investments are not enabled and such year is used as baseline/reference scenario).

Nevertheless, in all scenarios, the water storage is not increased. The water storage installed on the island is oversized due to the size of the boats for water delivery which brings around 800–1000 $m^3$ of water at the same time. Therefore, the size of the water tanks needs to be designed to store a large amount of water at once. In the model, water delivery is dispatchable in all timesteps and thus the storage is not used fully. This can be seen in Fig. 7 by looking at the blue line, which represents the water storage level in the case of water delivery via maritime transportation (the year 2020 is used as a reference since no desalination plant is installed). The yellow curve represents the water storage level in the case in which the whole water consumption is covered by the RO plant and with a high RES share (i.e. the year 2050 is used for this

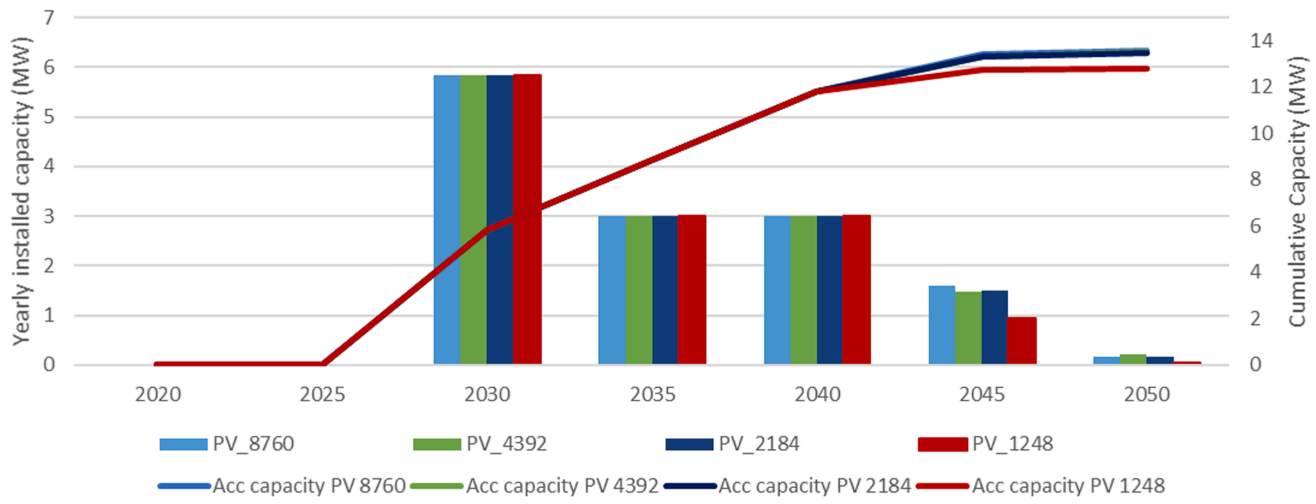

**Fig. 4.** Photovoltaic installed capacity in models with different time slices.

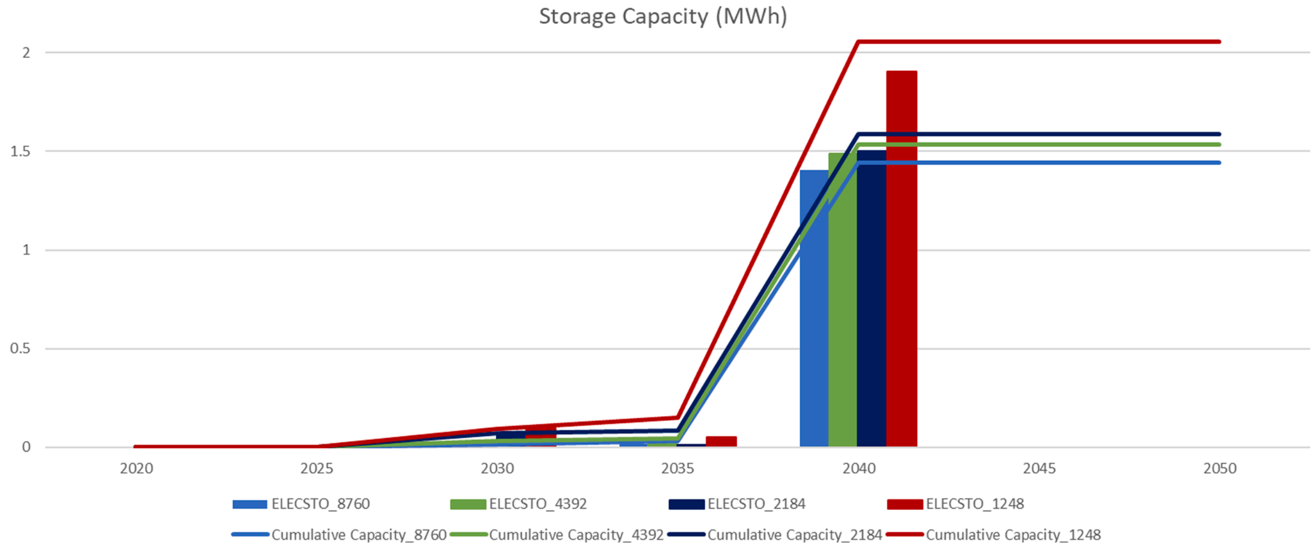

**Fig. 5.** Installed storage capacity in models with different time slices.

**Table 5**

Battery cumulative capacity in 2050.

| Model | Battery size (MWh) | Relative Error (%) |
|---|---|---|
| 1248 | 2.05 | +42 |
| 2184 | 1.59 | +10 |
| 4392 | 1.53 | +6 |
| 8760 | 1.44 | – |

purpose).

On the other hand, when the water can be produced on the island using renewable electricity, the water storage is used up to its maximum capacity in the summer months which are both peaks in water demand and PV production. Thus, it can be concluded that the water storage is used mostly to not oversize the RO desalination plant and to optimally exploit the PV production thus offering flexibility to the grid. Nevertheless, it is interesting to notice that it is not used as seasonal storage even though the cost of storage is much lower than that of batteries (i.e. 150 €/$m^3$ is equivalent to 42.85 €/kWh considering the RO producibility of 3.5 kWh/ $m^3$). Fig. 7 can also be useful to notice how the dispatching strategies change with different time slices even though the yearly results are comparable. Different peaks are seen in the Storage levels for the different time resolutions. These peaks should match since each hour in the 1248 model also represents 7 h in the 8760 model. However, this is not the case. The 1248 model (Fig. 7a) presents the same summer peaks as all the other models but in addition, it also has 2 peaks in hours 320 and 510 (i.e. 3rd of April and the 28th of May, respectively). The 2148 model also presents a peak at the end of May but not one in April. Furthermore, the models with 4392 and 8760-time slices only have two summer peaks. Hence, considering that the 8760 is the most precise model and is used as a reference, the results show models with at least 4392 should be preferred since this is the lowest time resolution for optimising the dispatch (of those that have been studied) since these have similar comparable dispatching strategies to the model with an hourly resolution.

Fig. 8 shows the operating cost (i.e. fixed and variable costs) and the Annual emissions obtained with different timesteps.

As expected, no significant differences are found between models both in terms of emissions and operating costs. All models reach zero emissions by 2045 and the reason why this happens is analysed in detail in the next section. The operating cost in 2020 was the same for all scenarios and it is equal to 6.48 M€/y and most of it is due to the delivery of drinkable water both for the high cost, 10 €/$m^3$, and the high losses in the water network (i.e. 53 % as mentioned in the previous section). Water delivery also has a significant impact in terms of emissions. In the year 2020, this sector constitutes 10.02 % of the total $CO_2$ emissions; thus, it cannot be neglected when planning the decarbonisation of insular energy systems. In contrast, diesel delivery does not affect the overall emissions since the emission from diesel delivery only amounts

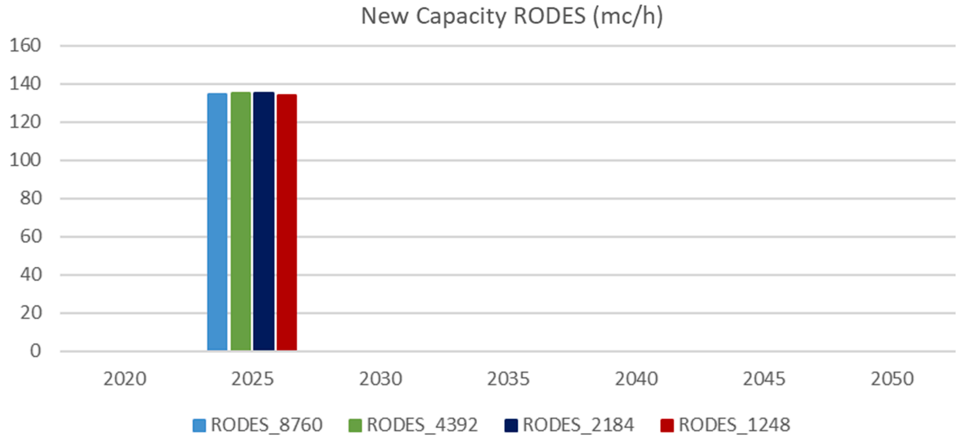

**Fig. 6.** Reverse Osmosis Desalination plants installed capacity in models with different time slices.

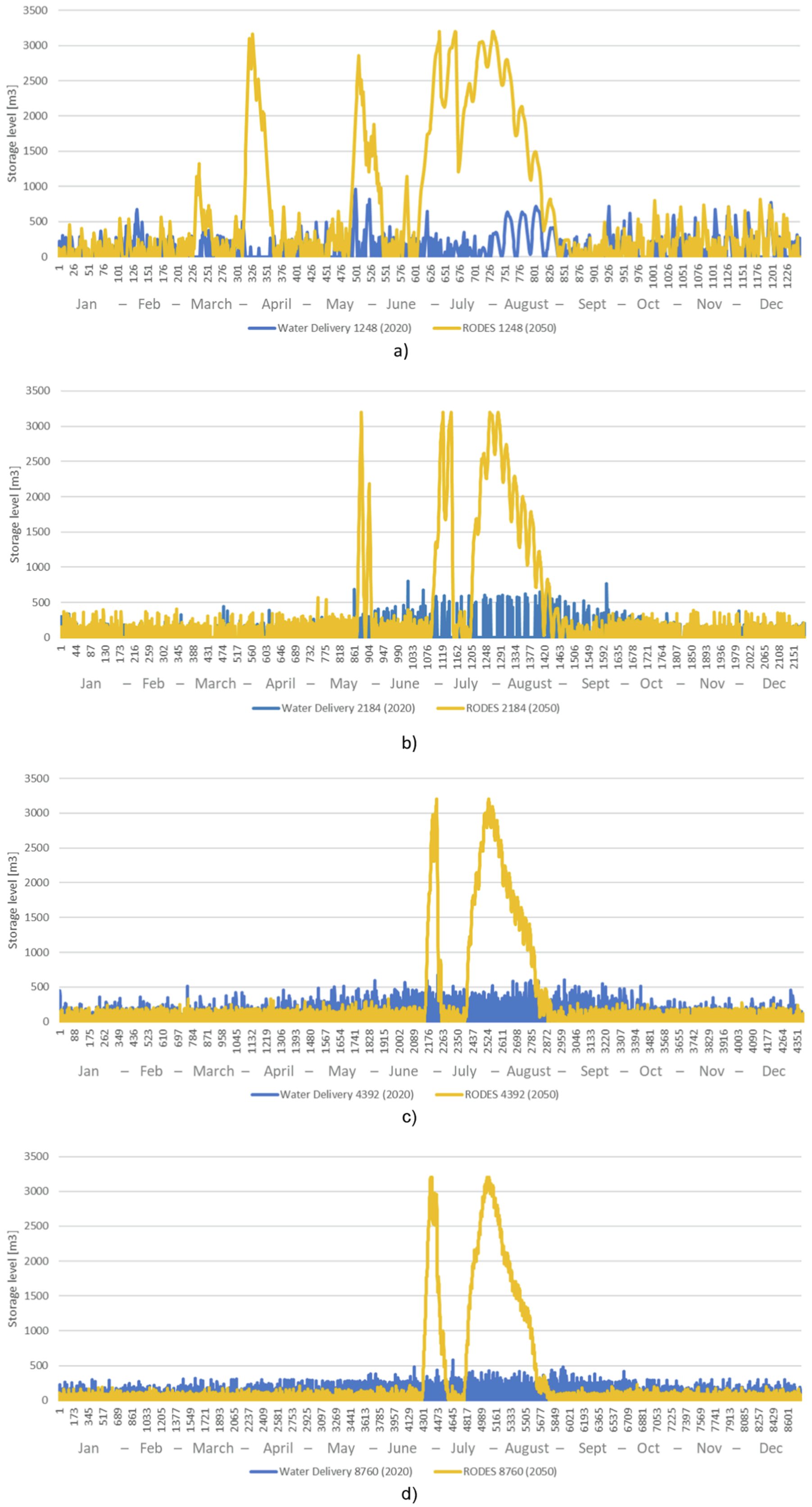

**Fig. 7.** Water storage level in the years 2020 (100% reliant on water delivery) and 2050 (100% reliant on Reverse Osmosis desalination plant supply) in the different models with a) 1248, b) 2184, c) 4392 and d) 8760-time slices.

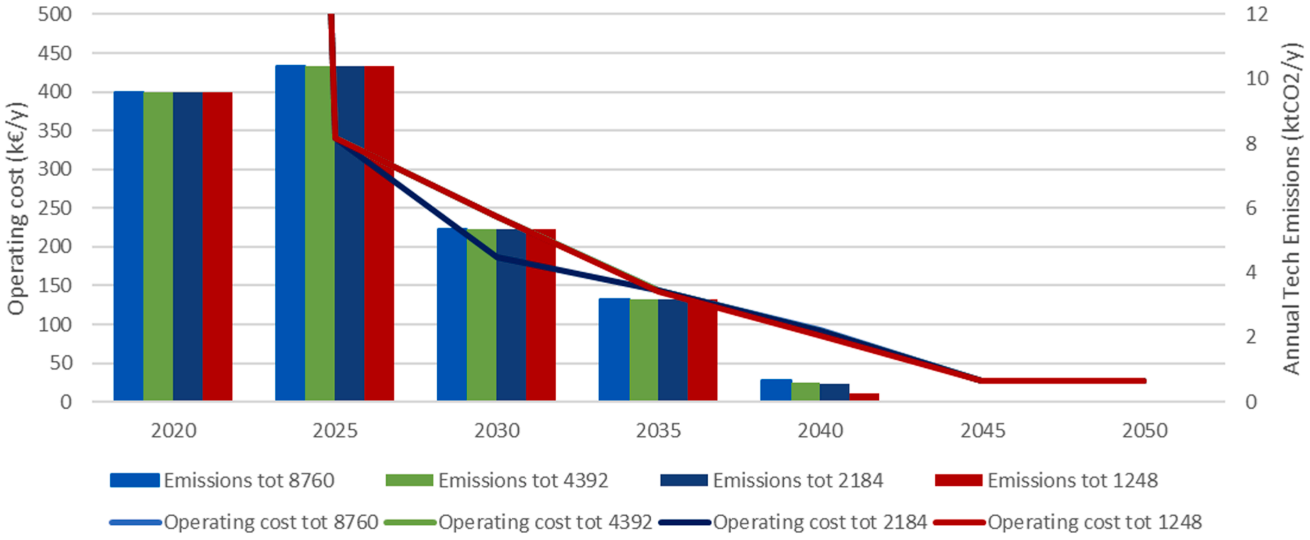

**Fig. 8.** Operating Cost and Annual $CO_2$ Emissions of models with different time slices.

to about 4 $tCO_2$/year.

Thus, it can be concluded that different timesteps may affect the obtained results, especially if dispatching strategies are of interest. For this reason, in the next section where different policies are analysed and yearly and cumulative values are analysed, only the model with 8760 timesteps has been used. Given the small size of the energy system (in terms of technology), the running time was not prohibitive despite the large time resolution.

Additionally, another important outcome is that when analysing insular energy systems the energy consumption, and related emissions, for the delivery of goods and services must be considered when planning the energy transition of the island and its full decarbonisation.

### 4.2. The impact of policies

As regards the water sector and precisely the installation of a RO Desalination plant (RODES), the results are not impacted at all by the different policies as shown in Fig. 9. The same can be said also for water storage which is not increased in all scenarios.

An overall capacity of 134.18 $m^3/h$ is installed to fully cover the water demand of the Favignana island. The optimal solution thus completely substitutes the existing water delivery system that is not used even in summer when the water demand peaks. Nevertheless, even in these different scenarios, water storage is not used for seasonal storage. It is worth underlining that such results have been obtained with average costs for water delivery, RO plant investment cost and efficiency. Different values might lead to different solutions, but the very high price of water delivery suggests that such a solution from a mere techno-economic analysis is always a path that needs to be further analysed in detail. Also, the flexibility that can be offered to the grid when high-RES shares are reached, as shown in Fig. 7, is an additional incentive to invest in RO technology. This outcome is relevant also for all other islands that can use such results as a benchmark. Of course it must be considered that the main drivers for this kind of projects is the population, connected to the amount of water consumed, and the distance from the mainland.

As far as the power sector is concerned, Fig. 10 shows the different installed PV capacities in the scenarios.

It can be seen that all scenarios, except the MARKET scenario, end up with a similar overall installed capacity of PV close to 12 MW. The MARKET scenario reaches a much lower value of 2.68 MW which does not lead to full decarbonisation.

The first preliminary conclusions can thus be drawn from the fact that PEN and PEN_MAR lead to the same results. This suggests that considering the emissions connected to the diesel delivery does not impact the results of the optimal installed PV capacity even when a carbon tax system is in place. The impact of water delivery is not significant since the water supply is completely reliant on a RO plant in

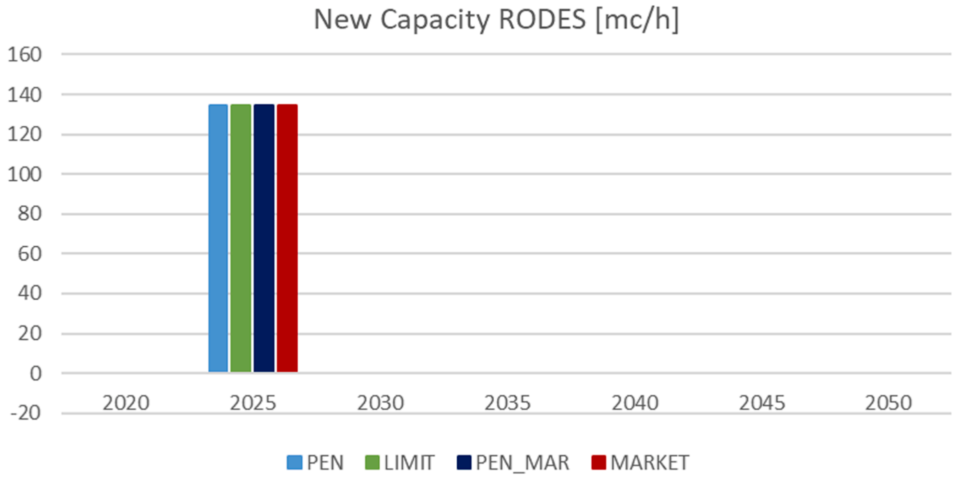

**Fig. 9.** Reverse Osmosis Desalination plant installed capacity in different scenarios.

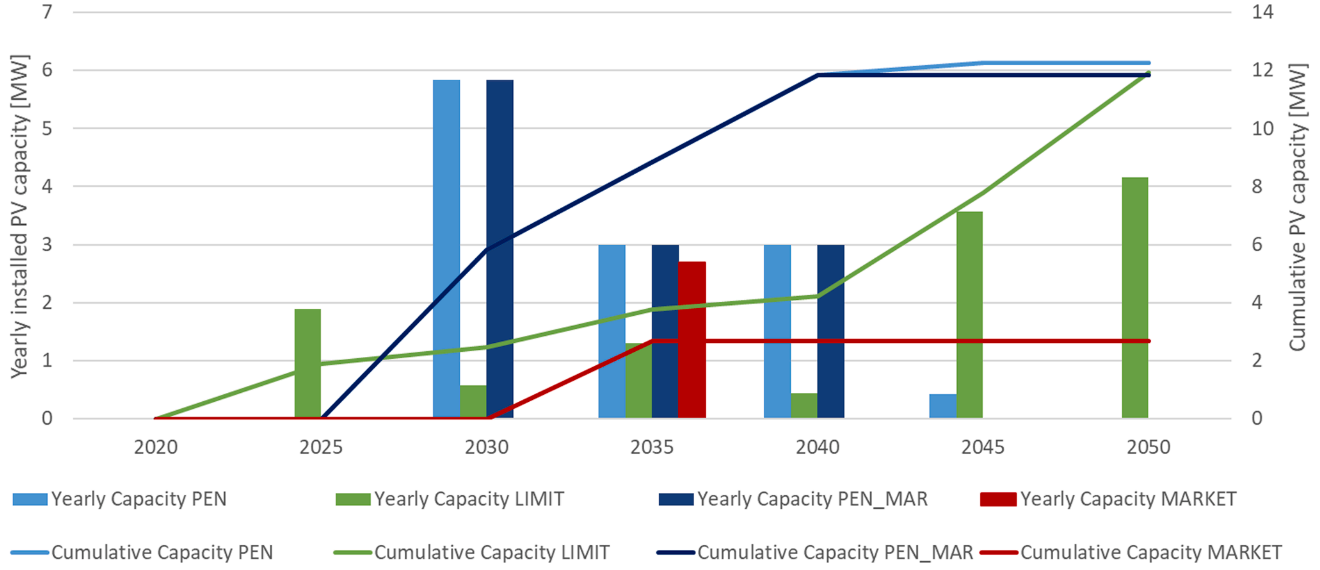

**Fig. 10.** Cumulative and yearly Photovoltaic installed capacity in different scenarios.

both cases from 2025 onwards.

It is interesting to notice that in all scenarios with carbon taxes, the system fully relies on PV and a 100 % RES share is reached before 2050. Thus, the conservative assumptions on carbon taxes do not impact the obtained results; indeed, higher carbon taxes would not lead to different results since a 100 % RES share is reached before 2050 in both PEN and PEN_MAR scenarios.

It is also interesting to see the investment throughout the years in the different scenarios, shown in Fig. 11.

Fig. 11 provides an interesting outcome; if PEN and PEN_MAR scenarios have very similar cumulative investment costs. However, the LIMIT scenario leads to a much lower overall investment. Thus, on one hand, the use of a carbon tax would speed up the transition process but on the other hand, it would also lead to an increased economic effort.

The MARKET scenario is of course the one that requires the least investment because of the lower overall PV capacity. These different pathways have also an impact on the operating cost and most importantly on the overall emissions. This can be seen in Fig. 12, which shows the operating cost, and in Fig. 13, which shows the Annual and cumulative $CO_2$ emissions.

The MARKET scenario, as expected, has the highest operating cost, due to the fuel costs for diesel generators that are still used in 2050 as can also be seen in Fig. 13.

To build the cumulative emissions curves, non-simulated years have been assumed to be equal to the previous evaluated year (e.g. years in the range 2021–2024 are equal to 2020). Based on this assumption, the following conclusion is drawn:

- The LIMIT scenario is the first one to relevantly reduce emissions by installing PV systems for a capacity of 1.89 MW in 2025 (see also Fig. 10). Nevertheless, the scenarios PEN and PEN_MAR reach lower cumulative emissions already in 2035 installing 8.83 GW of PV against the LIMIT scenario that in 2035 sees an overall installed capacity of 3.77 MW. Also, considering the total emissions from 2020 to 2050, PEN and PEN_MAR scenarios lead to the lowest emissions.
- All scenarios, except LIMIT, increase their emissions from 2020 to 2025 due to the shift to a RO desalination plant instead of water delivery without installing any PV (see Fig. 10).
- The PEN scenario in 2020 has lower emissions than other scenarios because it is the only scenario that does not consider emissions related to the maritime sector as shown in Table 1. Excluding such emissions leads to an underestimation of the overall emissions by

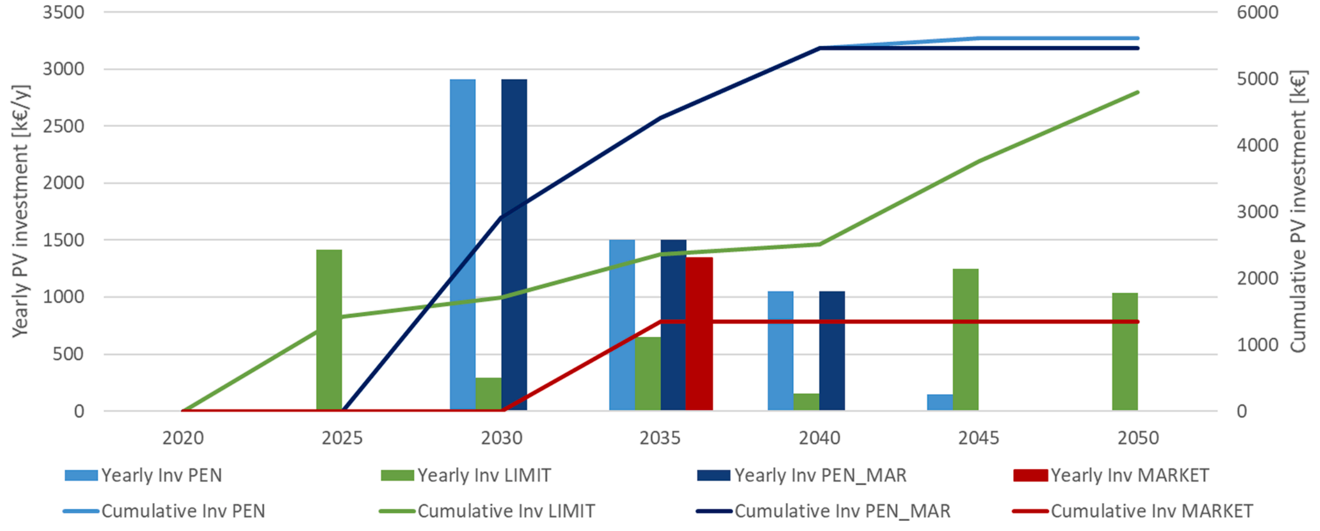

**Fig. 11.** Photovoltaic yearly and cumulative investment in different scenarios.

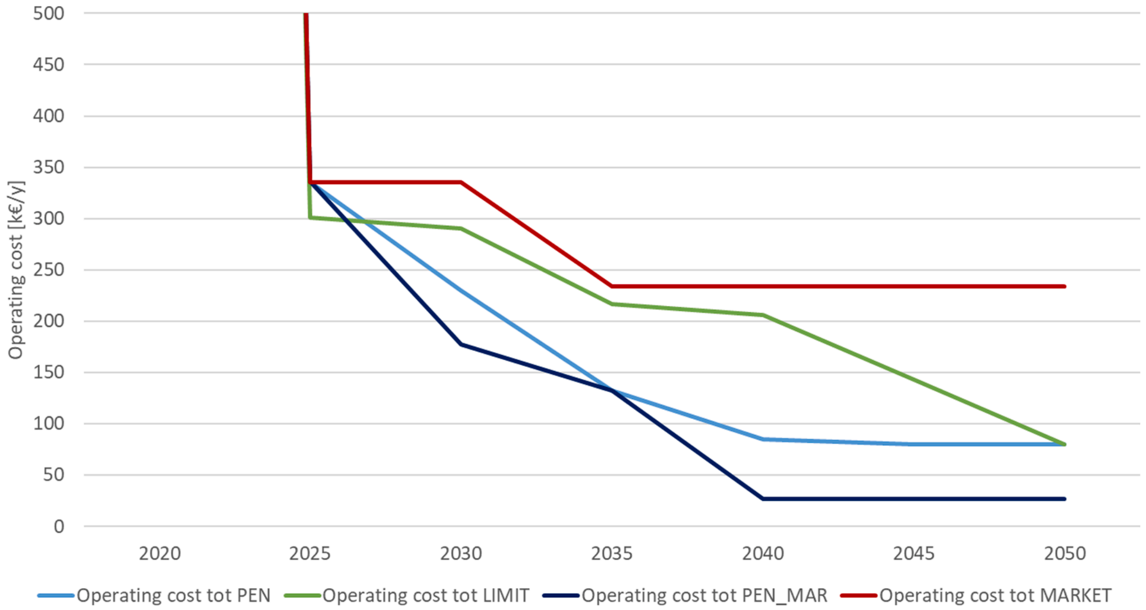

**Fig. 12.** Yearly operating cost of the different analysed scenarios.

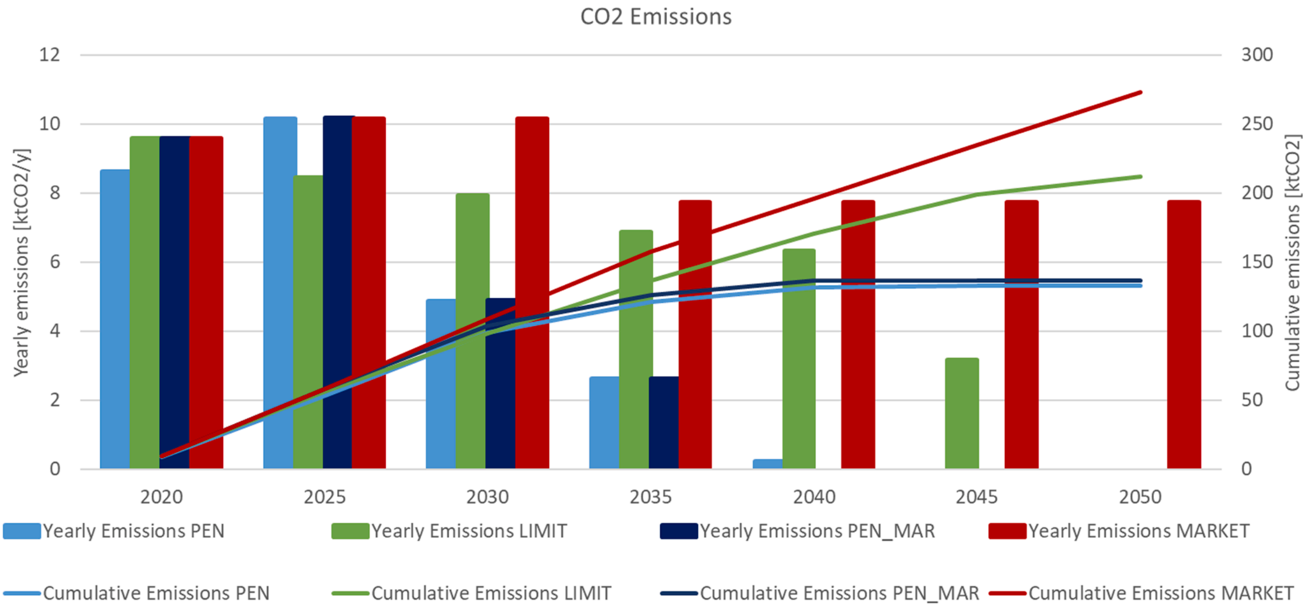

**Fig. 13.** $CO_2$ yearly and cumulative emissions in different scenarios.

about 10 % of the total, most of which are linked to water delivery. This fact also leads to another outcome the PEN scenario sees the largest increase in $CO_2$ emissions from 2020 to 2025. This is because installing the RO desalination plant without installing any PV system, means that in order to meet the new demand for water production the electricity produced by the diesel generators is increased and thus the emissions related to the water production (i.e. the electricity that is fed to the RO) increase. This highlights the importance of considering the emissions related to water delivery when analysing the opportunity of installing a RO plant. This is of course true for this specific case study but it is also relevant for all insular energy systems and it is especially true for all those islands that are further away from the mainland.

- The only scenario that does not lead to a 100 % RES share is the MARKET one thus indicating that without the correct policies and regulations full decarbonisation will not be reached by 2050.

The results of the installed capacity of storage indicate that battery storage is installed in all scenarios. Fig. 14 shows the results of installed storage capacity expressed in MWh.

In the PEN and PEN_MAR scenarios, a significant capacity of storage is installed only in 2040 when the installed PV reaches a value of 11.83 MW. Until 2035, no storage is installed despite the installed PV capacity being 8.83 in the PEN scenario. A small storage capacity of 113 kWh in the PEN_MAR scenario until 2035. The LIMIT scenario shows an interesting insight since it does not install a relevant storage capacity until 2050 when no emissions are allowed. In previous years, the optimal solution is to curtail PV power, and waste energy, instead of installing battery energy storage and exploiting such energy. With the adoption of a carbon tax, the installation of renewables is accelerated leading to the optimal management of renewable energy. However, this analysis does not investigate the grid stability but only analyses the optimal energy management from an economic point of view. Thus, such results should

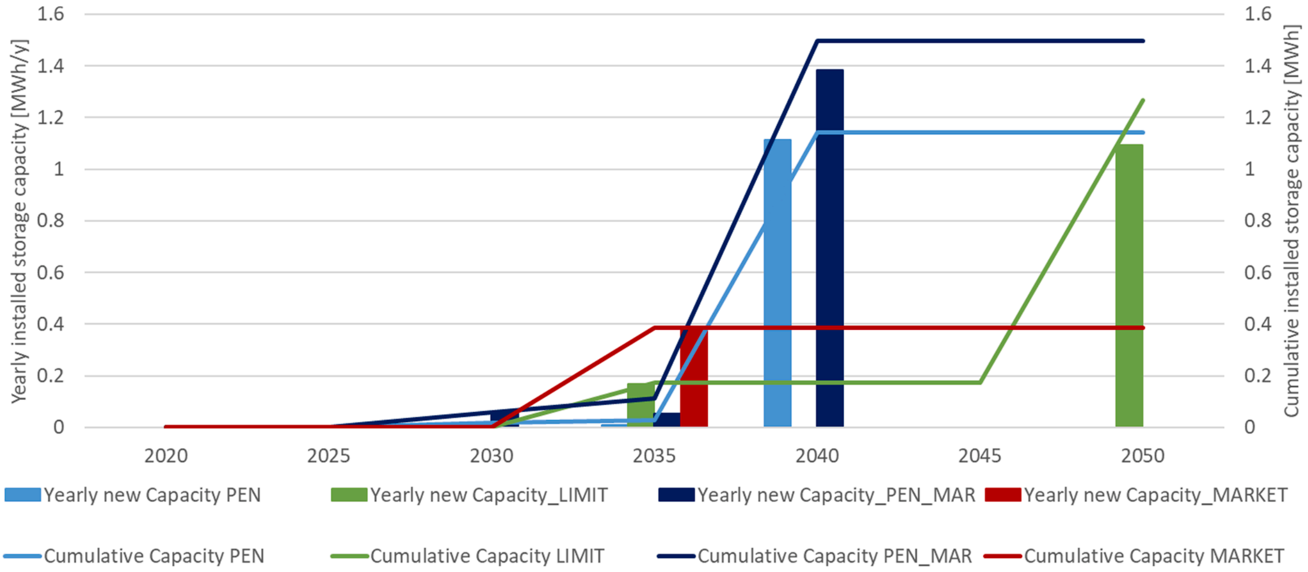

**Fig. 14.** Yearly and cumulative installed battery storage by analysed scenario.

also be verified with the results obtained by a grid stability analysis.

The overall installed capacity of storage is directly proportional to the installed PV capacity. Thus, the scenario with the highest storage capacity is PEN_MAR with an installed storage capacity of 1.5 MWh while the MARKET scenario has the least installed storage capacity equal to 0.39 MWh.

It is worth noticing that all the obtained results are relevant for all insular systems. Indeed, as explained in the introduction, insular energy systems around the world are all very similar and suffer the same issues thus similar results would be obtained. The key factors that could affect the results are the population, that is the main driver for electricity and water consumption, and the distance to the mainland that affects the energy consumed for delivering goods and services.

## 5. Conclusions

This study analyses the insular energy system of the island of Favignana while also considering the water using the OSeMOSYS modelling framework. The main conclusions of the study are as follows:

- Different time steps can significantly affect the results both in terms of overall investment and transition pathways. The effect of time-steps is most significant in the dispatching strategies. Another difference can be found in the installed storage capacity and the results suggest a recursive trend in which models with lower timesteps tend to overestimate the storage capacity. Thus, the optimal time resolution should be identified also depending on the model complexity, the computational effort and running time. It must be noticed that the results might be affected by the simplicity of the model in terms of analysed technologies and storage.
- The importance of considering the emissions connected to the water delivery service has been proved. Indeed, they represent 10 % of the overall yearly emissions in the baseline scenario (i.e. 2020). Thus, they should not be neglected when planning the decarbonisation of islands. In addition to having the highest emissions, water delivery by boat also bears by far the highest costs. When RO desalination is considered in the least-cost model, it is consistently chosen in all the scenarios. Even the scenario with a carbon tax that did not consider the emissions of the water delivery shifts completely to a RO plant even though this translates into higher $CO_2$ emissions and thus cost. Considering that average cost and efficiency values have been considered for this analysis, it shows that such results are relevant for other insular energy systems.
- Although all scenarios resulted in a water system fully supplied by a RO desalination plant, no investment in water storage is needed. The reason lies in that the storage currently installed is highly oversized. Also, the water storage is not used as seasonal storage but only to reduce the size of the RO plant. The maximum level of the water tanks is reached only in summer when both the PV production and the water demand meet their peaks. It should be noticed that no limit on the critical excess production or stability has been set. Therefore, a portion of the energy is simply wasted (i.e. PV power is curtailed). This leads to a potential for energy storage to store the curtailed energy. However, the installation of storage depends on the trade-off between the cost of installing storage vs the cost of curtailing the electricity.
- The MARKET scenario simulates the case in which no particular policies are put in place to decarbonise the island. In this case, all investments in PV plants are delayed until the year 2035 when the PV price drops. This is the only scenario that does not lead to a zero-emission system thus suggesting that special policies are needed for the full decarbonisation of small islands by 2050.
- The establishment of a carbon tax, increasing from 50 €/$tCO_2$ in 2020 to 140 €/$tCO_2$ in 2050, leads to a fully decarbonised energy and water system on the island and the lowest cumulative emissions. Also, no relevant differences are found in whether the carbon tax comprises maritime transport or not (for the transport of water and diesel, no other form of maritime transport has been considered).
- The establishment of a carbon tax seems to be more effective than setting a yearly limit on emissions. Setting an emission limit seems to leave more room for decision and planning thus enabling investors to wait for cheaper prices of PV leading to lower overall investments but higher overall emissions between 2020 and 2050.

In the end, the presented analysis has responded to the main scientific questions that it aimed to tackle. Future studies shall be developed to build upon the obtained results and further validate them. Indeed, some limitations must be mentioned such as the simplicity and reduced size of the analysed energy system. Thus, in the future similar analysis should be carried on more complicated and technology-rich systems. This would surely make arise the issue of computational time to run a model with hourly resolution. Nevertheless, small energy systems such as the one analysed in this paper should be used as a benchmark to test novel time series clustering methods for the construction of the typical day. Moreover, future studies should analyse how different carbon taxes could impact the island's energy transition. Also, future studies might decide to investigate other technologies in terms of renewable generators, storage and technologies for water desalination. Nevertheless, the presented analysis can be a reference for future studies about insular energy systems since most islands energy systems have similar features and encounter analogous issues.

## CRediT authorship contribution statement

**Daniele Groppi:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization. **Shravan Kumar Pinayur Kannan:** Conceptualization, Methodology, Software, Writing – original draft. **Francesco Gardumi:** Conceptualization, Investigation, Writing – review & editing. **Davide Astiaso Garcia:** Supervision, Investigation, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Most of the data are publicly available and duly cited. The hourly electricity load data were provided by the DSO of the island and cannot be shared.

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