PRODES Promotion of Renewable Energies for Water Production through Desalination

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Example of project development opportunities in Greece, Italy, Spain and Portugal

Deliverable 5.2

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1. Introduction

A desk-based survey was performed to identify niche-markets in the involved countries. Within these markets, representative project development opportunities were highlighted and are presented in this report as examples of cases where RE-desalination options would be suitable solutions which make financial sense and bring additional benefits for the consumer with high quality water and the environment through low-impact solutions. For the selection of the examples presented in this report, priority was given to public bodies where the project if implemented will have also high visibility.

The concrete examples do demonstrate that in the current market conditions and with the technologies available in the market there are already several cases where the application of RE-desalination is feasible. Main barrier is the lack of knowledge about these options and this report helps to overcome this barrier.

In Greece a small community on an island was examined and it was shown that the solar energy reverse osmosis plant can deliver water at comparable cost with conventional desalination, taking into account the feed-in tariff for the PV system. Most importantly, the cost of water from the PV-RO would be much cheaper than the conventional option if the real cost of electricity was taken into account and not the heavily subsidized diesel generated grid electricity.

In Italy it was shown that the waste heat from bio-gas turbines, fed by the bio-gas produced in the anaerobic digester of the sewage treatment plant can be used to drive the multi-effect humidification desalination system. This would deliver the deionised water used in the sewage plant for industrial scopes with lower cost than the method currently employed. Several other options were also examined including stand alone RE-desalination systems and the comparison gives interesting results.

In Spain the application of reverse osmosis powered by wind and PV was considered for a small island in the Canaries. The cost would be only slightly higher than the current solution of water transferred through a pipe in the sea. However, it would be a more reliable solution and the quality of the water would be higher.

Finally in Portugal, the installation of a solar thermal multiple effect humidification in a small touristic island has proven to be a cost effective solution, providing water around 43% less costly than of the current boat transported water used for bathing and washing. It would also provide 8-9 times less costly water for drinking than the present bottled water solution, while reducing the ecologic footprint of the island.

It is important though to stress that these are just examples. The costs mentioned for the desalination and energy systems are indicative and cannot be taken as the actual costs of the equipment. Also the calculated costs of the water produced are very strongly dependant on the specific conditions of the chosen examples. The actual cost in another location or by employing slightly different technology could be lower, or higher.

2. Greece

2.1 Situation in Greece

In the mainland of Greece there is not actually any serious lack of water resources. The mountainous terrain is ideal for storing water in large basins. Therefore, not any serious problems are encountered, although most of the country's population lives in those areas. Also, on the west side of Greece, the rainfalls are very intense for many months per year.

The Greek islands on the other hand can be divided into two main categories, depending on their location. Beginning with the western ones (Ionian Sea), the rainfall is quite intense during the winter period. Consequently, not any serious problem, concerning the water supply, is reported in those islands, although during the summer period numerous tourists visit them. In contrary, the eastern islands (Aegean Sea) can be further subdivided into two categories: the large ones and the small ones. Usually, the larger ones have a well-developed water network and care has been taken on the provision of adequate water quantities. On the other hand, the smaller islands, located mainly to the center of the Aegean Sea belonging to the Cyclades prefecture, face water availability problems. In some of them, although water networks have been developed, not sufficient water supply infrastructures exist, to satisfy the demand of year round inhabitants and visitors. In most of the cases, the water comes from boreholes and wells of quite high salinity. Moreover, salinity is not constant throughout the year, showing the highest values during September and October, since usually the rainfalls have not yet started.

All the above are summarised in Figure 1, where the mean annual precipitation values for all Greek districts are shown.

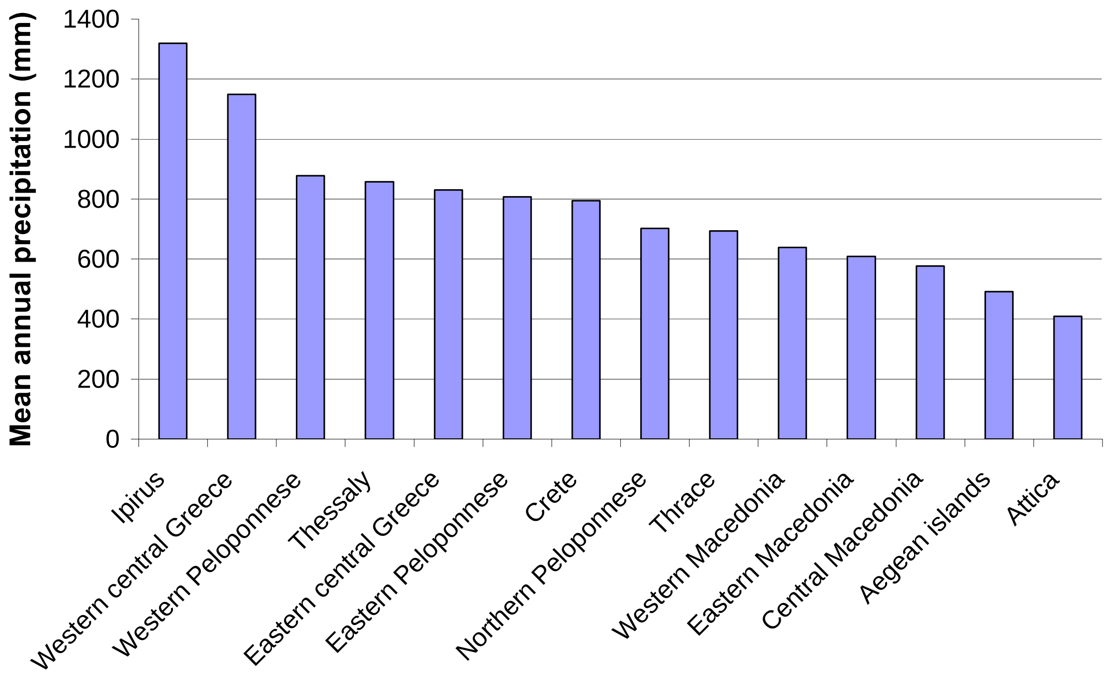

Figure 1. Mean annual precipitation in the Greek districts [9]

One interesting observation is that Attica, where Athens is located, has the lowest mean annual value. Nevertheless, in this area many infrastructures exist, in order to provide adequate water, meaning that not any serious problems have arisen. On the other hand, in the Aegean islands the precipitation is low as well, and more specifically the ones that belong to the Cyclades prefecture, the rainfall is even lower (around 370 mm/year). Therefore, it is concluded that the most severe water problem is located in these areas.

For the aforementioned reasons, this report will focus on the smaller Aegean Sea islands, belonging to the Cyclades prefecture, and most specifically in some isolated areas, where the lack of water is even more intense.

In order to have a general overview of the spatial mean annual precipitation, Figure 2 is of help, where the precipitation map of Greece is shown.

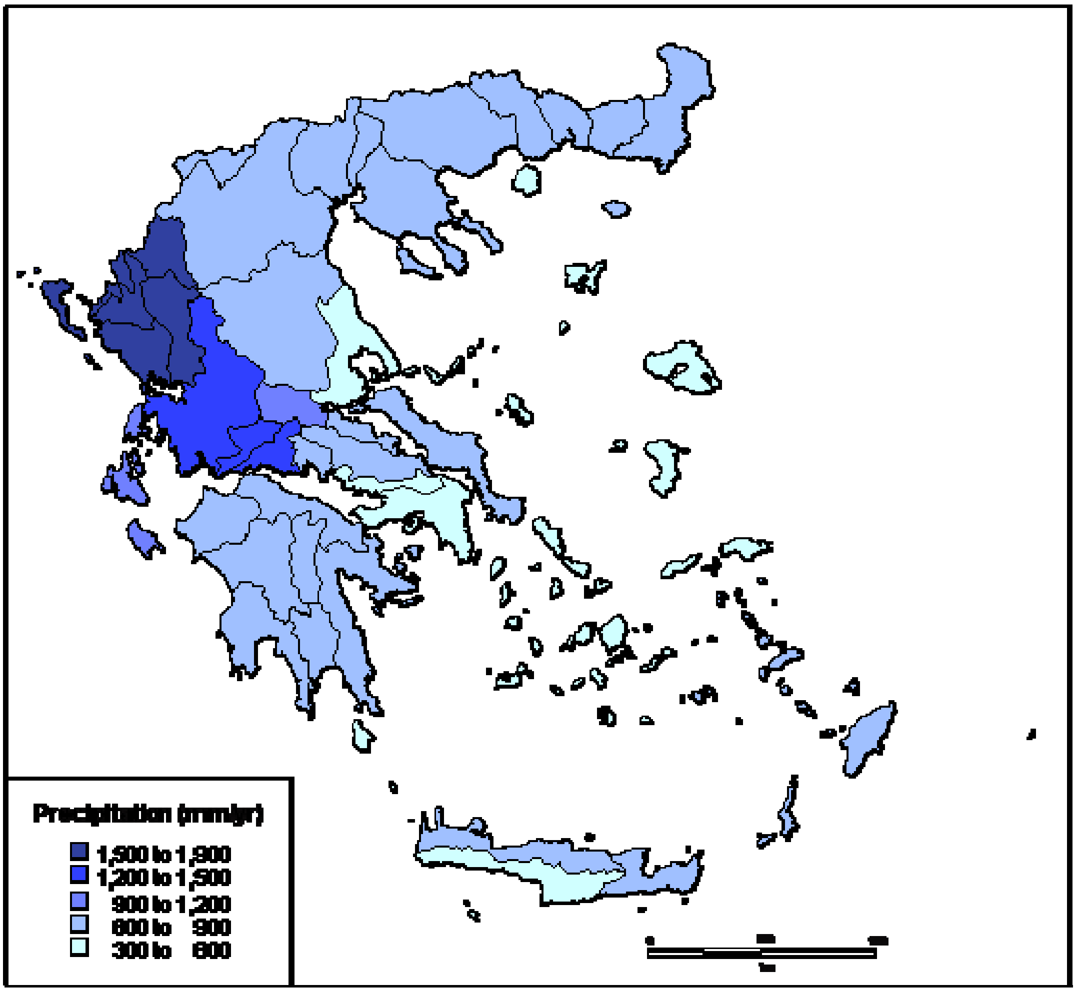

Figure 2. Precipitation map of Greece [2]

2.2 Small Aegean Sea islands

The most common ways of water provision in the small Aegean islands is either from wells or by transporting it from other areas. Transportation is not desirable, since not only the water cost can be extremely high (reported values of 7–8 €/m^3), but also it is not a sustainable way of covering the water needs, since lots of CO_2 emissions are produced from this process. Additionally, transported water is usually not drinkable.

A crucial aspect of the islands of concern is that the electrical grid in most of them cannot sustain large increase of electricity demand, since the capacity of the existing power lines is low. The existing ones are of medium or even low voltage. Desalination powered by conventional energy is not actually a sustainable solution, since in these small islands the electric grid is usually autonomous (not interconnected) and the specific energy production cost for the electric company is extremely high. This is because electricity in most of the cases is produced by small diesel engines, which in their majority are quite old. Therefore, the cost of fuel and its transportation is also included in the specific electric energy cost, which sometimes reaches the values of 0.20–0.40 €/kWh for the small and medium islands and can be up to 0.80 €/kWh for the very small islands.

One attractive solution would be to take advantage of the thermal wastes of the existing power industries, in order to desalinate water. But again the water distribution needs remain, since usually the power plants are located in isolated areas. In addition, during the summer months when the water requirements are high, the available waste heat would be enough only for a limited water production.

Also, large or medium–scale renewable energy applications are difficult to be installed in those places because of limitations of the electricity grid. This is made more intense, when having in mind that in smaller islands it is extremely difficult to find the required land, where the medium–scale solar or wind plants will be installed.

2.3 Selection of a specific case

There are quite a lot Aegean Sea islands, where a small–scale renewable energy desalination unit can be utilized. In most of them the mean wind speed (Figure 3) is high for many hours per year and also the solar irradiance is quite intense not only during the summer, but also during the winter period (Figure 4). This makes them ideal for those kind of applications, especially in small isolated communities, which are usually tourist destinations.

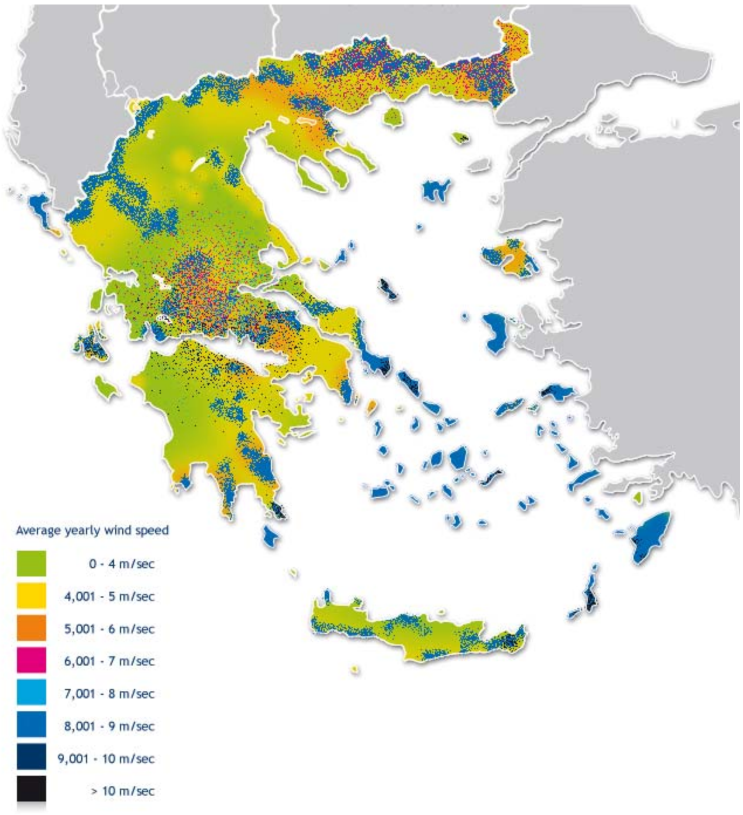

Figure 3. Average annual wind speed (m/s) map of Greece [14]

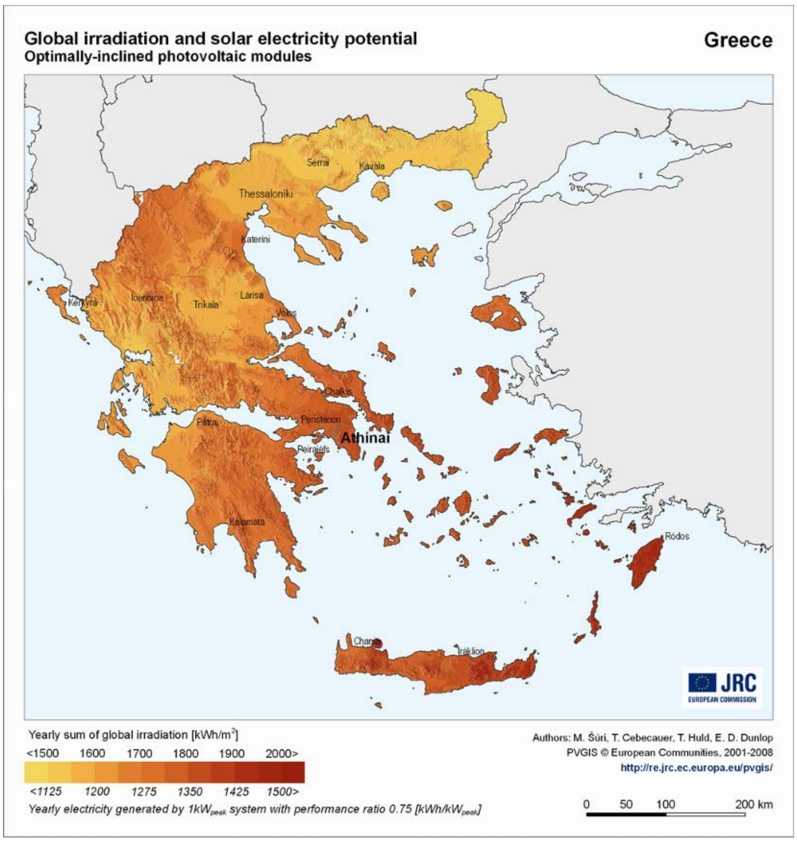

Figure 4. Solar intensity (kWh/m^2) map of Greece [15]

The survey of the candidate islands depends on some specific factors, which the most important ones are listed below:

- Availability of water resources from drilling installations or from basins (seasonal). In order for a RE-desalination application to be more welcomed in a specific area, it would be important this area to face intense water scarcity.
- Power flexibility of the existing power plant. The larger the power plant, the more cost-effective would be to integrate a desalination plant powered by electricity from conventional energy sources, which doesn't favour the RE-desalination concept.
- Population (seasonal). In case the temporal distribution of the population maximizes during the summer period, it would be desirable to promote desalination applications supplied by solar energy.
- Quality of the existing water (potable or not). In case the available water quantities are of low quality, desalination producing drinking water can be an important advantage.
- Distance from possible areas, from where fresh water can be transported. When the distance increases, the cost increases accordingly. An important factor also is the distance of an isolated area from the port of an island. In that case an extra cost of inland transportation is required, which is added to the total water transportation cost.
- Use of water (agricultural, potable, industrial etc.). In case the most important use of water requires non-drinkable water, then the use of desalination, which produces water of high quality, would be unnecessary.
- Specific electric energy production cost. This factor is an important one for the selection of an area, where RE-desalination can be applied, since the higher the production cost, the better is for the RE-desalination system.

Figure 5 is the map of this prefecture, depicting the numerous islands.

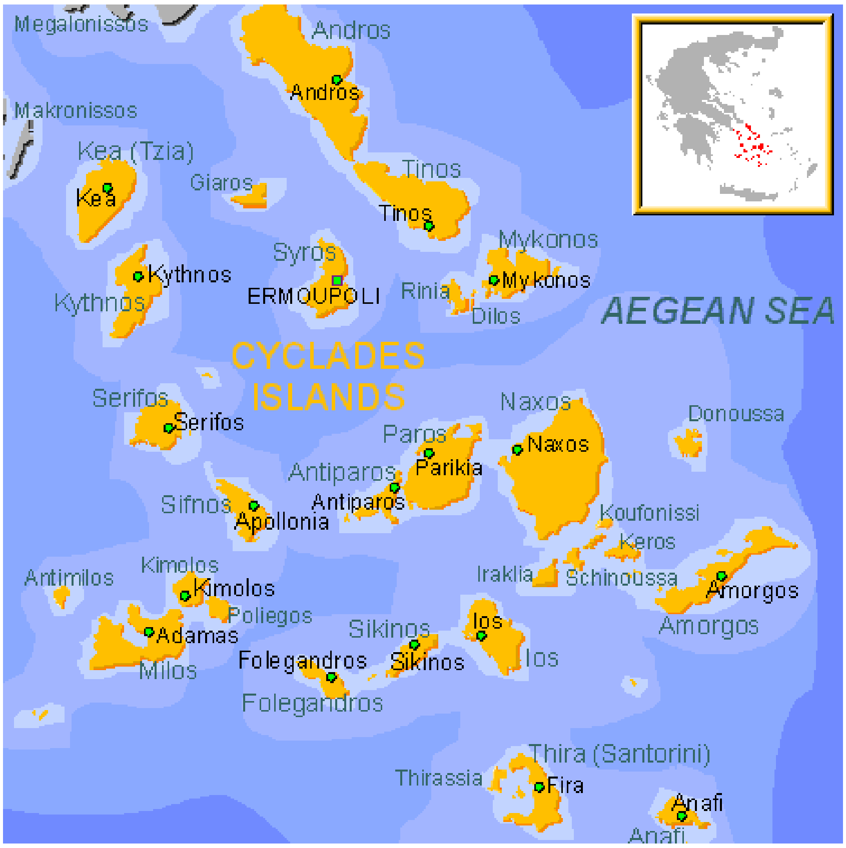

Figure 5. Map of Cyclades prefecture [16]

In the Cyclades prefecture the problem with the provision of water is critical, since the precipitation is quite low during the whole year. In Table 1 we can observe the precipitation for each island belonging to this prefecture [17].

Table 1. Surface and mean annual precipitation for the Cyclades islands

Cyclades island	Surface (km^2)	Precipitation (hm^3)	Precipitation (mm)
Amorgos	121	45.9	379.3
Anafi	38	14.4	378.9
Andros	380	144	378.9
Antiparos	35	13.3	380.0
Folegandros	32	12.1	378.1
Ios	108	40.9	378.7
Kea	131	49.6	378.6
Kimolos	36	13.6	377.8
Kythnos	99	37.5	378.8
Milos	151	57.2	378.8
Mykonos	85	32.2	378.8
Naxos	428	162.2	378.9
Paros	195	73.9	378.9
Serifos	73	27.7	379.4
Sifnos	73	27.7	379.4

Sikinos	51	15.5	303.9
Syros	84	31.8	378.6
Thira	76	28.8	378.9
Tinos	194	73.5	378.8

Because of the low precipitation values in most of these islands, there are many drilling installations for the provision of water. Nevertheless, sometimes the water transportation from other areas is also necessary, in order to cover the needs of the local population and the numerous tourists visiting these islands.

Figure 6 shows the specific electricity production cost for some representative islands of this prefecture. One important remark is that in the smaller islands the energy cost is quite high, in the order of 0.30 €/kWh, whereas in the larger ones having a higher population, the specific cost is decreased almost to 0.10 €/kWh.

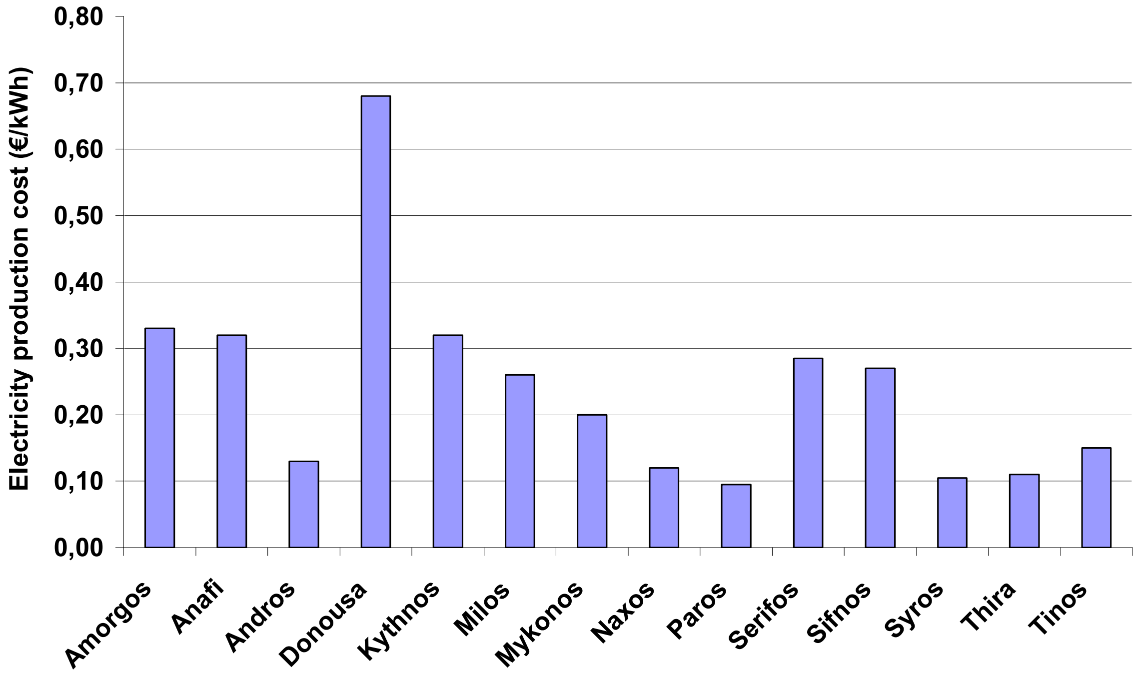

Figure 6. Specific electricity production cost for islands of the Cyclades prefecture [18,19]

The water use of the Aegean islands can be also seen in Figure 7. It becomes evident that the major sectors having almost the total water consumption are the irrigation and the domestic one.

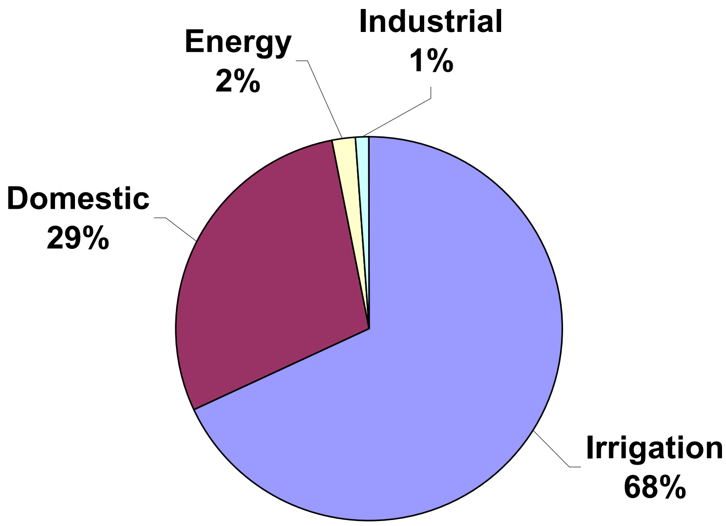

Figure 7. Water use per sector for the Aegean islands [9]

The survey for the selection of an appropriate are for the application of a RE-desalination system would focus at this stage only in the smaller islands, where the circumstances are ideal for the installation of such systems. In all the islands of the Cyclades prefecture the solar and wind potential is quite high (see Figures 3,4), and in most of them there are not adequate water quantities and extra measures are put forward, in order to cover the water demand (drilling, transportation etc.) mainly during the summer period due to the great number of visitors. Another important feature of these islands is that the electric production cost is quite high. Having the last parameter in mind, the first screening of candidate areas can occur, by further considering the ones, which have an increased electric production cost, above 0.30 €/kWh. The remaining islands are namely Amorgos, Anafi, Donousa, and Kythnos. These four islands have all an important potential for establishing RE-desalination applications. The one finally chosen to be further investigated is Kythnos as a representative example of a small island suitable for application of RE-desalination.

2.4 Current status in Kythnos Island – the Agios Dimitrios community

As was mentioned before, Kythnos island gathers all the required features and there is an urge for finding a sustainable solution for the water provision. It is situated in the west Cyclades prefecture and there is a huge issue, concerning the availability of water. There are plenty of drilling installations distributed in many places on the island, approximately 14, and there is a plan of constructing 3 or 4 additional. But most of them provide non–potable water of quite high salinity. During the summer months this problem becomes more intense, because of the numerous tourists visiting the island (mainly during July and August). Also, communities are usually far from the port of the island. Therefore, in the case that water is transported to the island, it results to an extra cost of inland transportation due to the cost of water distribution. Concerning the power plant of the island, it is not interconnected with the power system of the mainland or with another island. Therefore, in this autonomous energy system there are diesel engines for producing electric energy, having a quite high specific energy cost (in the order of 0.32 €/kWh). Figure 8 illustrates Kythnos island location in the map of Greece.

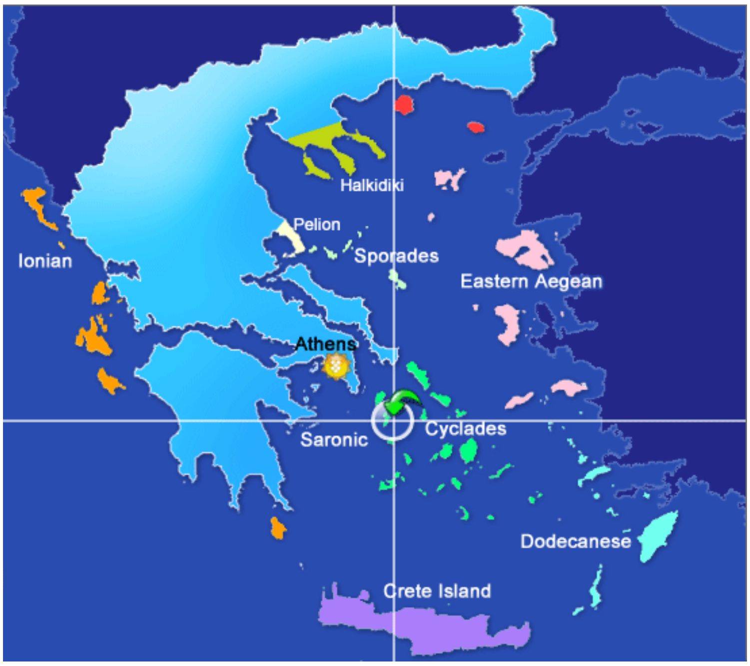

Figure 8. Map of Greece and Kythnos island [20]

A community located on Kythnos island is Agios Dimitrios. This community has been chosen for further investigation, since it is a small one and thus a small–scale system can be installed for the provision of water. It is a seaside community located on the south part of the island (see following Figure 9).

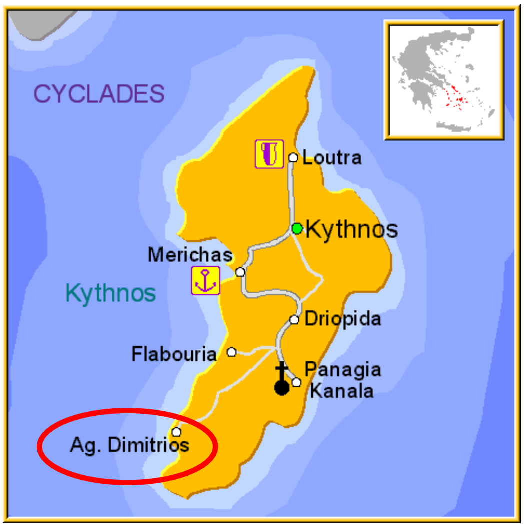

Figure 9. Map of Kythnos island showing the location of Agios Dimitrios [21]

There is one drilling installation at the parities of Agios Dimitrios. This installation provides water to the community, which is of high salinity (estimated values of around 1500 ppm) and non–potable. During September and October the water salinity has the yearly highest value, because the recent precipitation is negligible and also the reserved water quantities are minimum. Additionally, during this period it is possible that the water reservoir will empty, if the previous winter season is dry. This actually occurred in 2007, when transportation of water was initiated, because of the lack of water (distance from the port is 18 km), not only for this community, but also for other communities in Kythnos island.

In the area of Agios Dimitrios the drilling installation is equipped with a quite large reservoir tank with a capacity of about 500 m^3. The pumping of the water takes place many hours during the day, controlled by an adjustable control unit, in order to provide water depending on the seasonal demand. The pump operates more hours during the summer months, in order to fill the reservoir (mainly during the night), so that during the day the whole installation (pumping plus the tank) can cover the needs for water. Although the houses in this community are scattered, there is a quite extended water distribution network.

The community plans to construct a second drilling installation, in order to cover the future water needs, since the existing one is approaching its limits. Although the latter has been retrofitted with a new pump, having a much higher nominal capacity than the older one, still the issue is not so much related with the pumping and storing processes, but with the underground water availability. The addition of the second drilling installation is believed that it will resolve this specific issue, but with a considerably high installation cost, because it will include the construction of a second reservoir tank too. As this community is enlarged year by year, a similar problem might arise in the near future. Another feature of the water provided from the wells is that it is non–potable. And as the water resources are limited every year, the water's salinity will steadily increase.

It should be stressed at this point that the cost of the drilling installation, the pumping and the reservoir tank, together with the running costs, is covered by the Municipality of Kythnos. In the aforementioned costs, the cost of the water distribution network and its maintenance should be also added.

2.5 Water demand in Agios Dimitrios community

The community mainly serves as a tourist destination, since it is situated next to the sea. Therefore, during the winter there are very few inhabitants, whereas during the summer the population increases significantly. This fact can complicate the issue of water provision, because the seasonal variation is very extreme. In the following Figure 10, an indicative seasonal water demand for the community of Agios Dimitrios can be seen.

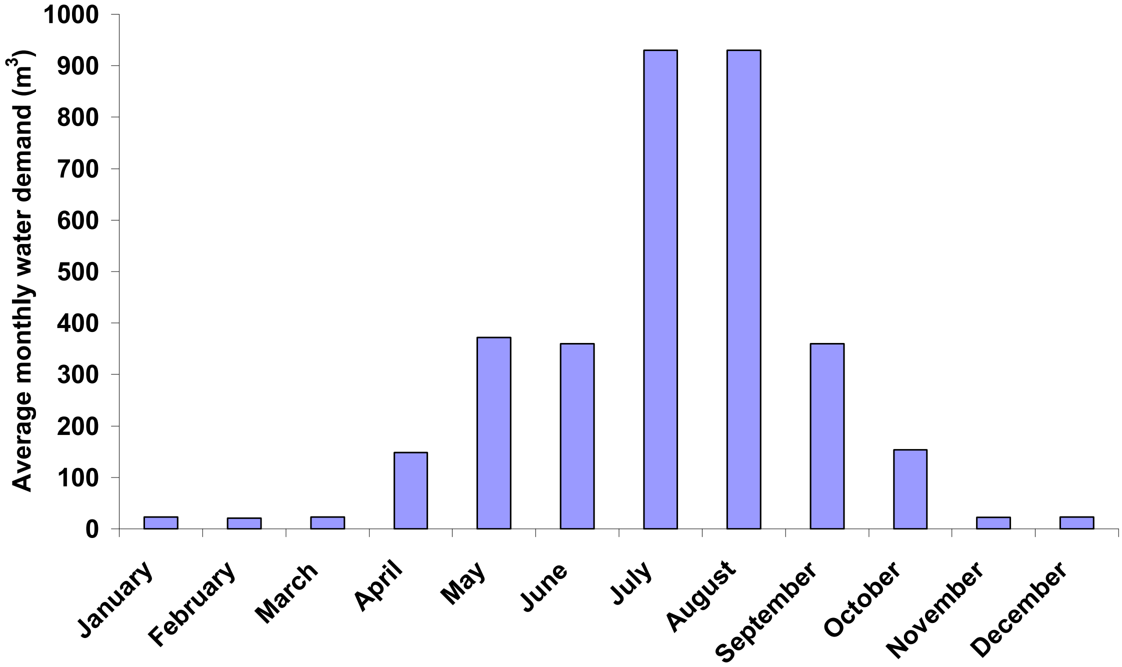

Figure 10. Monthly water demand in Agios Dimitrios community

During the winter period approximately 5 households are inhabited and the specific water demand is around 50 lt/day/person. Whereas, during July and August the households inhabited increase to around 100, having a specific water demand of 100 lt/day/person. For the rest of the summer period there are more or less 40 households inhabited having the same specific water demand (100 lt/day/person). The annual total water demand is calculated to be equal to 3367.2 m^3.

2.6 Cost of water provision

Concerning the operational cost of the drilling installation, the main cost is that of the operation of the pump. The depth of the water reservoir is 50 m below the sea level and the drilling installation is around 100 m above the sea level. The total pumping head is then 150 m. Once the water is pumped and stored in the reservoir, no pumping process is required, since water flows by gravity. Considering also the hydraulic losses and the pump's efficiency, the annual electric energy demand for the water pumping is calculated to be equal to 1911.6 kWh per year. As was mentioned before, the specific energy production cost for the Greek islands is quite high. In this island, the cost is approximately 0.30 €/kWh, while the electricity tariff for the consumers is only 0.10 €/kWh, and this cost has been considered in the current estimations. The total operational cost of drilling along with its maintenance and the possible replacement of some components (control system, pump's parts etc.) is then estimated to be around 600 € per year.

2.7 Scenarios for water supply

The existing drilling installation is close to its capacity limits, especially during the summer season. There are some plans for a second one to be constructed, in order to cover the future needs of this community. Although the operational cost of such an installation is quite low, the cost for constructing a new one can be extremely high. The latter depends on the depth of the well, the construction of a second reservoir tank, the capacity of the equipment etc. An approximation of the installation cost of the second drilling plant (drilling, piping, pumps, reservoir tank etc.) would be 40,000 €, considering that it is of the same capacity as the existing one. Both drilling plants (old and new one) together are also approximated to have the same operational and maintenance cost as the existing one (600 €/year).

Another possibility is to construct a small desalination plant next to the sea, powered by electric energy, which would provide the additional water. The two systems (existing drilling and desalination plant) can operate simultaneously, covering the total water needs. This scenario seems to be attractive, if the difficulties identified in such small electric grids related to the power production are ignored. The electric power plants usually operate close to their limits during the summer months, since the tourists visiting this island, especially in July and August, are many. The power demand then is increasing substantially and the production scheduling of the power company becomes much more complex. Considering also the high specific electric energy production cost, it would be extremely difficult for such a plant to acquire a license of installation and operation. Nevertheless, if such a conventional desalination plant is built, its cost is approximately 50,000 €, covering around the half water demand of the summer months. The operational cost of such plant (electric energy, maintenance, membranes' replacement, water pumping at a higher altitude (100 m) etc.) is almost 1,000 € per year, in order to provide with the half of the total water demand. In that case the operational cost of the existing drilling plant diminishes almost to half (300 €/year), so that the total annual cost of the existing drilling and the desalination unit together will be equal to 1,300 €.

The third scenario, which seems more promising, and introduces a renewable energy application, is to desalinate seawater with a conventional desalination unit, which is powered by wind or solar energy. Because of the seasonal distribution of the water demand, which becomes intense during the summer months, it is favorable to use solar energy, since then the solar radiation is high and the productivity increases accordingly. On the other hand, wind energy has a more uniform distribution between the winter and the summer months, being not so intense during July and August, where the peak water demand is seen. Therefore, the most attractive technology for such application, which has been also long–term tested and is commercially available, is the PV–RO one. Other technologies could be used as well, even a hybrid one (combined solar and wind energy with desalination), but for the needs of the current report, the PV – RO one is considered to be ideal. This specific plant can produce electric energy for desalinating water, and in the cases that there is an excess of power production, it can supply it to the electric grid. Therefore, its use has a hybrid purpose; to cover a certain quantity of the water demand and also to supply the grid with electric energy, having some economic benefit. Although its installation cost is quite higher than those of the other two scenarios discussed before, it can gain some benefit during its economic lifetime. From the economic point of view, it can be more beneficial than the other solutions, even without considering the CO_2 emissions avoidance cost. The installation cost of the desalination unit (RO unit) is again around 50,000 €, while the energy production unit cost (PV unit) is around 25,000 €, when 50 m^2 of conventional flat–plate PVs are installed with an approximate nominal power capacity of around 6 kW_p. In that case the PV–RO unit covers half of the water demand during the summer months, and the excess power production, which is around 4,500 kWh/year, is sold to the electric grid. The benefit from this, when introducing the specific cost of 0.50 €/kWh (equal to the cost of the feeding tariff for power production from PVs, which has been introduced in the greek islands), is almost 2,300 € per year. Of course an optimization can take place, in order to find the most suitable capacity of the PV unit from the economic point of view, but this is not the purpose of this report. Since the PV unit has low maintenance needs, the operational cost can be approximately equal to that of the desalination unit's, which is 700 € per year, since no electric energy from the grid is used to operate the RO unit. The operational cost of the drilling installation is again half, since it covers the half annual water demand, and is equal to 300 € per year. The total annual cost will be then 1,000 € for that scenario (existing drilling and PV–RO unit).

In the following Table 2 the cost of the three scenarios discussed is presented, in the case that the electricity price is 0.10 €/kWh. The NPV values are negative for all scenarios, since it is considered that **the produced water is supplied to the inhabitants of this community for free.**

Table 2. Scenarios under investigation

Scenarios	**Installation cost (€)**	**Annual cost (€)**	**Annual benefit (€)**	**Net Present Value* (€)**
Addition of a second drilling plant	40,000	600	–	-49,000
Construction of a conventional powered desalination plant (RO)	50,000	1,300	–	-69,340
Construction of a solar powered desalination plant (PV–RO)	75,000	1,000	2,300	-55,660

* The NPV is calculated considering an interest rate of 3% and the economic lifetime of the installation equal to 20 years for all three scenarios.

While the first scenario seems the best, having the higher NPV, it should be reminded that the water production from the RO unit is potable of high quality, introducing a significant advantage of that technology. This means that with a "smart" control system, depending on the weather conditions and the water demand, the community can be supplied with potable water for some hours per day, avoiding the mixing of potable water with the drilling water. This advantage is non–negligible, when taking also into consideration the relief of the conventional power production system, when electricity is supplied to the grid in case the PV-RO system is applied. Also the values of the NPV for the last two scenarios show that their economic viability is quite close, and having in mind the restrictions posed from small non-interconnected electricity grids, the third scenario gains an important advantage. Nevertheless, in the third scenario the increased installation cost is equated with the produced electric energy during the 20 years of operation. If a larger PV unit has been implemented (e.g. 100 or 150 m^2), then the benefit would become more pronounced after few years of operation (NPV value closer to zero or even positive, see Appendix for such comparison).

All the above figures correspond to the case, when the electricity price is 0.10 €/kWh, which is actually the one that the consumer pays to the power company (in this case the municipality of Kythnos), and not the real energy production cost. If the latter value is included in the previous calculations, the following Table 3 occurs, showing a more significant advantage of the PV–RO solution, in comparison to the conventional powered RO unit or even the drilling installation.

Table 3. Scenarios under investigation introducing the real electricity cost (0.32 €/kWh)

Scenarios	**Installation cost (€)**	**Annual cost (€)**	**Annual benefit (€)**	**Net Present Value* (€)**
Addition of a second drilling plant	40,000	1,000	–	-54,900
Construction of a conventional powered desalination plant (RO)	50,000	2,500	–	-87,200
Construction of a solar powered desalination plant (PV–RO)	75,000	1,200	2,300	-58,600

* The NPV is calculated considering an interest rate of 3% and the economic lifetime of the installation equal to 20 years for all three scenarios.

It becomes evident that the PV–RO can be competitive to the conventional powered RO unit, especially in areas where the real electricity production cost is high, as well as the solar energy availability, such as the ones met in most of the small greek islands. By observing

Table 3, it seems that the RE-desalination scenario is by far the most sustainable, considering also that the water production is drinkable, unlike the one provided by the drilling installations.

2.8 Implementation of the PV–RO system

The scenario discussed concerning the PV–RO technology can be easily adapted to the landscape of this community. First, the PV system is of small–scale (around 50 m^2) and can be installed next to the existing reservoir, where there is land available (see Figure A.1 of the Appendix). This is of importance, since the power system of this plant can be away from the community for security reasons and not to disturb the natural environment. Another reason is that in such communities the cost of land is very high (estimated to around 10,000 €/acre), so that it would make unbearable the planning and installation of such system, if the cost of land is incorporated in the total system's cost. The desalination unit, whose capacity is low and is of small size as well, can be placed next to the sea in the parities of the community in a rocky area. The distance from the PV unit to the desalination unit is 600–700 m approximately. Since the grid system in this community is of low–voltage, no special power cables are required, diminishing the complexity of both the control and the equipment, and the safety hazards. Electric power can be produced from the PV unit and transferred to the desalination unit, which is not far away.

In Figure 11 is illustrated the water production of each plant for the current scenario. It is clearly seen that the drilling unit operates mainly during July and August, in order to satisfy the increased water demand during this period. The most important thing is that during 9 months of the year (January to April, June and September to December) the water distributed in this community can be potable, bringing an important advantage of the system.

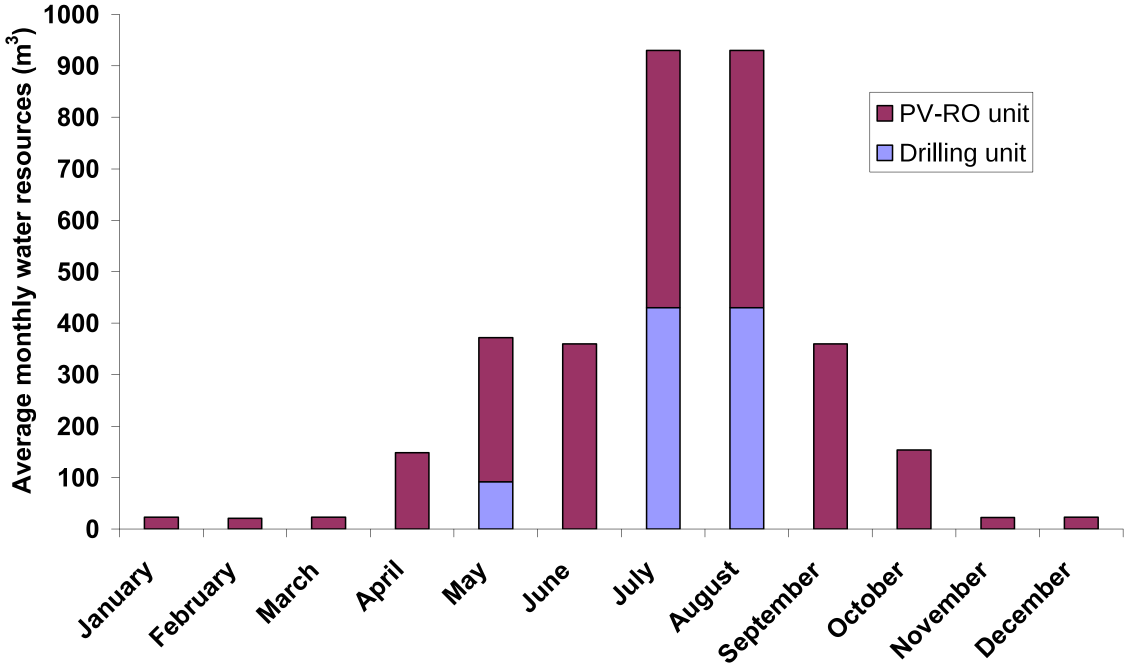

Figure 11. Water production from the PV–RO and drilling unit

While in Figure 12, the electric power sold to the grid for every month of the year can be seen.

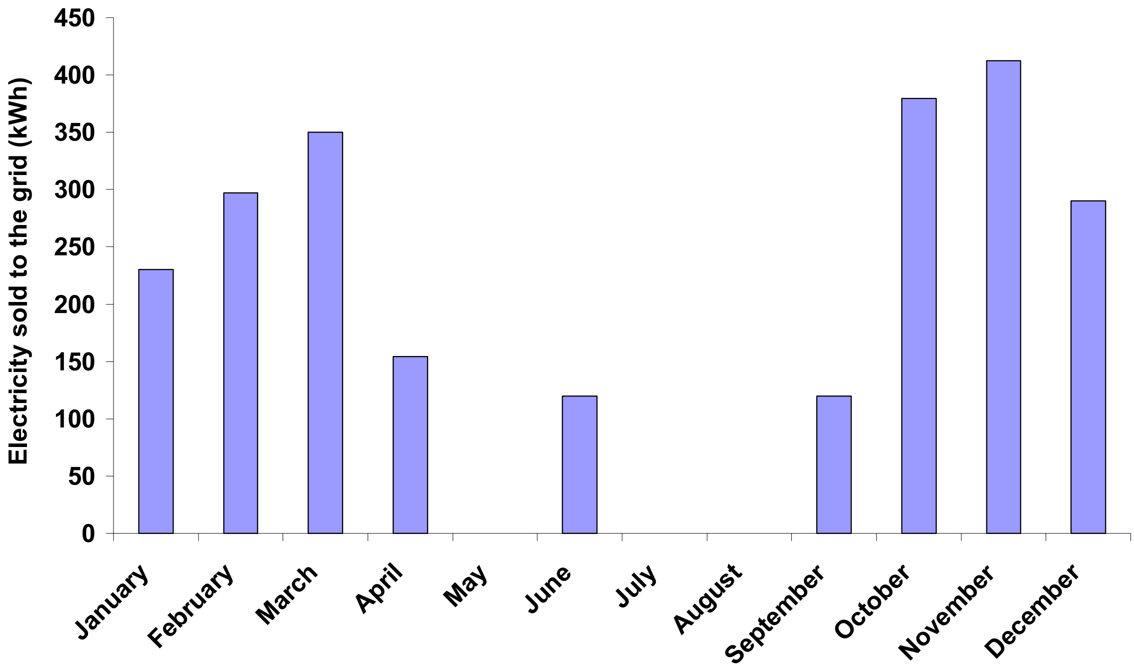

Figure 12. Excess electricity produced from the PV unit and sold to the grid

Although during the winter period the solar radiation is low, and the electricity production of the system is also kept low, the water produced can cover the extremely low water demand of this period for this community. For this reason there is adequate excess electricity production during the winter months.

2.9 Conclusions

It becomes evident that renewable energy applications are quite mature now days and can be utilized for seawater desalination not only in small communities, but possibly also in larger ones. The scenarios investigated of the current report revealed this, showing that from the economic point of view, a solar energy plant for RO desalination can provide fresh water at an equivalent water cost as the conventional units. If we take into consideration the real electricity production cost, then this solution gains a significant advantage, especially in areas where this cost is high.

This is extremely promising for the future, since although these technologies are quite new, their market–penetration should become large. Of course with a more detailed analysis and capacity optimisation of the PV unit, an optimum solution could be reached, but this is beyond the scope of the current report. Nevertheless, some preliminary effort is given in Appendix, showing that this topic can be further investigated and more sustainable systems to be identified.

Annex – I: View of the Agios Dimitrios community

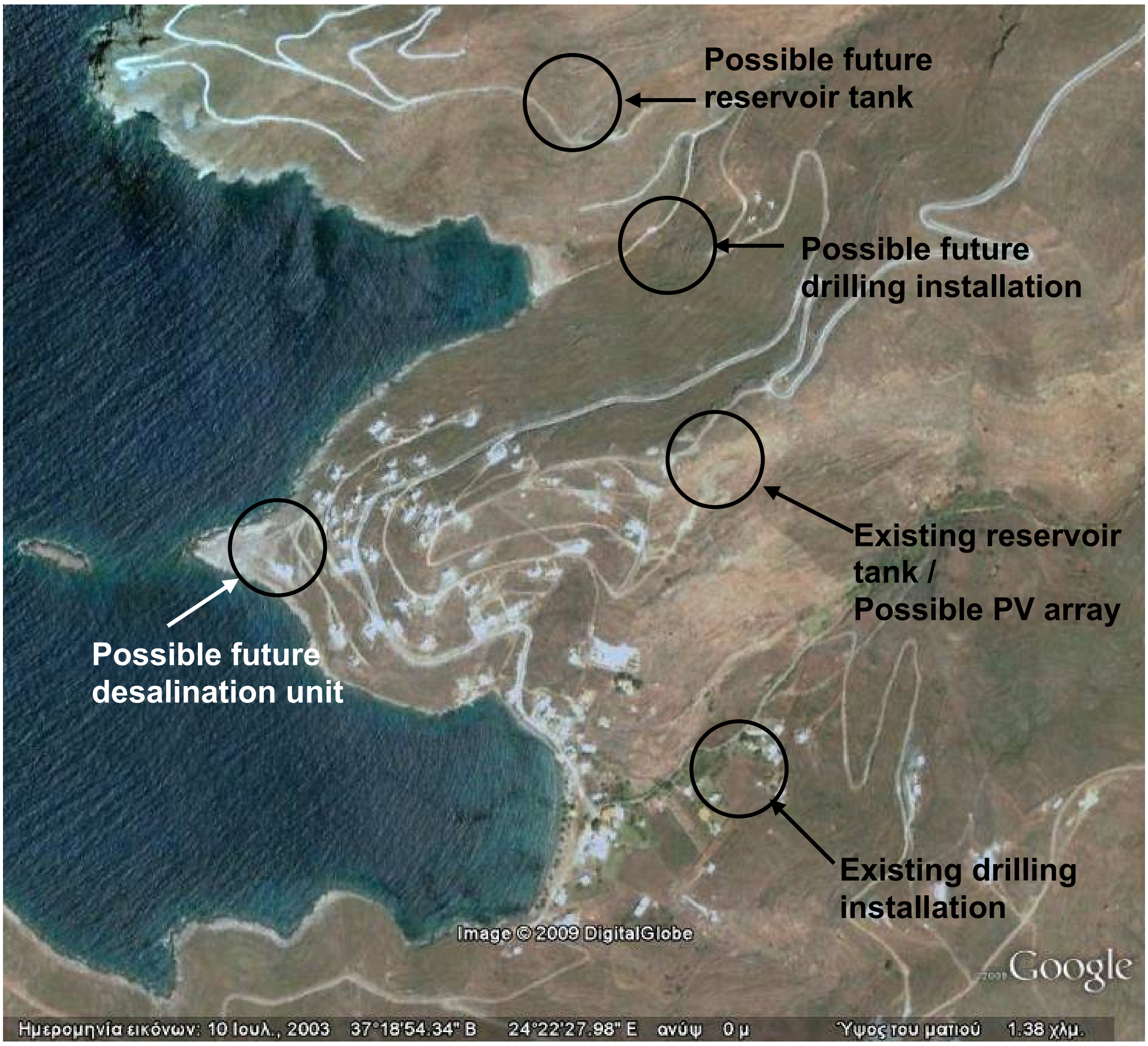

Figure A.1. View of the Agios Dimitrios community [22]

Annex – II: Parametric investigation of the PV collectors' area

The selection to use 50 m^2 of PVs for the scenario described is based on the covering of the half of the total water demand during the summer months by the PV–RO unit. This design has been chosen, in order not to overestimate the capacity of the PV unit. Of course this report should not be a technical one and in no case constitutes a complete techno-economic study. Nevertheless, in case the PV unit is larger than the one selected here, there will be more excess electric energy sold to the grid, thus making this scenario even more viable. The NPV value becomes even positive after a specific PV capacity, even without selling the produced water, rather just providing it for free to the Agios Dimitrios community. The variation of the NPV with the PV collectors can be seen in the following Figure.

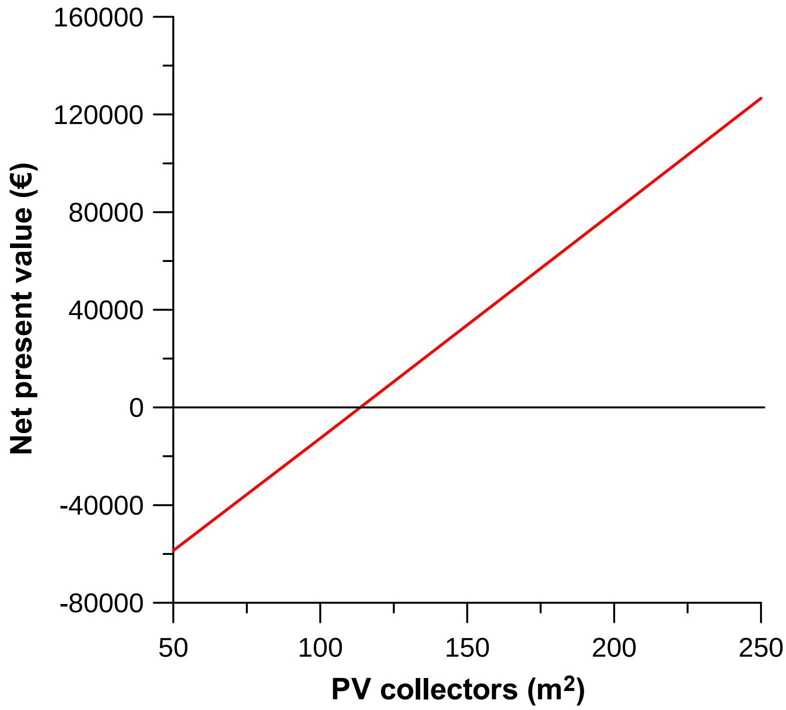

Figure A.2. NPV for the PV–RO unit for various PV collectors' area

Annex – III: List of literature

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3. Italy

3.1 Report summary

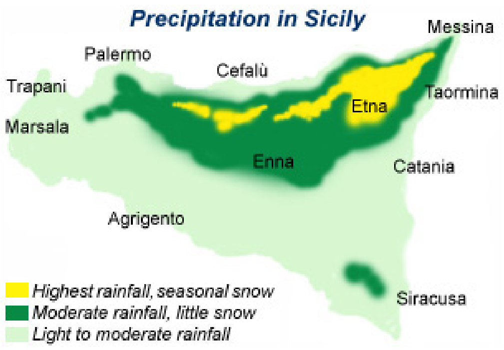
Sicily is one of the driest regions in Italy, but it is also one of the most abundant in terms of solar energy and seawater / brackish water availability.
In the present report an original case study has been analysed consisting in the production of desalinated water to be used for civil and industrial use within a large sewage treatment plant located at Acqua dei Corsari, within the district of Palermo.
The present approach consists in analaysis three different kind of energy sources coupled with two different desalination technologies:

- heat produced by biogas turbines, which is normally wasted through the cooling circuits, used to power a Multiple Effects Humidification (MEH) unit;
- heat produced by solar thermal collectors, installed in a free area available within the plant, used to power a Multiple Effects humidification unit;
- electrical energy produced by photovoltaic panels installed on the roof of one of the buildings of the plant, used to power a brackish Water Reverse Osmosis unit.

In all three cases a technical and feasibility analysis has been carried out along with a rough design of the systems.
Then the economical analysis was performed in order to assess the competitiveness of the proposed coupling schemes with conventional desalination processes and with the presently adopted unit for water softening of the plant in Acqua dei corsari, producing 5m^3/d of softenend water for industrial scopes.
Finally, some consideration have been done on the potential use of governmental subsides, considering the actual one and proposing novel incentives schemes, for promoting the use of RE desalination technologies making them competitive with the conventional ones.

3.2 Water demand in Sicily

Severe water shortage is a recurrent problem affecting the coast of Sicily, especially the southern and West/North-West, and a solution is urgently needed. Southern Sicily, in particular, is one of the zones with lowest rainfall in Italy, with values of only 400 mm of rain per year (similar to that of north African regions). Furthermore, traditional water sources are very modest: a few small springs and little surface water collected in dams and, generally inadequate to satisfy the entire need of the region. Taking into account the contemporaneous claims of large quantities of fresh water for agricultural, industrial and civil uses, it is then clear that water shortage represents a serious problem in Sicily.



The problem of water scarcity in Sicily has been made worse by significant leakages through the distribution networks, due to the ageing of the aqueducts, bad maintenance and abusive water plug. The population affected by water scarcity can be estimated in as much as 500,000 inhabitants, distributed along the southern and western coast in the districts of Caltanissetta, Agrigento, Palermo and Trapani [1].

An increase in the water supply could be realized, for example, by an improvement in the Sicilian dams's capacities, whose usefulness is, however, dramatically dependent on the rainfalls yearly variations. Therefore there is the necessity of a fresh water supply source, independent from rainfall and weather conditions. The sea, by means of desalination plants, is the only additional source able to ensure the required water supply independently from weather conditions. Hence, it is necessary to tackle and solve technical, economic and administrative problems related to the installation of desalination plants, in order to make available the resource to cover current deficit. With this aim a more coordinated action between the various institutes, national and regional governmental bodies involved with water resources management, should be undertaken.

In Sicily, during the 1970s, the CASMEZ (Cassa del Mezzogiorno, i.e. a State Fund for the South) developed a plan for the construction of a number of seawater desalination plants in order to reduce droughts problems and to ensure a viable alternative for water supply of the region. A brief overview of the desalination plant that presently operating in Sicily is presented in the following.

3.3 Sicily's desalination plants

The first sea water desalination plant has been installed in Sicily in 1974. In this plant, located in Gela (CL), 4 MSF unit were designed and constructed to produce about 50,000 m^3/d of fresh water for industrial and civil use. The MSF plant was built inside the original ANIC (ENI's group) petrochemical plant of Gela, by a joint venture of CASMEZ and ENI with the aim of realizing the biggest desalination plant in Europe at that time (four 13,000 m^3/d MSF units). More recently, two other large plants were installed in Trapani and Porto Empedocle and a RO plant was added in the Gela site.

The RO unit in Gela had hollow fibres (HF) modules (capacity of 15,000 m^3/d). The first years of operation were characterized by important difficulties due to the low quality of feed seawater and to the sensitivity of the HF membranes. Afterwards, the HF modules were substituted by the Spiral-Wound ones, which are guaranteeing better operational results.

In Trapani a MED-TVC plant is operating since 1995 and consists of 4 Multiple Effect Desalination units with 12 effects each, equipped with a thermal vapour compressor powered by steam at about 35 bar. The total capacity of the plant is 36000 m^3/d.

The Porto Empedocle's plant is the smallest between the three main Sicilian plants, with a total capacity of about 4800 m^3/d. Three MED (four effects) units with mechanical vapour compression (MVC) were started-up in 1992. In the last three years the MVC units have been replaces by a 10000 m^3/d SWRO plant.

However, the use of desalination in Sicily is not only limited to the large plants just mentioned, but it referes to several other smaller plants, which have been installed and are operating in the minor sicilian islands of Pantelleria (TP), Lampedusa (AG), Linosa (AG), Lipari (ME), and Ustica (PA). In all these cases, the use of desalination has solved the significant problem of water supply in small islands, which was traditionally faced by water transport in ship, with an estimated cost of 10-12 Euros for cubic meter, and a very poor quality of the shipped water. A map with the position of the desalination plants presently operating in Sicily is exhibited in figure 1.

In Pantelleria there are two desalination plants, the first one is an MVC (2 modules) with a total capacity of 3200 m^3/d and the other one is a EDR (2 modules) plus a RO (1 module) with a total capacity of 1100 m^3/d. In Lampedusa there are 2 MVC modules and 1 RO with a fresh water production of 950 m^3/d, in Linosa 2 MVC modules guarantee a production of 500 m^3/d, in Lipari have been installed 3 MVC modules with a total nominal capacity of 4800 m^3/d and in Ustica 2 MVC modules of 1000 m^3/d.

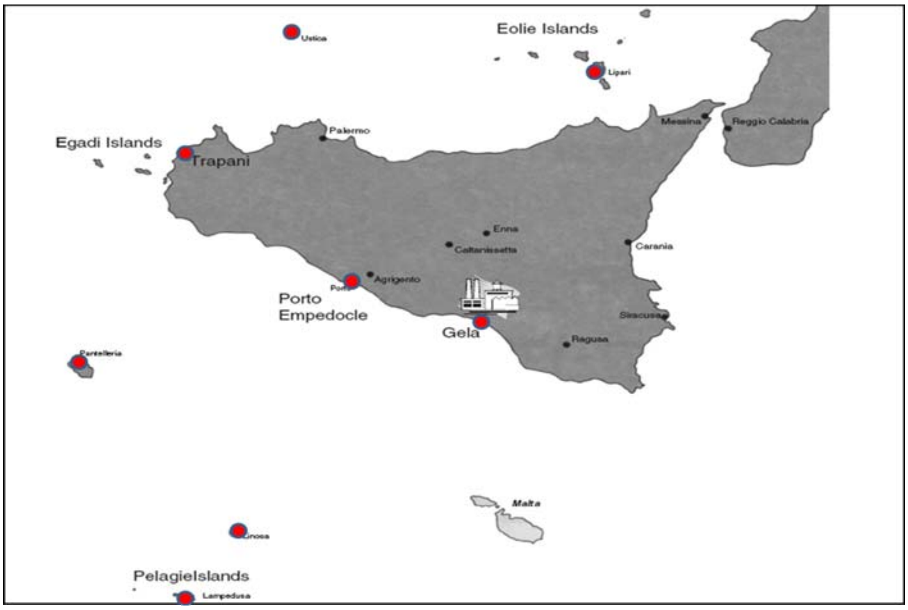


Figure 1. Location of desalination plants in Sicily and Sicilian minor islands

The total fresh water production of Sicilian desalination plants is around 44.3 Mm^3/year (about 5% of the regional demand), as it can be seen in the following table 1 [2].

Table 1. Desalination plants in Sicily [2]

Plant	Technology	Capacity (nominal)		Capacity (nominal)	Operation days	Capacity (actual)
		m³/d	l/s	m³/y	d	m³/y
Gela	MSF	13.200	153	4.818.000	330	4.356.000
	MSF	13.200	153	4.818.000	330	4.356.000
	MSF	13.200	153	4.818.000	330	4.356.000
	MSF	13.200	153	4.818.000	330	4.356.000
	MSF	14.400	167	5.256.000	330	4.752.000
	RO	16.848	195	6.149.520	330	5.559.840
Trapani	TVC-MED	8.700	100	3.175.500	330	2.871.000
	TVC-MED	8.700	100	3.175.500	330	2.871.000
	TVC-MED	8.700	100	3.175.500	330	2.871.000
	TVC-MED	8.700	100	3.175.500	330	2.871.000
Porto Empedocle	MVC	1.600	18	584.000	310	496.000
	MVC	1.600	18	584.000	310	496.000
	MVC	1.600	18	584.000	310	496.000
Lampedusa	MVC	450	5,2	164.250	300	135.000
	MVC	450	5,2	164.250	300	135.000
	MVC	50	0,6	18.250	300	15.000
Linosa	MVC	250	2,9	91.250	310	77.500
	MVC	250	2,9	91.250	310	77.500
Pantelleria "Maggiuluvedi"	EDR	450	5,2	164.250	300	135.000
	EDR	450	5,2	164.250	300	135.000
	RO	200	2,3	73.000	300	60.000
Pantelleria "Sataria"	MVC	1.600	18,5	58.400	310	496.000
	MVC	1.600	18,5	58.400	310	496.000
Lipari	MVC	1.600	18,5	58.400	310	496.000
	MVC	1.600	18,5	58.400	310	496.000
	MVC	1.600	18,5	58.400	310	496.000
Ustica	MVC	500	5,8	182.500	310	155.000
	MVC	500	5,8	182.500	310	155.000
Total		135.198	1.561,6	46.719.270		44.267.840

I

In order to overtake droughts problems in Sicily there is the necessity of increasing the total desalination capacity of the island by installing new plants distributed according to the water demand. Presently, the existing plants are powered by Conventional Energy Sources, but taking into account the targets of the Kyoto Protocol for what concern the reduction of CO_2 emissions, there is the necessity of an increase in the fresh water production, without any further increase in the amount of CO_2 that is released in the atmosphere.
With this aim, the coupling between non-conventional energy sources, such as RES (renewable energy sources), and desalination should be taken into account by the government in order to ensure at the same time social and environmental benefits. In this work several different scenarios have been analyzed for the production of fresh water for civil and industrial use at the sewage treatment plant of Acqua dei Corsari, located in

Palermo, through the use of different kind of Renewable Energy sources. In particular the three different scenarios include: 1) the use of waste heat from biogas turbines, 2) and/or solar thermal energy to power a Multiple Effect Humidification unit, 3) and the use of solar photovoltaic energy to power a Reverse Osmosis unit. In all cases the salty water source is a brackish water spring located close to the plant and presently just disposed within the sewage due to the high salinity, which makes it unusable for civil or industrial scopes.

3.4 The case study: Fresh water supply to a sewage treatment plant

3.4.1 The Acqua dei Corsari sewage treatment plant

The “Acqua dei Corsari” plant has been designed in order for a nominal capacity of 440000 “equivalent people”, although it has been designed to treat both civil sewage and wastewater from the landfills of the city of Palermo [source: www.amap.it].

The plant is constituted by three main lines:

- **Sewage line,** consisting in:

  screening, grit removal, fat and grease removal, pre-aeration, primary sedimentation, biological treatment (fixed-film system first, followed by activated sludge reactors), secondary sedimentation, disinfection, disposal through a sea outfall infrastructure;

- **Sludge line,** consisting in:

  thickening, anaerobic digestion (with biogas production), chemical treatment and mechanical dewatering, disposal;

- **Biogas line,** consisting in:

  biogas gathering from the sludge anaerobic digester, storing in a gasometer, energy production by two biogas turbines.

Figure 2. View of the “Acqua dei Corsari” plant

Presently, the company operating the plant is looking upon a revamping plan for the biogas turbine aiming at substituting the old biogas turbines with new and more efficient ones. Indeed, the present analysis has been also presented to the company as a proposal to include the construction of a desalination unit within the revamping plans.
In particular, biogas turbines provide thermal energy at two different temperatures: exhaust gas from combustion at about 400°C and cooling water at 85°C. The former stream is sent to a heat exchanger in which water is warmed up to be used as heating fluid for the anaerobic digesters. On the other side, according to the initial project of the plant, the cooling water dissipates the low-grade (85°C) heat through a heat exchanger first and then in evaporative towers.

3.4.2 Fresh water needs at the Acqua dei corsari plant

As in all industrial plants, fresh water needs at the Acqua dei corsari plant can be divided in water for civil use and water for industrial use. Focusing in particular on this latter case, the sewage treatment plant requires significant amounts of sweetened water for the cooling water loops of biogas turbines, blowers and compressors, which circulates in semi-closed loops, which present some losses mainly due to the evaporation in the cooling towers. Moreover, small quantities (less than 100 lt/d) of distilled water are also required for the laboratories. Thus, in the current analysis, the total desalinated water need has been estimated to be equal to 10 m^3/day.
It is worth noting that, currently, the Acqua dei Corsari plant is not working at its maximum capacity so the fresh water need is just 5 m^3/d, that is fulfilled thanks to a softening system with ionic exchange columns able to treat water from the city network and reduce its hardness to less than 5°f.
In order to analyse the potential alternatives to the use of the current softening system, it is necessary to estimate first the actual cost of softened water used in the Acqua dei Corsari plant. Such cost is due to the ionic exchange columns investment and replacement (10 years lifetime) costs, consumption of salt for resins regeneration and purchasing of water from the network.
Using a conventional method of analysis for desalination system, the cost has been calculated as:

$$Cost\ of\ water\ [€/m^3] = \frac{Columns\ cost}{365 * daily\ capacity * lifetime * \omega} + \frac{Cost\ of\ salt\ used\ weekly}{weekly\ capacity} + network\ water\ cost$$

where ω = 0.8 is a factor taking into account the possible inactivity periods during the installation lifetime.
The following table reports the average values used for the calculation.

Table 2. Costs for current water softening

Nominal capacity	5	m^3/d
Columns cost	5000	€
Columns lifetime	10	years

Salt cost	0.25	€/kg
Weekly salt consumption	100	Kg
Network water cost	1	€/m^3

From the above data, a cost of 2.05 €/m^3 has been calculated for the softened water presently used at the Acqua dei Corsari plant. It must be noted that it is a remarkable cost, which indicates the usefulness of evaluating some alternative processes to obtain soft fresh water.

3.4.3 Spring brackish water availability in the plant

A brackish water spring has been found in the proximity of the plant and since its flow rate is about 90 m^3/h it is reasonable to think about a way to use it. The available water is quite clear and currently it is just collected in the drainage system of the plant to be disposed within the treated sewage into the sea. However, water salinity, especially its hardness and chlorides content, is much higher than the required for industrial use, thus indicating the need for a desalination step prior to the use of such a water for the make-up of cooling water in the closed loop circuits.
The following table shows the physical-chemical properties of the brackish water from the spring.

Table 3. Physical-chemical properties of the brackish water

Ions content	*mg/L*
Cl^-	1061
NO_3^-	228.5
SO_4^{--}	537.7
Na^+	538
K^+	12.5
Mg^{++}	169
Ca^{++}	400
HCO_3^-	779.73
Total dissolved solids (TDS)	3726.43

Total hardness	169,5 °f
Conductivity	4200 μS/cm
pH	8,2
Temperature	17 °C

A Langelier Saturation Index equal to 2.2 has been calculated indicating a very hard water (LSI>0). Moreover, the spring water cannot be sent to the current softening system because it is too hard, so there is need to think about an alternative way to exploit this natural source.

3.4.4 Waste heat and “solar surface” availability

As already mentioned before, a large amount of waste heat from biogas turbines is available within the plant. In particular cooling water circulates in the cooling circuit of turbines being available at a temperature between 80 and 90°C. Considering the need for soft (desalinated) water and the brackish water availability from the spring, it is reasonable to think about using part of the waste heat for powering a thermal desalination process.

Another alternative energy source is the solar energy and since the plant is located in the district of Palermo, which is characterised by high level of solar radiation, a further possibility is to exploit the available "solar surface", i.e. the surface of roofs and free land around the plant, in order to install solar collectors or photovoltaic panels to produce energy from the sun.

Among these choices it is necessary a distinction between thermal energy sources (waste heat and solar collectors) and electrical energy sources (photovoltaic panels) relevant to the choice of the desalination technology to be adopted.

Two different desalination technologies have been considered and three different scenarios have been analysed as alternative systems able to supply the sewage treatment plant with 10 m^3 of distilled water per day:

- MEH (Multiple Effect Humidification) unit powered by waste heat
- MEH (Multiple Effect Humidification) unit coupled with solar collectors
- RO (Reverse Osmosis) system powered by photovoltaic panels

In the following paragraphs both technical and economical analysis of all three scenarios will be presented.

3.5 MEH + WASTE HEAT scenario

The first option analysed to supply the plant with fresh water is a MEH unit coupled with the waste heat from biogas turbines. The Multi-Effect Humidification (SAL-MEH) technology is an innovative system developed by TiNOX-Mage Watermanagement based on water evaporation and subsequent condensation of the generated steam through a humidification/de-humidification process. Seawater (or brackish water) is heated by waste heat (or by the sun, as shown in figure 3), passing through a corrosion resistant heat exchanger. Hen, it enters an evaporation chamber where evaporation occurs and humidity content of the air stream increases. The saturated air moves to a condenser chamber by natural convection, so without any energy demand. Condensation takes place on a cold surface by transferring the condensation heat to the cold feed, which is therefore pre-heated, thus improving the overall thermal performance of the process [3].

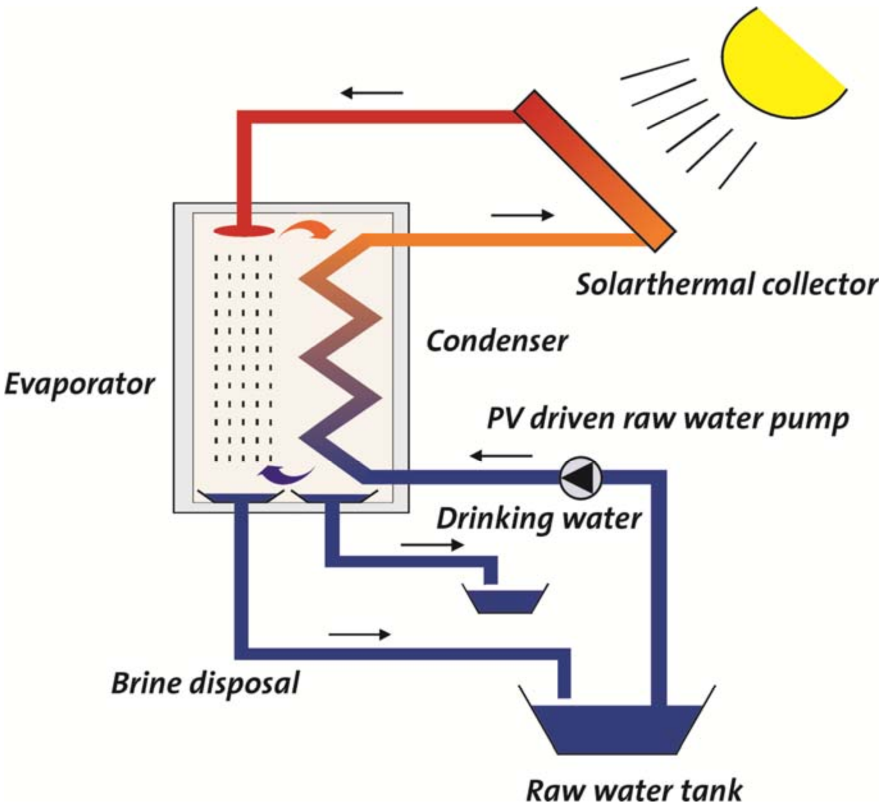
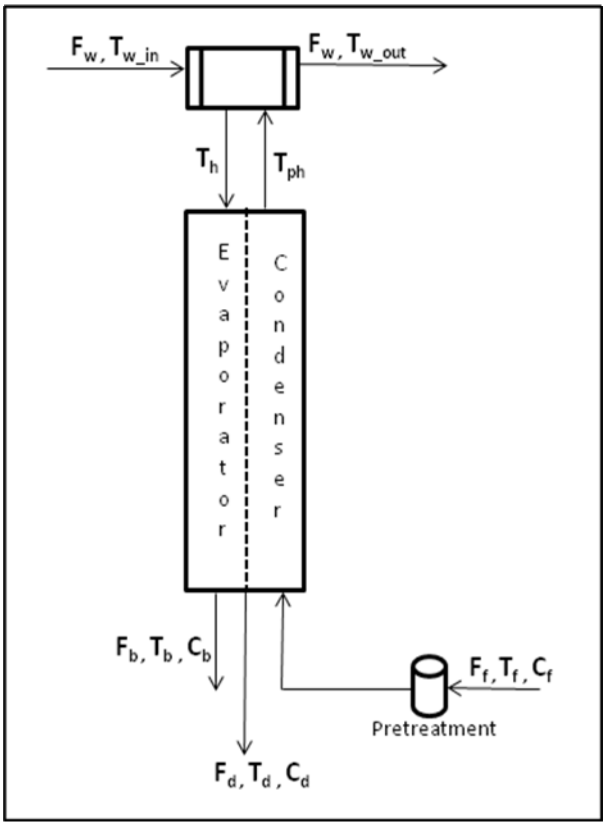


Figure 3. SAL-MEH system [www.mage-watermanagement.de].

One of the advantages of this desalination unit is the possibility to use low temperature heat for feed heating, which can be, as in the present case, waste heat available as cooling water at a temperature between 80 and 90°C. Although the process is insensitive to high salt contents and no significant pre-treatment of raw water is needed, in the present analysis the plant has been designed with a feed pre-filter and a system for the addition of anti scaling agent is also provided in order to protect the heat exchanger and the evaporator from the highly scaling potential of the brackish water to be treated.

In the design of the unit, which is necessary for the technical and economical analysis, some parameters have been assumed to be constants, e.g. the temperature difference between the evaporator and the condenser $\Delta T_{hot\text{-}cold}$ = 8 K (based on literature data), the salt concentration in the distillate stream is supposed zero and the inlet temperature in the evaporator is assumed to be 83°C (assuming a waste heat source at 85°C).
Moreover, also the temperature difference between inlet and outlet feed water in the heat exchanger is 8 K. In order to determine all the unknown values of this system it is necessary to write 7 equations, as reported below.
A spring water flow rate equal to 100 m^3/day has been estimated to obtain 10 m^3/day of distillate water. It is remarkable that during condensation, the main part of the energy used for evaporation is regained and used for preheating the feed.



$$
\begin{cases}
F_f = F_b + F_d \\
F_d \cdot \lambda = F_f \cdot c_p \cdot (T_{ph} - T_f) \\
F_f \cdot c_p \cdot (T_h - T_{ph}) = F_w \cdot c_p \cdot (T_{w\_in} - T_{w\_out}) \\
T_b = T_f + \Delta T_{hot\text{-}cold} \\
T_{ph} = T_h - \Delta T_{hot\text{-}cold} \\
T_d = T_b \\
C_b = \dfrac{F_f \cdot C_f + F_d \cdot C_d}{F_b}
\end{cases}
$$

Figure 4. MEH scheme adopted for the design of the unit

In the equations, λ is the latent heat of evaporation/condensation (assumed to be 2350 KJ/Kg) and c_p is the specific heat of water (assumed to be 4.19 KJ/KgK).
In the following table 4 the specifications of the designed MEH unit are reported.

Table 4. Summarising data of the MEH+waste heat scenario

Variable	Description	Value	Unit
F_f	Brackish water (feed) flow rate	1.45	Kg/s
T_f	Feed temperature	30	°C
C_f	Feed concentration	3.73	g/l

$\Delta T_{hot\text{-}cold}$	Temperature difference evap/cond	8	K
T_{ph}	Preheated feed temperature	74	°C
T_h	Hot feed temperature	82	°C
F_w	Waste heat fluid (water) flow rate	1.5	Kg/s
T_{w_in}	Waste heat fluid (water) inlet temperature	85	°C
F_d	Distillate flow rate	0.116	Kg/s
C_d	Distillate concentration	0	mg/l
T_d	Distillate temperature	32	°C
Q_{waste}	Thermal duty (waste heat)	48.6	KW

3.5.1 Sustainability analysis

The sustainability of the process in this case is mainly based on the optimum coupling of the MEH unit with the available energy and water sources of the Acqua dei Corsari plant. Since the MEH unit is able to work with a low grade heat source, the possibility of using waste heat for the production of fresh water represents a perfect match between the reduction of high grade energy consumption and the reduction of waste heat disposal to into the environment, both affecting positively the environmental sustainability of the process. The economic sustainability is also positively affected by the use of waste heat, which is actually a zero-cost energy source. Moreover the use of a natural brackish water spring for obtaining distillate water instead of using ionic exchange columns contributes to the reduction (although for a very small quantity) of fresh water subtracted from the network for civil uses.

Looking again to the environmental benefits, a way to estimate the advantage of coupling a MEH unit with the waste heat source is the calculation of the CO_2 amount produced by the same process powered by conventional energy sources (fossil fuels). Almost 1200 thermal KWh/day are required as thermal duty in the heat exchanger in order to have hot feed water at the optimal temperature for the evaporator. The use of conventional fuels to obtain the same amount of energy would bring a daily emission in the atmosphere equal to 270 Kg of CO_2 [www.enel.it]. Finally, it is also interesting to estimate how many trees would be necessary in order to absorb this amount of carbon dioxide. Since a tree is able to absorb in the average 7.7 kg of CO_2 in a year [www.novambiente.it], the same process powered by fossil fuel would require about 12800 trees in order to absorb the whole amount of CO_2 produced by this process.

3.6 MEH & Solar Thermal Collectors scenario

The second scenario analysed is the coupling between the MEH desalination unit and solar thermal collectors for providing the thermal energy required by the MEH unit.
Sicily has got a great potential for solar power exploitation due to its favourable climatic conditions and the use of renewable energy sources gives environmental, economic and social benefits. On the other side, desalination processes usually require large amounts of energy, and the continuous use of fossil fuels contributes to the generation of green house gases in addition to various pollution products. Thus, the use of solar energy alleviates a considerable part of air pollution problems.
The main disadvantage of RES is the intermittent and variable intensity, while the desalination processes are designed for continuous steady state operation. In order to overtake coupling problems some energy storage systems have been developed allowing 24 hours a day operation. Usually for solar thermal collectors this is possible by using a heat storage tank that allows the plant to work during night and on overcast days. Heat is partially transferred into an insulated hot liquid reservoir during the day, and used for powering the desalination unit at night.
Given the above considerations, it must be noted that such a system can be classified as a stand-alone system and therefore benefits of all the advantages of stand-alone devices (no need for auxiliary units, possibility of installation almost everywhere and, therefore, suitability for remote sites) but it also suffers for the higher costs due to the need of over-sizing the solar collectors, the desalination units and of buffering systems to store the energy to be used in no-sun conditions.
For what concern the coupling between MEH and solar collectors, the operating temperature of the MEH-system, that should be around 80 °C indicates as a good choice the use of ETC (evacuated tube collectors) as it can be seen in the figure 5. ETC is a well known technology and the main disadvantage of this technology is the initial capital costs that is high if compared with flat plate collectors. Following there is a brief description regarding the design of the solar collector system.

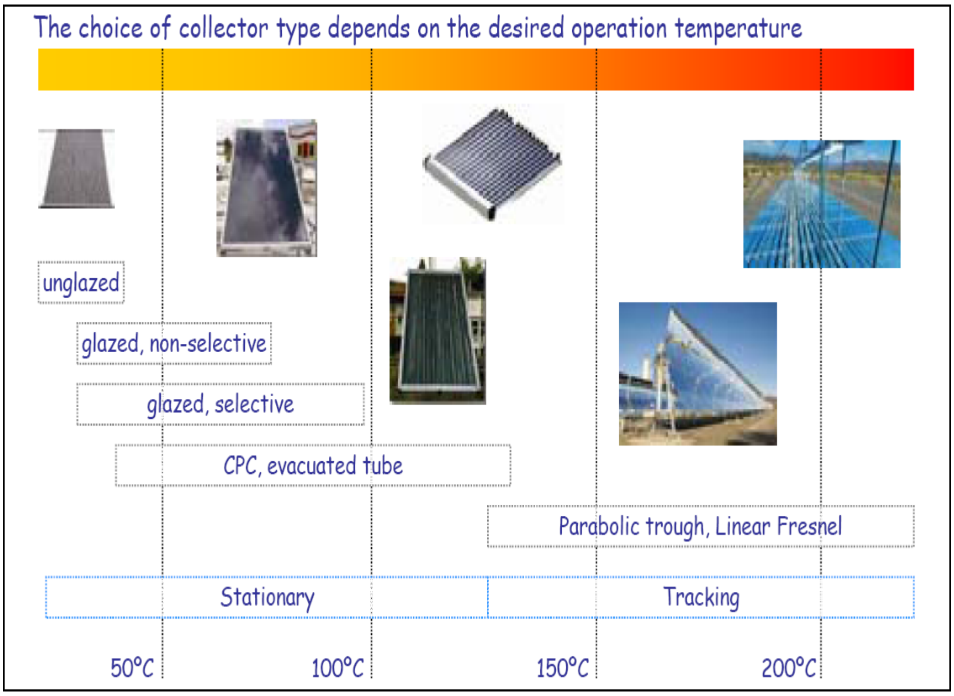


Figure 5. Optimal operating temperature range for different kinds of collectors

3.6.1 Design of ETC+ Heat Storage Tank

The use of a heat storage tank is justified by the necessity of continuous operation for best performance at the Acqua dei Corsari's plant. As it concerns the design of solar collectors field, it significantly depends on the mean radiation over the optimal inclined surface. In our case, the calculation has been done by using the radiation on a surface inclined of 30° and facing south. As it can be seen in figure 5, the radiation over this surface, in the selected site within the district of Palermo, is variable during the year.

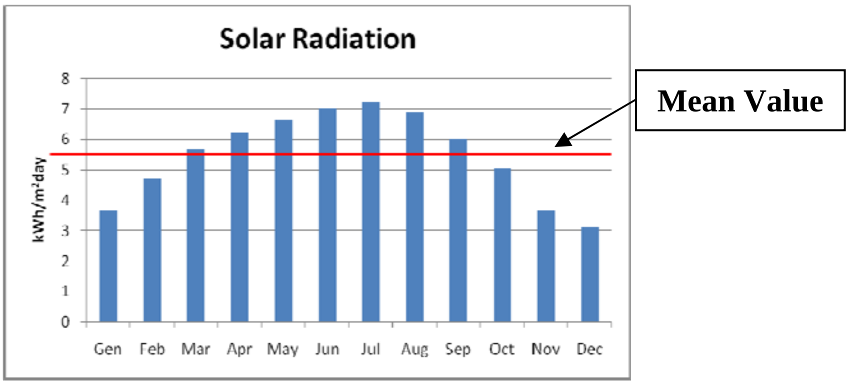


Figure 6. Yearly variation of solar radiation in the district of Palermo (monthly average solar radiation expressed as energy per square meter per day)

The simplest approach has been adopted for the design of the solar thermal collector field, which consists in calculating the collectors' surface by the following equation:

$$A_{Collector} = \frac{E.d.}{\eta_{total} I_{\beta}}$$

with

$$\eta_{total} = \eta_{overcast}\eta_{collectors}\eta_{system}$$

where:
E.d.= energy for the desalination process [kWh/day];
I_{β}= solar radiation over a β° inclined surface [kWh/m^2 d];
$\eta_{collectors}$= efficiency of the collectors (assumed 65%);
$\eta_{overcast}$= efficiency due to the lower irradiance in cloudy days (assumed 80%).
η_{system}= efficiency due to heat losses of the thermal storage system (assumed 80%)

Therefore, the design of the solar thermal collectors may be done by using the yearly mean radiation (red line), or the minimum average radiation (the one in December) or the maximum mean radiation (the one in July). In the first two cases, the surplus of energy during some periods of the year will require an increase of the capacity of the desalination plant with the intention of use all the heat obtained.
In order to evaluate the main technical differences between the three options a quick analysis has been performed, whose results have been summarised in the following figure 7 reporting the average production and the values of nominal capacity (N.C.) of the MEH unit, which allows the exploitation of the entire amount of heat collected.

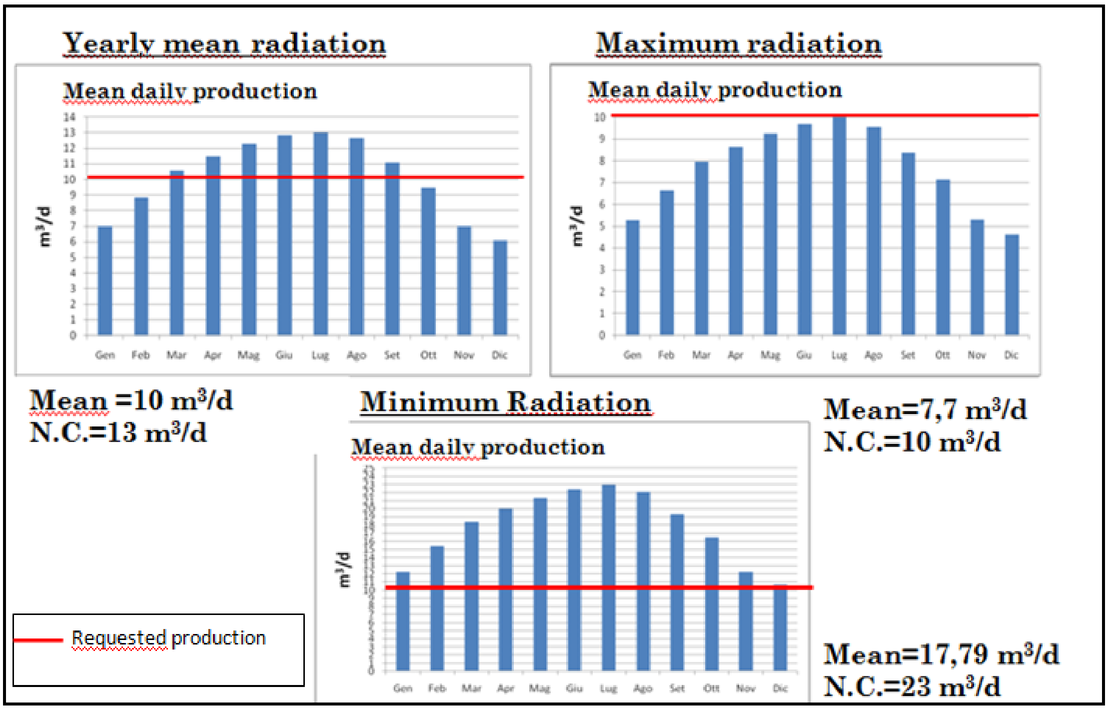


Figure 7. Average and nominal capacity of the MEH desalination plant related to the design of solar filed with yearly mean, maximum or minimum solar radiation value.

With regards to the water needs of the plant the best choice could be the use of the yearly average solar radiation in order to ensure the desired production in the whole year, but guaranteeing a higher production during summer months (when water demand is higher) and lower production in winter months (when water demand is lower). In this way, it is possible to calculate the requested volume for the storage tank to allow 24h day operation. The design of the storage tank can be done, assuming 8 hours of solar radiation in a day, by the following equation:

$$Volume\ tank = \frac{\dfrac{\left(E.d.[kWh]\ \frac{16}{24}\right) * 3600}{\eta_{buffer}}}{\rho * c_p * \Delta T_{tank}}$$

In which:
η_{buffer}= thermal storage efficiency (assumed 85%)
ρ=density of the fluid [kg/m^3]
ΔT_{tank}= temperature difference available in the storage tank (assumed 20°C)
C_p= specific heat of the fluid [kJ/kg K]

The characteristics of the various equipments have been collected in the following table 5.

Table 5. Summary of technical specs of the main parts of the plant

Nominal Capacity 13 m^3/day	
Evaporative SAL-MEH surfaces	1040 m^2
Solar Thermal Collectors Surface	456 m^2
Plate heat exchanger surface (@ 800 W/m²K)	20 m^2
Nominal feed flow rate	1.7 kg/s
Heat Storage Volume	50 m^3
Effective annual production	3650 m^3

3.6.2 Sustainability analysis

The advantage of MEH desalination process coupled with solar thermal collectors is mainly related to the social and environmental benefits that a desalination process powered by a renewable energy source could provide.
In fact, the use of desalination processes powered by RES assures a reduction in the environmental impact related to the smaller amount of CO_2 released in the atmosphere.

Table 6. Energy request and CO_2 “saving” using RES to power the desalination unit

N.C. 13 m^3	
Thermal Energy requested	1515 kWh_{th}/day
Amount of CO_2	386 kg/day

Bearing in mind that a tree is able to absorb about 7.7 kg of CO_2 in a year [www.novambiente.it], the same process powered by fossil fuel would require about 18,300 trees in order to absorb the whole amount of CO_2 produced in a year. Therefore, the use of RES for powering a desalination process instead of CES allows a significant reduction in the environmental impact. Furthermore there is the social benefit due to the production of fresh water, which is used for industrial scope thus reducing the actual consumption of drinking water from the municipal water network.

3.7 PV-RO scenario

The third scenario considers a Reverse Osmosis process (RO) powered by photovoltaic panels (PV). The reverse osmosis process, in fact, can be used for the desalination of seawater or brackish water through a semi-permeable membrane. If salted water is fed to one side of the membrane with a pressure higher than its osmotic pressure, almost pure water will be collected on the other side of the membrane.
Typically the osmotic pressure of seawater is in the range between 2300-2600 kPa, but can reach up to 3500 kPa in some location [4]. The osmotic pressure of a brackish water, which is the case relevant to our study, is much smaller than the previous ones, and it can be between 100 and 300 *kPa* for a range of concentration between 2000 and 5000 *mg/L* [5], thus indicating that a much smaller pressure has to be used to pressurise the feed in order to obtain the required separation. It is worth mentioning that the relevant energy consumption will be proportionally lower than the case of Sea Water Reverse Osmosis (SWRO), where operating pressures arrive up to 60-70 bars and the final cost of permeate water can be from 2 to 5 times higher than the case of brackish water with such low salinity values.
A very important parameter in the reverse osmosis process is the recovery ratio, defined as the ratio between the permeate flow rate and the feed flow rate. Recovery ratio typically ranges between 35% and 60%, while for brackish water RO it can be up to 90%, depending on the initial feed salinity and on its scaling potential. In this study a relatively low recovery ratio of 15% has been chosen because of the large availability of feed brackish water, the ease of brine disposal (discharged within the sewage treatment plant itself), and also due to the feed hardness, which could cause scaling phenomena on the membrane.
Two different approaches can be used with PV-RO systems: grid-connected and stand-alone plants. In the first case, the energy required by the RO unit is provided by the PV panels during sun peak hours and by the electric grid during off-peak hours. Thus, the design of such systems provides a 24hrs/day operating RO unit coupled with a PV plant producing an yearly amount of energy equal to the energy consumed by the RO system in the year.
On the other side, for stand-alone systems, the plant can be designed for a yearly average radiation, with a RO unit oversized in order to use all the daily energy produced by PV panels in summer days and a battery bank able to store the energy which guarantees the continuous operation of the plant during 10, 12 or even 24 hrs/day. Of course this second approach offers the same advantages and disadvantages mentioned for the case of the solar-MEH system, thus being suitable for remote installations, but suffering for much higher costs of the produced water, as it will be shown in the next paragraphs.

3.7.1 Design of the RO unit

The membrane module is certainly the most important component in a reverse osmosis process. Among the current membrane modules available for desalination of brackish water, the ESPA2+ model has been chosen. The main characteristic of this membrane module are listed in the following table 7 [6].

Table 7. Illustrative specifications of commercial membrane module for brackish water Reverse Osmosis (ESPA2+)

Element model	ESPA2+
Membrane area, m^2	40.0
Permeate flow, m^3/day	41.6
Salt rejection, %	99.6
Salt passage, %	0.40
Test flux rate, l/m^2-h	43.5
Permeability, l/m^2-h-bar	5.0
Relative salt transport: salt passage x flux rate	0.261

The membrane surface required for the separation has been calculated by the following equation:

$$A = \frac{F_D}{N_A} = \frac{F_D}{NDP \times k}$$

where F_D is the permeate flow rate (10 m^3/d), *NDP* is the net driving pressure (Δp-$\Delta\pi$), k is the permeability coefficient, taken from table 6. By neglecting the salt passage through the membrane, assuming a recovery ratio of 15%, a polarization coefficient of 1.1, and a feed pressure of 4.8 atm, a total membrane area of about 39 m^2 has been achieved.

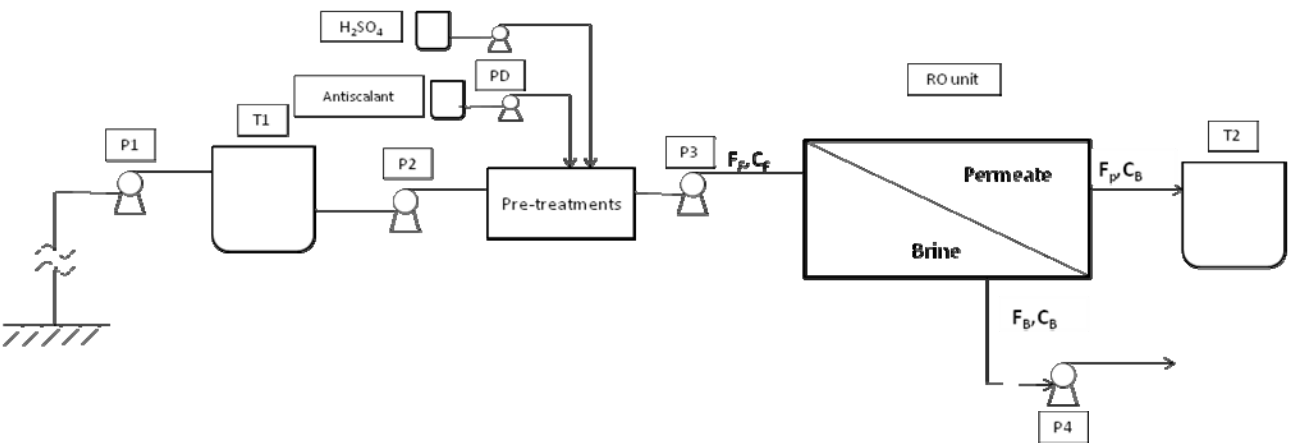


Figure 8. Flowsheet of the RO desalination plant

Therefore, in the case of grid connected RO unit the desalination process can be obtained by using just one membrane module, assuming 24hrs/day operation of the unit.
At the contrary, for the stand-alone system, a different approach has to be used. Given the high cost and environmental concerns related to the use of batteries, the typical approach for the design of such units is to assume 10 hrs/day operation, with a nominal capacity equal to 2.4 times the daily capacity and a battery system able to guarantee continuous operation during the working 10 hrs. Therefore, the optimum number of RO module is, in this latter case, of 3 modules, with a total membrane surface of 120 m^2, allowing the

required daily production of 10 m^3/d (as an average value during the whole year), with a maximum production of about 12.5 m^3/d during summer months, when solar energy is mostly abundant (see Fig. 11).

The total power consumption of the process, which counts for the pumps used for the intake of liquid, for getting through the pre-treatment step, for pressuring the feed up to 4.8 atm before entering in the reverse osmosis unit, and for brine disposal has been estimated to be about **20 kWh/d**, which will be distributed in the 24hrs for the grid connected case and in the 10 working hrs for the stand-alone system. Figure 8 shows a schematic flow-sheet of the plant.

3.7.2 Design of the PV field and battery system

The energy required by the RO process can be supplied by a photovoltaic field.

In the case of ***grid-connected system***, the PV field is designed to provide the amount of energy required by the desalination process throughout the year. During the sunny-hours it will convert the solar energy in electrical energy and the surplus will be given to the electrical network. During the dark-hours electricity will be supplied by the electrical network to the plant, but the net annual energy taken from the network will be equal to zero.

The total energy which can be supplied by the photovoltaic field depends on the climatic characteristic of the particular location and the type of photovoltaic panel. For crystalline silicon panels installed in the chosen location, i.e.”Acqua dei Corsari” in Palermo (38°5'28" North, 13°25'54" East, Elevation: 24 m a.s.l.) with an inclination of 30° and oriented to south (azimuth=0°), the average annual electricity production is of 1390 kWh/(kWp year), which leads to an average energy production of 3,82 kWh/(kWp day) [source: Photovoltaic Geographical Information System (PVGIS) of the European Commision].

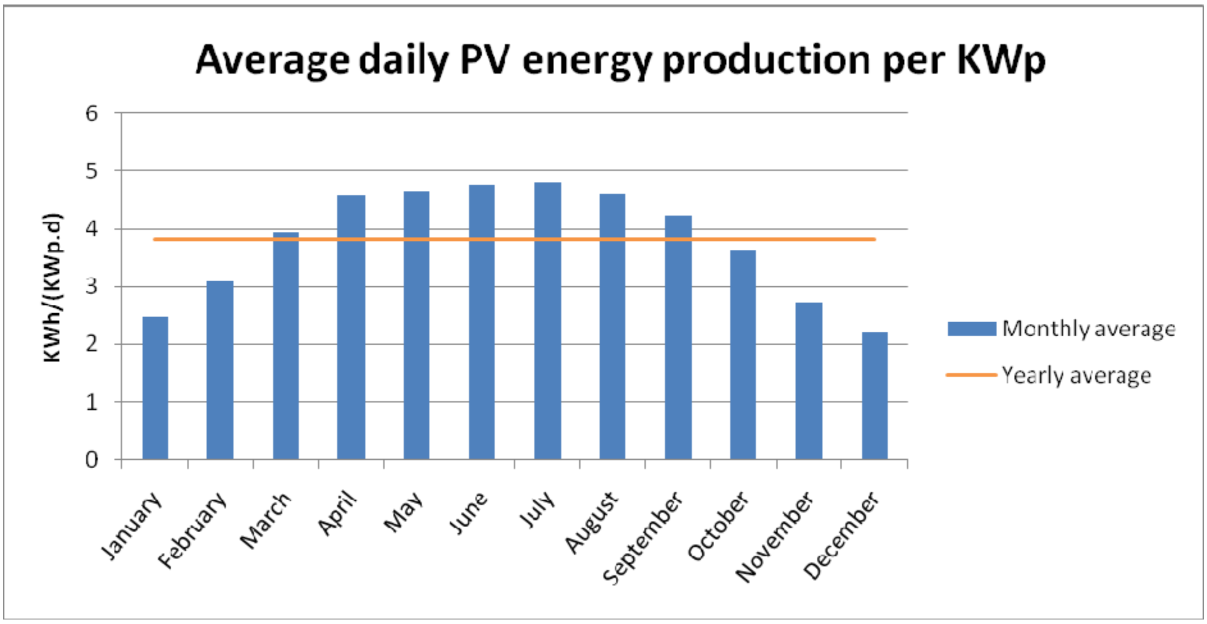


Figure 9.Average daily electricity production per kWp [source: Photovoltaic Geographical Information System (PVGIS) of the European Commission]

Therefore the total peak power that must be installed can be derived by the following equation:

$$P_{peak} = E_{required} / E_{d,average}$$

where

- P_{peak} is the total peak power installed in the photovoltaic field [kWp];
- $E_{required}$ is the daily amount of Energy required by the RO unit, [kWh/d];
- $E_{d,average}$ is the daily amount of energy produced by the photovoltaic field per installed kWp, [KWh/(KWp.d)].

The total peak power required is around **5.7 kWp**. A particular panel model must be chosen now in order to derive the number of panel needed and the total surface area occupied. A market research among some of the actual producers of photovoltaic panel led to the choice of the mono-crystalline silicon panel XM 72/125-190C by Sunerg®, which was the less expensive one among the high efficiency panels considered. Some of the characteristics of the panel are shown in table 8.

Table 8. Characteristic of the selected panel

	XM 72/125-190C
Peak Power [Wp]	190
Surface [m^2]	0,1257648
Dimensions [mm^3]	1576x798x35
Price [€]	700,00
Euro/Peak_Power [€/Wp]	3,68

By dividing the total peak power required by the peak power supplied by one panel, a number of 30 panels with a total surface area of around 38 m^2 has been estimated.
Figure 10 shows the photovoltaic field position on a roof of the wastewater treatment plant.

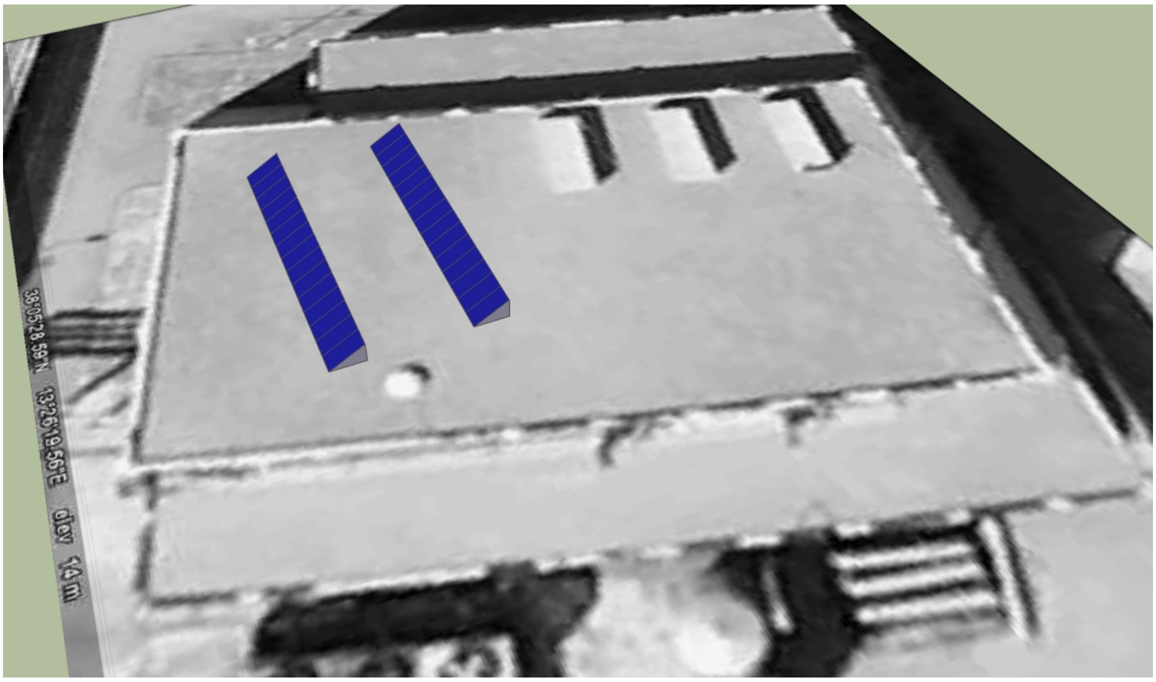


Figure 10. Locating of 30 panels on a roof of the plant

For the stand-alone case, the PV field has been designed similarly, in order to obtain an average eyearly production of energy suitable to produce the same amount of water as the grid-connected case. At the contrary, the design of the battery system has to take into account the daily variation of solar radiation, in order to provide a buffer for the continuous operation during the 10 working hrs per day.

Considering that for the already operated PV-RO units the ratio between the kWh of battery system and kWp of the PV field usually varies between 5 and 8 kWh/kWp (for 6-8 hrs operation per day), and assuming for the present case a ratio of 8 kWh/kWp installed (for the assumed 10hrs operation per day during summer days), a total capacity of the battery system of about 50 kWh has to be considered.

Figure 11 shows the average daily production in the different months of the year, which strongly depends on the energy produced by the PV panels (already presented in Fig.9). As expected the highest production is achieved in summer months, with a maximum value of about 12.5 m^3/d, while the daily production falls down to values of 6 m^3/d in December and January.

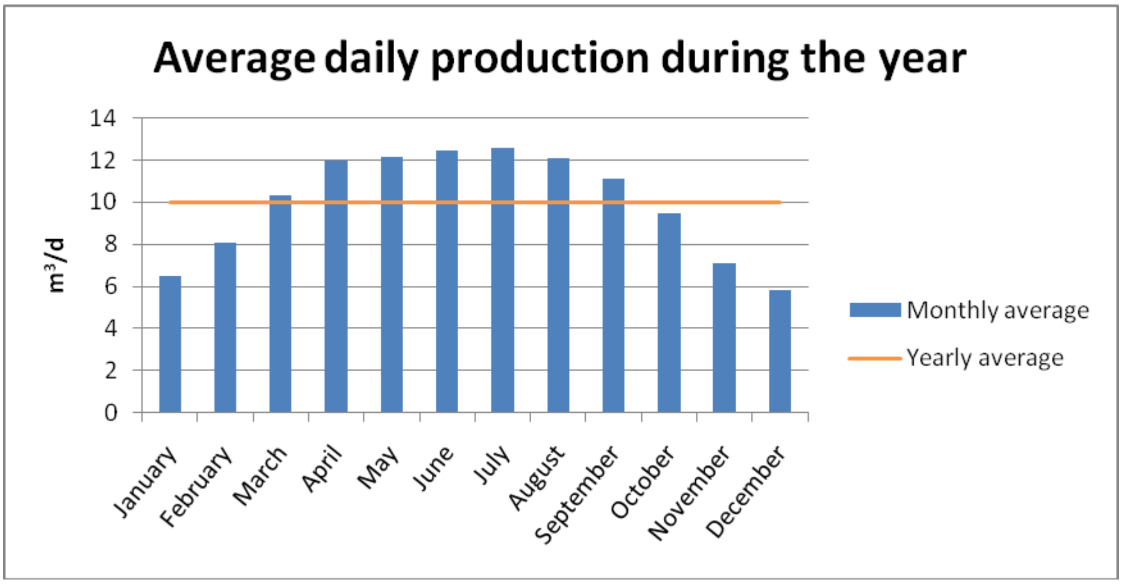


Figure 11. Average daily production of the stand-alone PV-RO plant, calculated as a monthly mean value during the whole year.

3.7.3 Sustainability analysis

So far, the Reverse Osmosis process, among all desalination processes, is one of the most commonly coupled with RES, especially when adopted for brackish water [7], because of its moderate energy consumption, low temperature operation and good modularity. Indeed, in this particular case, RO presents the advantage of lower energy consumption related to the very low salinity of the feed brackish water.

One of the main environmental benefits is related to the amount of CO_2 avoided in the atmosphere thanks to the use of a RES instead of a fossil fuel. This quantity can be estimated starting from the use of CO_2 factors, i.e. kilograms of CO_2 released by 1 MWh_t produced by conventional fuels. For oil fuel, for example, the CO_2 factor is around 255 kg/MWh_t [www.enel.it]. Since 1 electric kWh can be obtained by burning around 2.56 kWh equivalent fossil fuel [www.novambiente.it], the quantity of CO_2 avoided for any kWh_{el} produced by the photovoltaic field can be estimated as 0.65 kg of CO_2 (2.56 kWh * 0.255 kg/kWh). The analysed process (BWRO) consumes around 20 kWh_{el}/day, thus the use of PV energy avoids the release of about 4,750 kg of CO_2/year.

Referring again to the absorbing capacity of a normal tree of 7.7 kg of CO_2 in a year [www.novambiente.it], the same process powered by fossil fuel would require about 600 trees in order to absorb the whole amount of CO_2 produced by this process, which is much less than the case previously observed with the MEH technology, as the Brackish Water Reverse Osmosis presents much lower energy consumptions than thermal desalination processes.

3.8 Economic analysis

3.8.1 MEH+waste heat

In order to complete the analysis of the MEH unit powered by waste heat, a cost evaluation has been carried out by simply adopting the following equation.

$$\text{Cost of water} = \frac{\text{Cost of equipments}}{\text{Nominal capacity} * 365 * \text{Lifetime} * \omega} + \text{cost of chemicals} + \text{unitary O\&M costs}$$

where ω = 0.8 is a factor that takes into account the possible inactivity periods during all the lifetime of the installation. The operation and maintenance (O&M) cost has been suggested by the MEH patent owner based on their experience.
The following table shows the average value estimated for each variable.

Table 9. Summary of the cost analysis for the SAL-MEH unit powered by waste heat

Nominal capacity	10 m^3/d
Lifetime of installation	20 years
MEH unit	90,000 €
Titanium plate heat exchanger	1200 €
Pumps	1700 €
Tank for distilled water	890 €
Anti scaling agent	295 €/year
O&M	0.2 €/m^3
Cost of distilled water	1.89 €/m^3

The cost of distilled water is less than the current cost for the softened water, 2.05 €/m^3, therefore a MEH unit coupled with the waste heat from biogas turbines is an interesting option for the Acqua dei Corsari plant.

3.8.2 MEH+solar collectors

The main parameters and values used in the cost estimation are listed in table 10. The equipment costs have been obtained by a market research, asking quotes and checking price lists, but they still remain just estimates of the real cost of the plant.

Table 10. Parameters adopted used in the cost estimation for the solar MEH process

Nominal Plant capacity	13	m^3/d
Plant life	20	years
MEH plant cost for nominal capacity	9.000	€/(m^3.d)
Effective annual production	3650	m^3
ETC (unitary cost)	270	€/m^2
Heat storage tank (insulated 200 mm)	900	€/m^3

Distillate Storage Tank (PE)	180	€/m^3
Pumps, Filters	2100	€
Heat Exchanger	470	€/m^2
Pre-treatment (disinfectant and antiscalant)	0,013	€/m^3
O&M	0,2	€/m^3

The approximate cost of water produced can be obtained by the following relation:

$$Water\ cost\ \frac{€}{m^3} = \frac{Total\ Cost\ of\ equipment}{Effective\ annual\ production * Plantlife * \omega} + Cost\ of\ Chemicals(\frac{€}{m^3}) + O\&M$$

where ω = 0.8 is an operation coefficient and accounts for the periods when the plant is not active during its lifetime.
The cost of water is estimated to be 6,23 €/m^3, higher than the current cost of softened water through ionic exchange columns (2.05 €/m^3). The MEH process is then not economically competitive with the actual process, however, in order to make the process economically suitable for this kind of application a number of financial subsides can be derived given, for example, by the government in order to promote the use of green technologies for the production of fresh water. A simple analysis of possible incentives will be shown in the following paragraphs.

3.8.3 PV-Reverse Osmosis

The main parameters and values used in the cost estimation are listed in tables 11 and 12 for the case of grid-connected and stand-alone system respectively

Table 11. Economic values utilized for the grid-connected case

Plant capacity	10	m^3/d
Plant life	20	years
Specific RO plant cost for a 10,000 m^3/d size	1000	€/(m^3/d)
RO plant cost (for a 10 m^3/d capacity)	20000	€
PV field	21000	€
Electronic devices (5% PV field)	1050	€
Inverter	4500	€
Pumps	2400	€
Tanks	3500	€
Dosing pumps	600	€
Pre-treatment	0.035	€/m^3
O&M	1.00	€/m^3

Table 12. Economic values utilized for the stand-alone case

Plant capacity (average)	10	m3/d
Plant life	20	years

RO plant cost (nominal capacity 30 m^3/d)	54000	€
PV field	21000	€
Electronic devices (5% PV field)	1050	€
Inverter	7500	€
battery	4000	€
Pumps	4500	€
Tanks	4000	€
Dosing pumps	800	€
Pre-treatment	0,035	€/m3
O&M	2,5	€/m3

In the tables above, the cost of the RO plant has been estimated, as suggested in the literature [8], from the specific price of a similar plant with a bigger capacity (10,000 m^3/d) thanks to the six-tenths-factor rule, where the actual exponent is not 0.6 but 0.9 [8].

$$\left(RO\ plant\ cost\ for\ 10\frac{m^3}{d}\right) = \left(RO\ plant\ cost\ for\ 10{,}000\frac{m^3}{d}\right)\left(\frac{10}{10{,}000}\right)^{0.9} \cong 20{,}000\ €$$

while for the stand-alone case, similar calculations lead to a cost of the plant of 54,000 €.

The cost of the photovoltaic field, inverter, pumps, tanks and dosing pumps has been derived by market research, asking quotes and checking price lists. The cost for operation and maintenance has been set to about 1 €/m^3 for the grid-connected system and 2.5 €/m^3 for the stand-alone case and it accounts for the cost of manpower and for the cost of membrane replacement. The higher cost for the stand-alone system is related to the discontinuous operation of the plant, which can lead to a shorter duration of membranes, and the larger need for human control. Finally, the pre-treatments cost has been assumed to be about 0.035 €/m^3 as indicated in the literature for this kind of process [8].
The cost of water can be now calculated by the following equation for the case of grid connected system:

$$Cost\ of\ water\frac{€}{m^3} = \frac{Cost\ of\ equipment}{Plant\ capacity * lifetime\ of\ installation * \omega} + Cost\ of\ Chemicals + O\&M$$

where ω = 0.8 is an operation coefficient and accounts for the periods when the plant is not active during its lifetime.

For the case of stand-alone system a similar approach as the one adopted for the solar-MEH system has to be used, leading to the following equation:

$$Water\ cost\frac{€}{m^3} = \frac{Total\ Cost\ of\ equipment}{Effective\ annual\ production * Plantlife * \omega} + Cost\ of\ Chemicals\left(\frac{€}{m^3}\right) + O\&M$$

The above calculations lead to a water cost of 1.94 €/m^3 in the case of grid connected system, and 4,19 €/m^3 for the case of stand alone system.

In the first case the cost is slightly lower than 2.05 €/m^3, i.e. the current cost of fresh water through ionic exchange columns. Therefore the reverse osmosis process coupled with solar energy seems to be already a valid alternative to the current softening process used in "Acqua dei Corsari" plant. This is in good agreement also with the findings of the waste-heat MEH unit, thus indicating that the use of a desalination system powered by a non-conventional energy source can be a viable and economic alternative for demineralised water production, especially if a continuous source of energy (waste heat availability or grid connection) allows continuous operation of the desalination unit.
A different scenario has been depicted for the case of completely stand-alone RE system. In fact, in both cases the need for over-sizing the desalination unit, the necessity of energy storage systems and the higher costs of O&M related to discontinuous operations dramatically influence the cost, leading to values well above the case of grid-connected systems.
In the following paragraphs, it will be shown how the actual incentives available for PV energy production further reduce such cost, making this choice the most convenient among the ones here considered.

3.9 Incentives schemes

In order to make RE desalination processes more competitive compared to conventional ones, national incentives schemes may be adopted by the governments, aiming at promoting the development and use of such novel technologies, as it ahs already occurred for RES technologies.
In the case of MEH unit powered by waste heat from biogas turbine the scheme for estimating a possible subside could be based on the thermal energy used for a desalination process and taken form biogas turbine waste heat, which would be otherwise discharged into the environment. The clear benefit is the CO_2 amount avoided using waste heat instead of traditional fuel, which could for example be used to estimate the "equivalent trees" to absorb it and use this basis for calculating the subsides. However, even if no subsides were applied to the estimate of water price, the economic analysis sown above already shows an interesting cost of desalinated water , which is comparable, and even slightly lower, than the one declared by the Acqua dei Corsari company for the production of softened water.
In the following two paragraphs the other two cases have been considered, in which "conventional" Renewable Energies are used to power the desalination process. In both cases standard incentives or custom ones (specifically proposed for the scenario analysed) are presented along with the relevant economical analysis.

3.9.1 SOLAR MEH

In Italy two kinds of financial incentives exist for the installation of solar thermal collectors for civil uses:

- Tax deduction (Personal Income Tax) 55% of purchasing cost.
- *Solar Thermal Program* (regional incentives) 30% deduction of purchasing cost.

Nevertheless these incentives are not suitable for industrial applications as in the present case. Another incentive, which may be suitable for the present case study is related to the

White Certificates (WC) method. A white certificate, also referred to as an Energy Efficiency Credit (EEC), is an instrument issued by an authorized body guaranteeing that a specified amount of energy savings has been achieved. In Europe several countries have implemented a white certificate scheme or are seriously considering doing so. Italy started a scheme in January 2005; France a year later. Great Britain has combined its obligation system for energy savings with the possibility to trade obligations and savings. Denmark and the Netherlands are seriously considering introduction of a white certificate scheme in the near future. According to the Italian set of laws, WCs are associated to appropriate energy saving. Energy utilities must reach enforced annual targets of energy saving in two ways, either by Demand Side Management measures or by purchasing White Certificates. The cost of these certificates is currently 100€/TOE.

However a new mechanism of incentive for industrial plants, that could exhibit the environmental benefits of a desalination plants coupled with RES, has been proposed in the present study. This incentive is based on the amount of "equivalent trees" related to the CO_2 production of the desalination processes. The reduction in the amount of emissions related to the use of RES could be seen as an increase in the amount of trees planted in the country. Then an annual contribution of less than 1 euro for each "tree" could be proposed to the government. This new incentive named as "Ecologic Loan" could be used for each kind of desalination plant powered by RES but could be extended to other process powered by alternative energies.

Given the energetic analysis performed in chapter 6 and assuming an annual contribution (for the entire life of the plant, supposed to be 20 years) of **0.5 euro for each equivalent tree** saved by the use of solar collectors, the new estimated cost of desalinated water can go down to a value of about 3.72 €/m^3, which would be higher than the actual cost of soft water in Acqua dei Corsari's plant but comparable, in general, with many other stand-alone RE-desalination processes. A summary of the above considerations Is reported in Table 13

Table 13. Energy consumption and equivalent trees saved used in the "ecologic Loan" subsides scheme for water production through the solar MEH technology

N.C. 13 m^3	
Thermal Energy requested	1515 kWh_{th}/day
Amount of CO_2	386 kg/day
Equivalent trees	18300
Cost of water with the new "Ecologic Loan" subsides scheme	3,72 €/m^3

3.9.2 PV-RO

In Italy there are already incentives for the installation and use of photovoltaic panels, which are related to the energy produced by converting the solar radiation in electricity. These incentives also depend on the year of start-up, on the power installed and on the type of architectonic integration of the panels in the site of installation. Basically, panels on the ground are "not integrated", panels on the roof are "partially integrated" and panels used instead of structural elements are "architectonically integrated". In the present case of study, the photovoltaic field is "partially integrated" and, supposing that the start of operation will be on 2010, it will receive an incentive of 0.404 €/kWh of PV electricity produced.

As a result, considering the energy provided by the photovoltaic field and the daily production of desalinated water, the cost of water will be reduced by 0.78 €/m^3 thanks to the above incentive, thus the final cost will be of about 1.16 €/m^3 and 3.41 €/m^3 for the grid-connected and stand-alone systems respectively.

A summary of the discussed results is reported in table 14.

Table 14. Comparison of cost of production according to different processes

	Cost of production
Ionic Exchange columns	**2.05 €/m^3**
PV-RO grid-connected	**1.94 €/m^3**
PV-RO stand-alone	**4.19 €/m^3**
PV-RO grid-connected with incentive	**1.16 €/m^3**
PV-RO stand-alone with incentives	**3.41 €/m^3**

3.10 Conclusions

The potential of using different RE-powered desalination processes for the production of desalinated water from brackish water within a sewage treatment plant in Palermo has been analysed. Two non-conventional energy sources have been considered:

- Waste heat from bio-gas turbines, fed by the bio-gas produced in the anaerobic digester of the sewage treatment plant;
- Solar energy, used either for the production of thermal energy by means of solar collectors, and for the production of electricity by means of Photo Voltaic panels.

On the other side, two desalination processes have been taken into account, namely the Multi Effect Humidification process (SAL-MEH) and the Reverse Osmosis process (RO), leading to the following four different scenarios:

- MEH process powered by waste heat (grid-connected);
- MEH process powered by solar thermal energy (stand-alone);
- RO process powered by solar PV electrical energy with back-up from the electrical grid (grid-connected);
- RO process powered by solar PV electrical energy with a battery back-up system (stand-alone);

Where grid-connected systems are related to the availability of a continuous energy source (waste heat or electrical grid), and stand alone system are designed to be suitable for isolated installations, where no further infrastructure is available.

Technical and economical analysis have shown how the two grid-connected scenarios present similar advantages and disadvantages, with a cost of the produced water comparable or even lower than the actual cost of deionised water used in the sewage plant for industrial scopes (i.e. 2.05 €/m^3 including also the cost of fresh water from the municipal water network).
At the contrary the stand-alone scenarios suffer from a higher cost due to the generally higher cost of solar energy compared to waste heat, and to the need of storing the energy and over sizing the desalination units, in order to guarantee the continuous production required by the plant.
In general, the presence of governmental incentives can significantly reduce the cost of water, leading to values which are still higher than conventional sources but at an acceptable level, if one considers the peculiar features of these stand-alone systems.
In the following Table 15, a summary of the results is presented.

Table 15. Summary of the four RE-desalination scenarios analysed for the production of desalinated water through the use of renewable energies in a sewage treatment plant in Palermo (Sicily, Italy)

Scenario / Comment	Waste-heat MEH	Solar thermal MEH	PV-RO (grid-connected)	PV-RO (stand-alone)
Plant reliability	High	Medium	High	Medium
O&M complexity	Medium	Medium	High	High
Sensitiveness to feed water quality	Low	Low	High	High
Energy consumption	High	High	Low	Low
Dependence of energy consumption on salinity*	Low	Low	High	High
Estimated water cost [€/m^3]	1.89	6.23	1.94	4.19
Estimated water cost with energy incentives [€/m^3]	1.89**	3.72***	1.16****	3.41****

* The use of seawater as a feed can influence dramatically the cost and complexity of operation in RO based plant, while it is usually much less influent in thermal processes.
** No incentives have been considered for the case of waste heat powered systems.
*** A novel incentive has been proposed based on the amount of “equivalent tree” saved by the use of solar energy instead of fossil fuels, assuming an annual contribution of 0.5 €/equivalent tree for the entire life of the plant (supposed to be 20 years).
**** PV energy governmental incentives have been applied, based on the kWh produced by PV panels.

References

[1] Cipollina A., Micale G., Rizzuti L., A critical assessment of desalination operations in Sicily, Desalination Vol. 182 (2005), Issuel-3, November, pp.1-2

[2] Beccali M., Sorce M., Galletto J., "The potential of renewable energies in Sicily for water desalination applications" – in "Solar Desalination for the 21st Century", Proceedings of the NATO Advanced Research Workshop, held in Hammamet, Tunisia, 23-25 February 2006 Eds. Rizzuti L.; Ettouney H. M.; Cipollina A.((2007), ISBN-10: 1-4020-5506-4.

[3] Muller-Holst H., Solar thermal desalination using the Multi-Effect Humidification (MEH)-method " – in "Solar Desalination for the 21st Century", Proceedings of the NATO Advanced Research Workshop, held in Hammamet, Tunisia, 23-25 February 2006. Eds. Rizzuti L.; Ettouney H. M.; Cipollina A.(2007), 400 p., ISBN-10: 1-4020-5506-4.

[4] Perry, R.H., Green, D.W., 1997, Perry's Chemical Engineers' Handbook. McGraw Hill, New York.

[5] Sagle, A., Freeman, B., 2004. Fundamentals of membranes for water treatment. In: Arroyo, J.A. (Ed.), The future of desalination in Texas, vol II, Texas water development board, Austin, TX, pp. 137-153.

[6] Cipollina A., Micale G., Rizzuti L., Seawater Desalination, Springer-Verlag, 2009.

[7] M.T.Chaibi "An Overview of solar desalination for domestic and agriculture water needs in remote arid areas", Desalination 127 (2000) 119-133.

[8] G. Fiorenza, V.K. Sharma, G. Braccio, "Techno-economic evaluation of a solar powered water desalination plant", Energy Conversion and Management 44 (2003) 2217–2240.

4. Spain

4.1 Situation in the Canary Islands

The Canary Islands are a Spanish archipelago located just off the northwest coast of mainland Africa, 100 km west of the border between Morocco and the Western Sahara. The Canaries are a Spanish Autonomous Community and an Outermost Region of the European Union. The 7 major islands include (from largest to smallest): Tenerife (2,034 km²), Fuerteventura (1,659 km²), Gran Canaria (1,560 km²), Lanzarote (845.94 km²), La Palma (708.32 km²), La Gomera (369.76 km²) and El Hierro (268.71 km²).

The Canary Islands is a region with a total lack of conventional energy resources and a historical restricted availability of fresh water. On the other hand, this archipelago has relevant resources in terms of wind and solar energy; thus, it makes sense to consider the potential uses of local RE resources to power desalination units. This link between water and energy was concluded several years ago and it was the starting point of a specific R&D line in this field, mostly assumed by the Canary Islands Institute of Technology, in collaboration with the University of Las Palmas de Gran Canaria. A specific paper summarizes the developed activities and projects[1].

The figure 1 represents the availability of wind resources in the Canary Islands archipelago.[2]

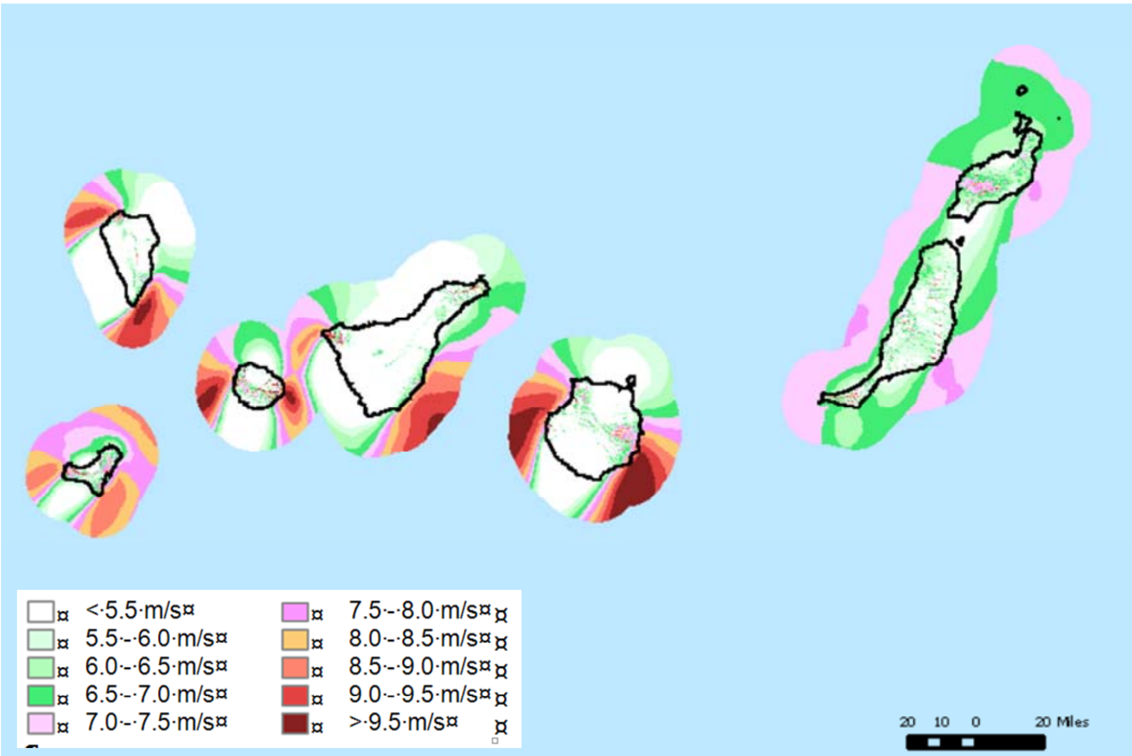


Figure 1. Wind map of the Canary Islands

[1] Subiela, V. et al, " Canary Islands Institute of Technology (ITC) experiences in desalination with renewable energies (1996–2008)", Desalination & Water Treatment 2009, pages 220–235.
[2] Wind map of the Canary Islands. http://hipocrates.itccanarias.org/recursoeolico/

The figure shows that all the islands have an interesting wind potential with clearly identified areas with very high wind speed.

Concerning the solar resource, there is also an excellent potential, the figure 2 is an image of the solar map[3].

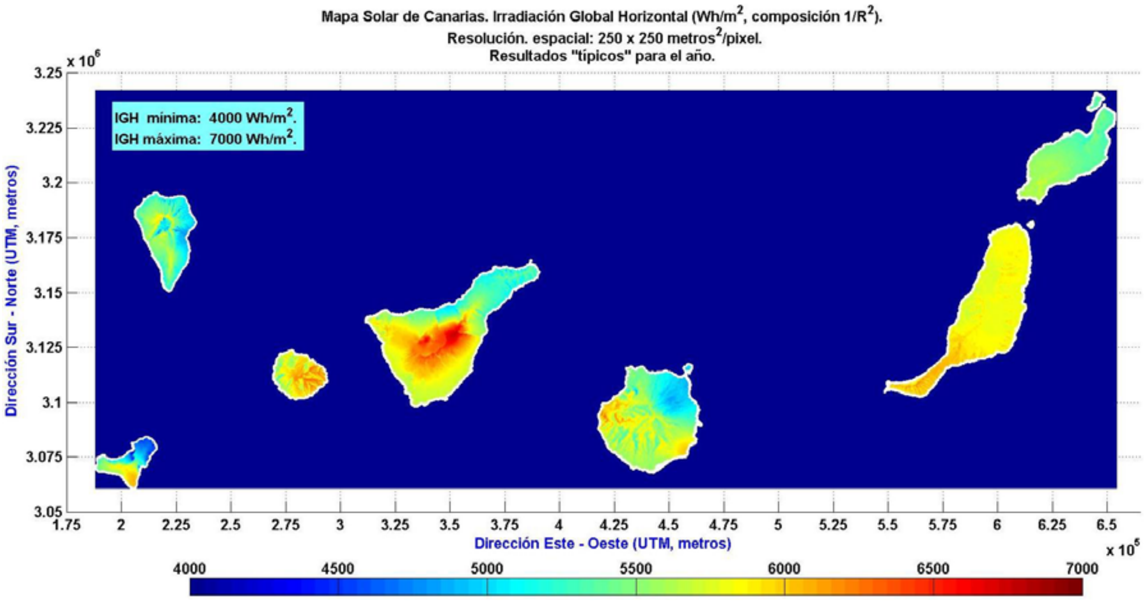


Figure 2. Solar map of the Canary Islands

On the other hand, the water supply situation in the Canary Islands is summarized in the enclosed table[4].

Table 1. Summary of water resources in the Canary Islands (2002)

WATER SOURCE (hm^3/yr)	ISLAND (*)						
	LZ	FV	GC	TF	LG	EH	LP
Surface water	0,1	1,8	11,2	5,0	3,4	0,1	3,5
Underground wáter (direct use)	0,1	0,2	60,0	180,0	11,1	1,9	72,9
Desalinated underground water	0,0	1,0	20,2	11,3	0,0	0,0	0,0
Seawater desalination	16,9	10,9	56,9	6,7	0,0	0,5	0,1
Reused water	3,8	1,4	7,2	8,0	0,0	0,0	0,1
TOTAL	**20,9**	**15,3**	**155,5**	**211,0**	**14,5**	**2,4**	**76,6**

(*) LZ: Lanzarote; FV: Fuerteventura; GC: Gran Canaria; TF: Tenerife; LG: La Gomera; EH: El Hierro; LP: La Palma

Despite the data are not recent, the situation of high dependence of desalination is clearly deducted from the data, particularly for the west islands (Lanzarote, Fuerteventura and

[3] Solar Map of the Canary Islands, ITC, Software Engineering Department
[4] Water Canary Islands Center Foundation. (www.fcca.es)

Gran Canaria). This situation is the result of a transformation process, happened from 60's, in which the tourism industry has become the main economic sector, reducing the role of the primary sector, and generating a progressive high quality water demand.

On the other hand, the continuous increment in the local population (2.100.000 inhabitants in 2009, one million more than in 1970)[5], has lead to a higher water demand.

4.2 Selection of the site: La Graciosa Island

In the north of Lanzarote is located the Chinijo Archipelago which includes the islands of La Graciosa, Alegranza, Montaña Clara, Roque del Este and Roque del Oeste (see Figures 3 and 4).

La Graciosa is the smallest inhabited island of the Canaries, and the major island of the Chinijo Archipelago. The whole archipelago is administrated by Lanzarote. It has a surface of 29.05 km^2.

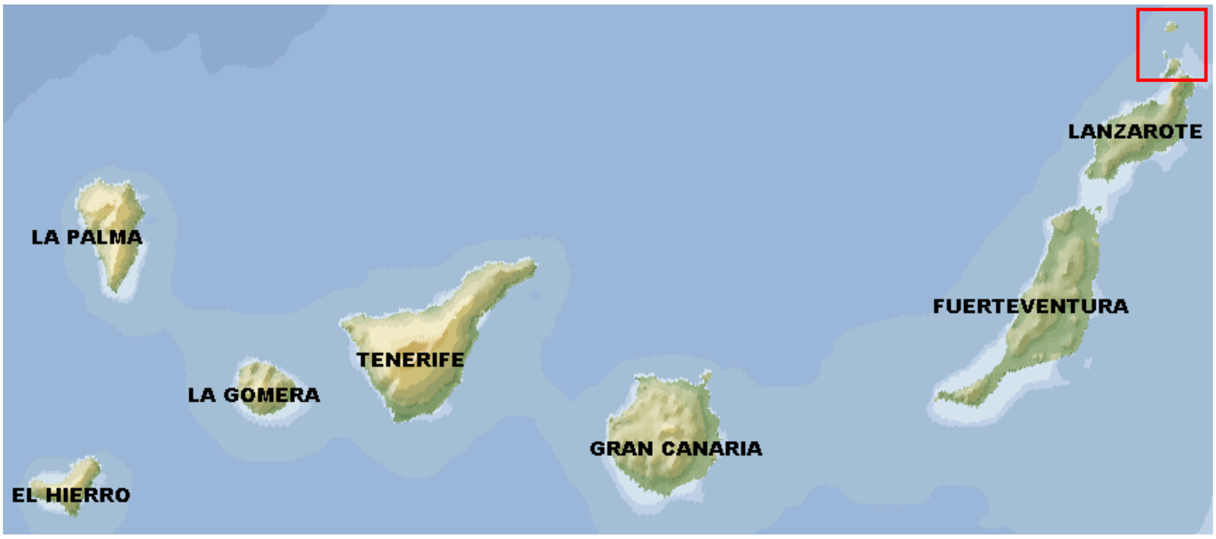


Figure 3. Geographic map of the Canary Islands. Red square indicates the Chinijo archipelago.

[5] Statistics of the Canary Islands Government

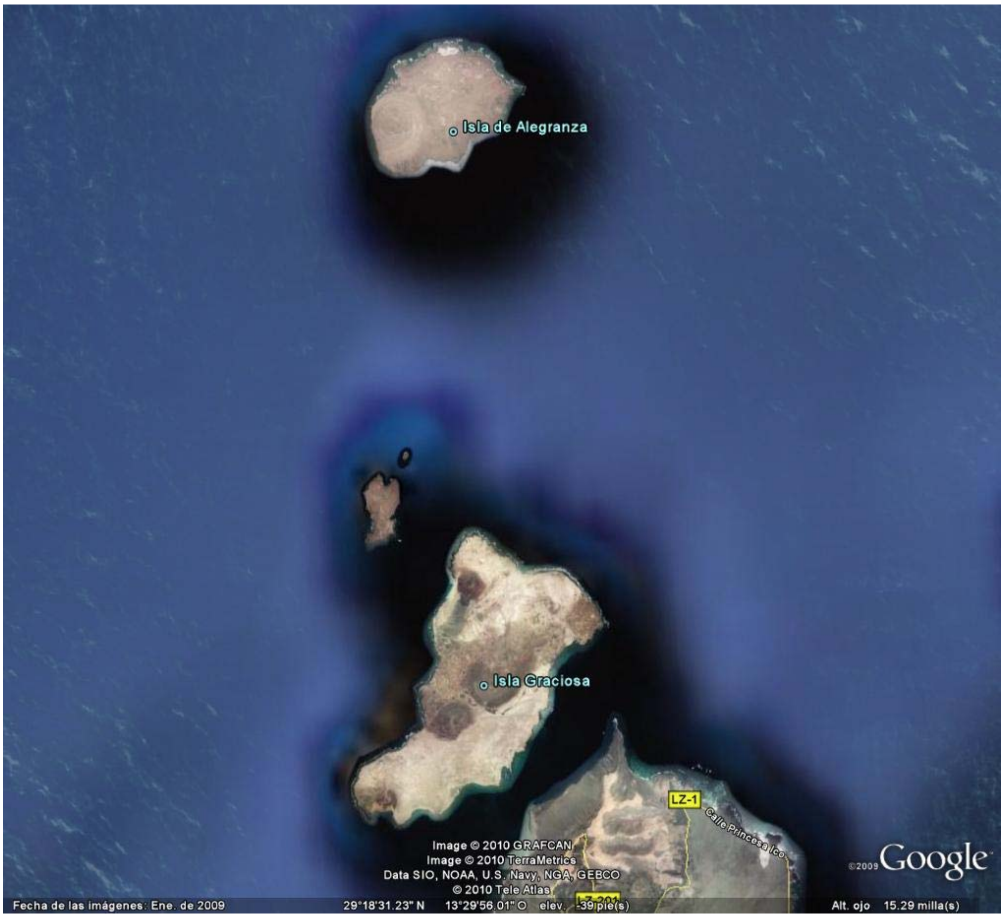


Figure 4. Map of the Chinijo archipelago, with La Graciosa island

La Graciosa is a small volcanic island located at the north of the island of Lanzarote. It has a population of 658 residents and it is supplied of water and electricity from neighbouring Lanzarote by a submarine pipe and a cable with a capacity of 1.3 MW. Given its small size, the reduced population, and the wind and solar radiation conditions, in combination with energy storage solutions, the island is an excellent site for a very high penetration of RE's up to 100%. Nevertheless, to make this possible, it would be absolutely necessary to introduce a set of energy saving actions addressed to maintain constant the electricity demand for a long time.

Figure 5. General aerial view of La Graciosa island.

The main relevant data of La Graciosa Island are the following:

- Total external dependence of water and energy: electricity supply is through an undersea cable connected to the Lanzarote Island, with a maximum capacity of 1.3 MW.
- Small annual electricity consumption: 3,485.039 kWh
- Peak power consumption: 668 kW
- Small size: 29 km^2
- Small population: 644 inhabitants in 2009 [6] [5]
- Presence of wind and solar energy: the average wind speed in the windiest area is 5.3 m/s. The estimated average daily solar radiation is 5 kWh/m^2.
- Environmental protection: La Graciosa Island is part of the Natural Park "Archipelago Chinijo" officially declared in May 1986. Space recognized as special sensitivity area.
- Water supply by an undersea water pipe connected to Lanzarote Island.
- Availability of local RE resources (see figure 6 below).

HGI values shown below have been extracted from the previous results obtained for the Solar Map of the Canary Islands (see figure 2).

The results extraction on the map of Lanzarote Island, zone of La Graciosa Island, has been held at the following coordinates (X, Y, UTM coordinates in meters, Z, obtained from digital terrain model in meters)

Pt.1 = [642872.5, 3234320, 35.4]
Pt.2 = [645372.5, 3237070, 213.5]
Pt.3 = [645122.5, 3239570, 17.6]

In the coordinates above, HGI expected values are (see table 2):

[6] Spanish National Institute of Statistics (www.ine.es)

	HGI(1)	HGI(2)	HGI(3)
January	3475	3530	3477
February	4357	4425	4362
March	5530	5611	5529
April	6135	6226	6146
May	6903	7005	6907
June	7088	7191	7083
July	6798	6899	6786
August	6448	6536	6440
September	5735	5816	5728
October	4715	4785	4717
November	3691	3750	3690
December	3145	3199	3146
Year	**5313**	**5392**	**5313**

Table 2. HGI values for La Graciosa.

HGI values expressed in Wh/m^2/día, and represent the monthly averages of daily accumulated IGH (values from January to December) and annual average daily accumulated IGH (value of the year).

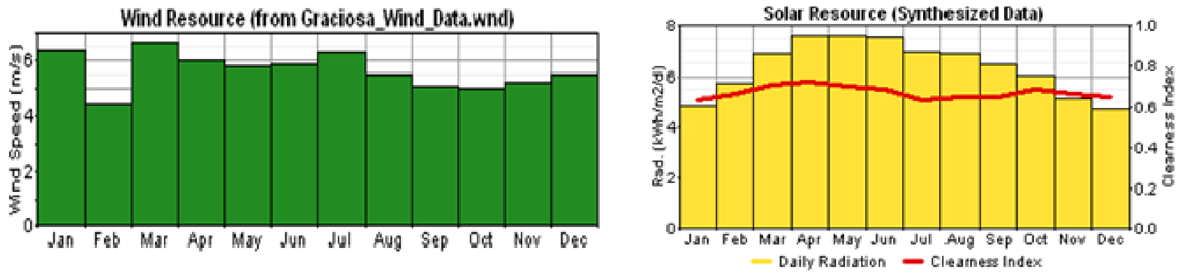


Figure 6. Annual solar and wind resources in La Graciosa Island.

The total dependence of external water supply has meant periods of time with total lack of fresh water due to failures in the undersea pipe. Drinking water supply to the island of La Graciosa is made from the north of the island of Lanzarote by means of an undersea pipe (figure 7), bridging a gap of 400-500 meters; this pipe is covered with stones of the place as it is located in a protected area. It follows the coast of Lanzarote up to the nearest point of La Graciosa (1,138 meters) where the pipe enters the sea and out of La Graciosa runs to the existing reservoir. [7]

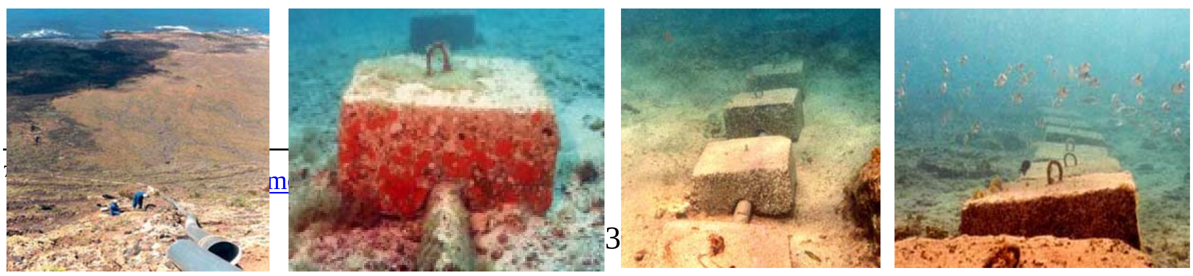


Figure 7. Photos of the undersea pipe installed between Lanzarote and La Graciosa for water supply.

Nº of concrete cubes: 472 units.

Pipe under water: 1,138 m.

Pipe in Lanzarote: 3,900 m.

Pipe in La Graciosa: 1,000 m.

The current system of water supply to the island of La Graciosa is creating serious problems to INALSA (Insular de Aguas de Lanzarote, S.A.) due to the constant breaks in the underwater pipeline that runs through the water channel between Lanzarote and La Graciosa, which increases the water distribution network losses and the electricity consumption, in addition to the staff costs. It is therefore necessary to ensure the service to the island and optimize the price of water distributed in it; for that reason, the viability and modernization plan of INALSA (2008-2012) includes the installation of a reverse osmosis desalination plant with two modules of 250 m^3/day each. [8]

4.3 Fresh Water demand in La Graciosa community

The inhabitants of La Graciosa Island are located in two main settlements with a total population of 644 people.

During the months of July to September the island goes from almost 700 people to triple its population. That is the reason why, during this period, which coincide with the summer holidays, water demand on the island increases dramatically (see Figure 8). Increments in water demand of almost 3000 m^3 have been registered between the months of June and August. The annual total water demand is calculated to be equal to 77,824 m^3 (from June 09 to May 10).

[8] http://www.datosdelanzarote.com/itemDetalles.asp?idFamilia=22&idItem=3787

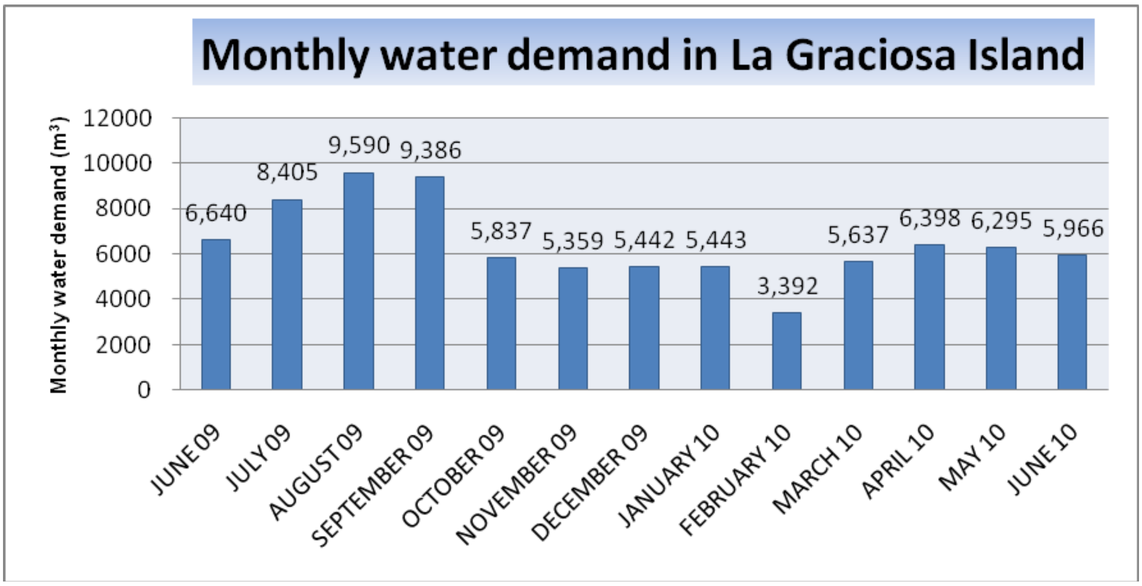


Figure 8. Monthly water demand in La Graciosa Island.

4.4 Cost of water supply

The estimated water cost associated with the water supply in the Graciosa Island, by the undersea pipe, is about 155000 €/year[9].

The prices paid by the users depend on the amount of water consumed and the type of sector; for the case of domestic users, the tariffs system is the following:

Water Tariffs in Lanzarote	2010
	€/m3
< 10 m^3	0.60
From 11 to 30 m^3	0.98
From 31 to 40 m^3	1.62
More than 40 m^3	3.35

Table 3. Lanzarote water tariffs published in the water company's website (http://www.inalsa.es/tarifas.asp?lang=esp)

4.5 Implementation of the RE powered desalination system

This section presents an elemental technical and economic analysis of the alternative water supply based on a desalination plant coupled to RE desalination system. The system consists of the following main elements:

- Feed water pump and seawater reverse osmosis unit
- A hybrid RE generation system: PV field & wind generator
- Set of batteries, as back up system

[9] INALSA (Local water supply company). Personal communication.

This proposal is based on the planned idea[10] of installing a RO unit in La Graciosa Island, with a capacity of 500 m^3/day and the long experience of ITC in wind and solar autonomous desalination systems.

The **technical assessment** is based on the following considerations:

- Calculated from the data of the highest water demand month (August). The data is 9,590 m^3; 10000 m^3 will be considered for the calculation.
- Solar peak hours in August: 217 (7 hours /day x 31 days / month)
- Relation "(wind energy / wind nominal power)" in August: 200 hours / month [kWh/kW].
- Distribution of energy generation: PV (50%), wind (50%)[11]
- Average daily operation hours of RO unit in August: 12 hours/day
- Specific RO energy consumption: 4 kWh/m^3
- Energy efficiency of RE generation system: 65%

The calculation process is as follows:

1) Determination of energy demand from RO unit: 10000 m^3 x 4 kWh/m^3 = 40000 kWh
2) Energy from autonomous system: 40000 kWh / 0.65 = 61538 kWh
3) Energy from hybrid system:
   - PV: 30769 kWh
   - Wind: 30769 kWh
4) Estimation of installed power
   - PV: 30769 kWh / 217 h = 142 kW
   - Wind: 30769 kWh / 200 h = 154 kW
   - RO unit:
     - Daily water production: (10000 m^3 / month) / (31days/month) / (12 hours / day) = 27 m^3/h
     - Estimated power: 27 m^3/h x 4 kWh/m3 = 108 kW

The **economic assessment** is based on the following considerations:

- Cost of RO unit: 1,200 € / daily cubic meter installed (nominal capacity)
- Cost of PV system: 5,000 € / kWp
- Cost of wind system: 4,000 € / kW

[10] Proposal defined within the future water supply plan for La Graciosa Island, as an alternative to the current supply by the undersea pipe.
[11] Relation Energy / Power is very similar for both systems

- Lifetime of system: 15 years
- O&M cost: 30 %

Thus, the estimation of the most relevant costs is as follows:

- Cost of RO unit: 1,200 € / (m^3/day) x 27 m^3/h x 24 h/day = 777600 €
- Cost of PV system: 5,000 € / kWp x 142 kWp = 710000 €
- Cost of wind system: 4,000 € / kW x 154 kW = 616000 €
- Total cost: 2.1 M€
- Monthly cost = 2.1 M€ / 15 years /12 months/yr x (1+0.3) = 15 k€/month
- Cost of water (in August): 15 k€/month / 10000 m^3 = 1.5 €/m^3
- Cost of water (annual): 15 k€/month x 12 months / 78000 m^3/yr = 2.3 €/m^3

4.6 Conclusions

The implementation of autonomous desalination by renewable energies is particularly interesting in small and isolated areas as the case of La Graciosa Island.

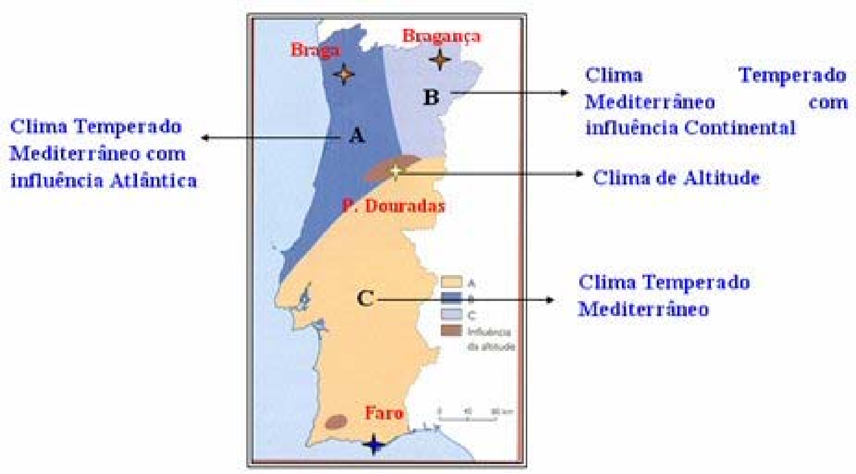
The local population water demand is 100% covered by the external supply of the undersea pipe; feed water is pumped from Lanzarote island with an associated energy consumption and cost (155000 €/yr). Taking into account this water cost given by INALSA (local water supply company) and the total water demand registered last year 77824 m^3 (see figure 8), the water supply cost in La Graciosa island is 1.99 €/m^3. The target place has important wind and solar resources that makes reasonable to think in a desalination system powered by these renewable energies. A very elemental analysis has been presented to evaluate how interesting could be this option. According to the economic results, the cost of water from the RE desalination alternative would be 2.3 €/m^3, i.e., close to the current water cost (1.99 €/m^3). So if a specific subsidy was implemented, then the RE option could be economically feasible. Thus, this is an interesting case to consider autonomous water provision.

5. Portugal

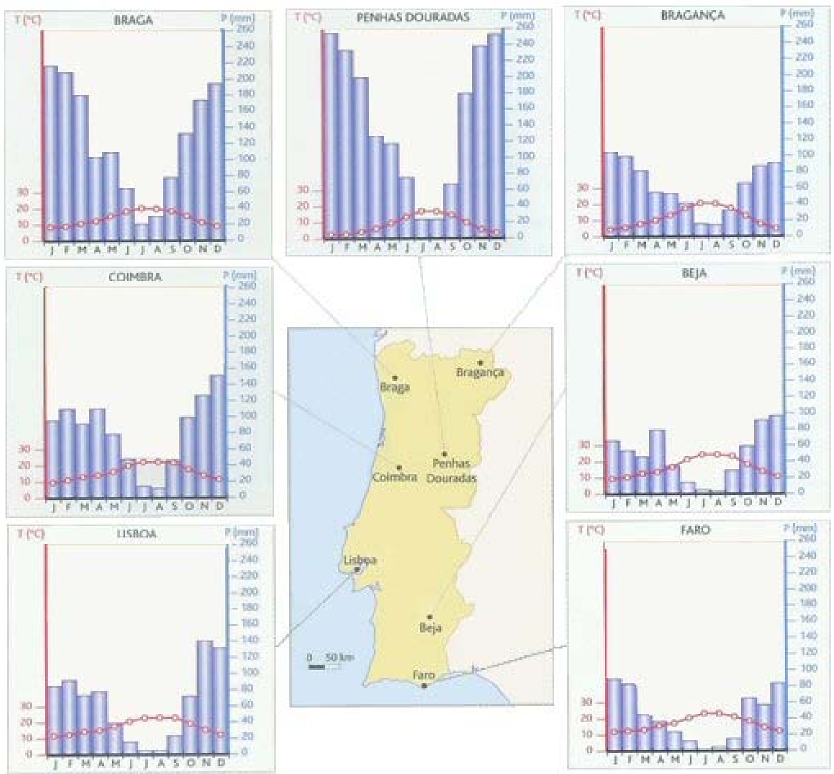
5.1 Climate and fresh water situation in Portugal

5.1.1 Climate

Portugal Mainland comprises about 89,300 km2 whose climate combines Atlantic and Mediterranean influences. The first is stronger in winter and responsible for abundant precipitation, especially in the Norwest region, and for the attenuation of the cold and dry winds coming from the interior of the Iberian Peninsula. The Mediterranean influence is felt more in the summer and in the southern and eastern regions, originating comparatively high temperatures and reduced precipitation.

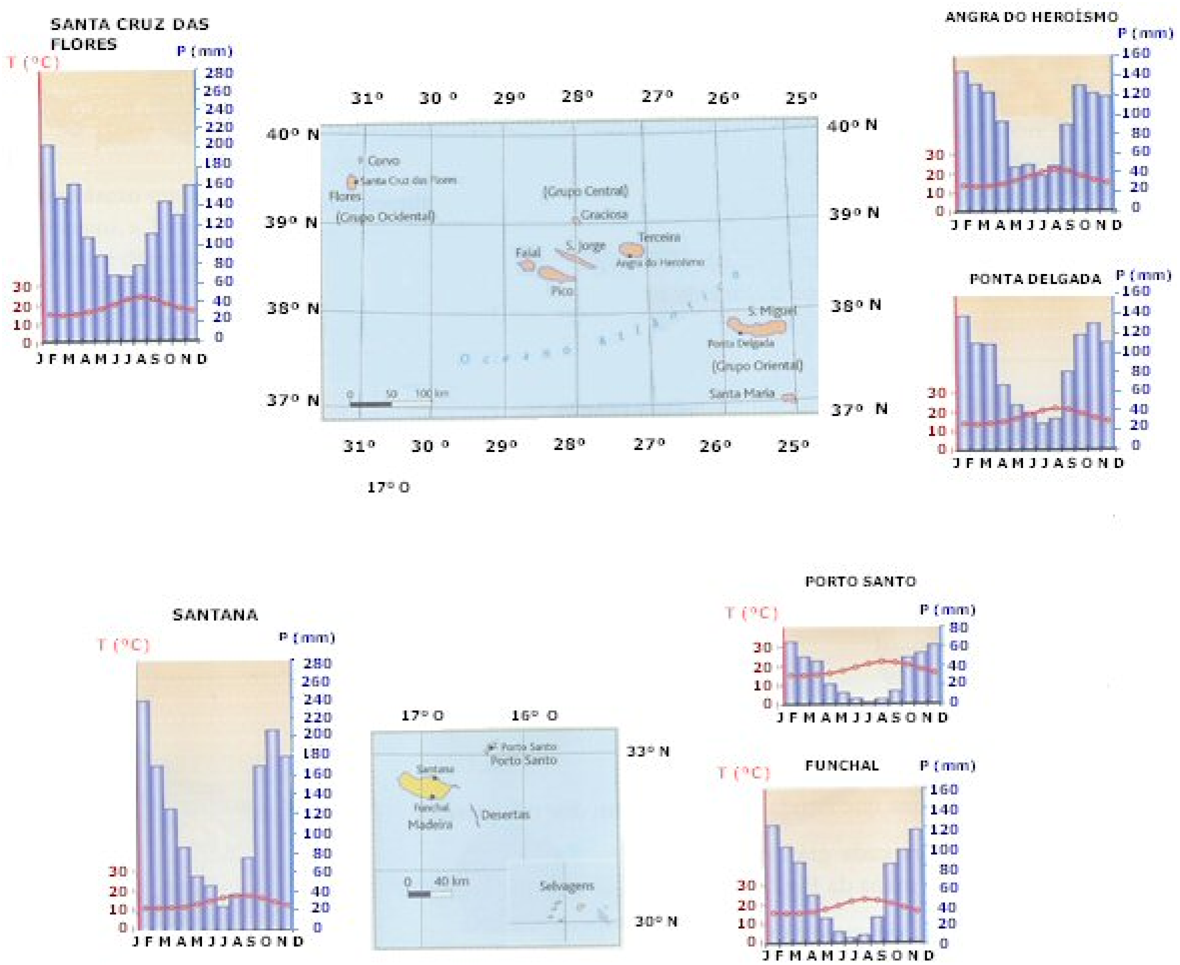


Climatic zones in the Mainland



Precipitation and temperature in some localities in the Mainland

In the autonomous region of the Azores Islands a mild mediterranian like climate with Atlantic influence exists, with more precipitation and a shorter dry season.
In the autonomous region of Madeira Islands there is a more typical mediterranic climate.



Precipitation and temperature in the Islands of Madeira and Azores region

As can be seen from the charts, the two regions with relatively reduced yearly rainfall are the South of the Mainland (Alentejo and Algarve) and the Island of Porto Santo.

5.1.2 Fresh water situation

In Portugal there is yet no serious lack of water resources, except perhaps at the end of a sequence of very dry (2-3) years and in the south (Algarve/Baixo Alentejo), when the usual reservoirs can come very close to their bottom levels.

A reference of 190 liter fresh water consumption per inhabitant of Portugal is normally considered.

In the mainland the regions of less abundant rainfall derive their water usage from the public water network, and hence do not have a serious water concern for now, even in big cities like Lisboa.

Since 1940 the total fresh water storage capacity in Portugal, including reservoirs, lakes and dams, has been increasing. In 2008 was estimated to be between 11.000 to 12.000 millions of m^3 of total capacity. The mountain regions especially in the northern regions and rivers coming from Spain provide water supply to the Mainland storages.

In the Island of Porto Santo a desalination plant with grid driven reverse osmosis is already working since 1979. The plant in Porto Santo is one of the first three plants in the world. The unit is property of the Regional Government and is managed by IGA - Investimentos e Gestão da Água, SA.

Reverse osmosis plant in Porto Santo

Fresh water price varies across the territory around a mean value of 1 € per m^3, which includes water, sewage and taxes. This is a rather low price compared to most European countries and does not encourage any special efforts to invest in alternative water sources, except for big enterprise consumers like hotel chains or perhaps industries.

The irrigated area in Portugal has been decreasing continuously from 1990 to 2005, probably because of a decline of agriculture activity over these years, and was in 2005 around 620.000 hectares.

5.2 Small Berlengas Islands

The Berlengas archipelago is a group of very small islands off the Portuguese coast near the city of Peniche, at 10 to 15 km. In the larger island (Berlenga Grande) there is an ancient fort and a lighthouse. The lighthouse utilizes a photovoltaic array. Berlenga Grande (or Ilha da Berlenga) is 1500 metres per 800 metres at 85 metres high. In this small island there are beaches and several caves, its waters are very clean with barrier reefs and vibrant marine life.

There are other groups of islets known has Estelas islets and Farilhões-Forcados islets, which do not have permanent human occupation.

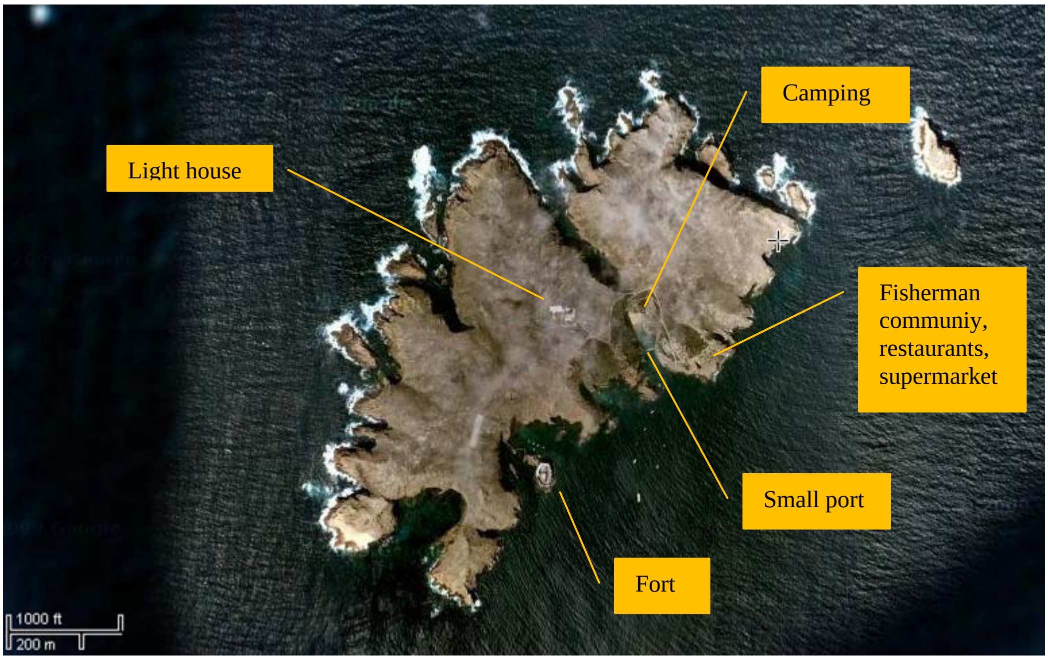
The archipelago has been declared a reservation area due to the local fauna (sea birds, mostly) on 1990, and has a pending request of qualification as Unesco reservation.

Coordinates:
39°26'59"N 09°30'57"W.

The distance to nearest port (Peniche) is 16 km.

Map of Berlengas and surrounding islands

5.2.1 Infrastructure



Satelive view of Great Berlenga

The main builded areas are:

- a fort, now partially converted into a resthouse with 20 rooms
- a small fisherman community
- 2 restaurants (at least one renting rooms also)
- camping area
- a small supermarket
- a lighthouse
- a small port

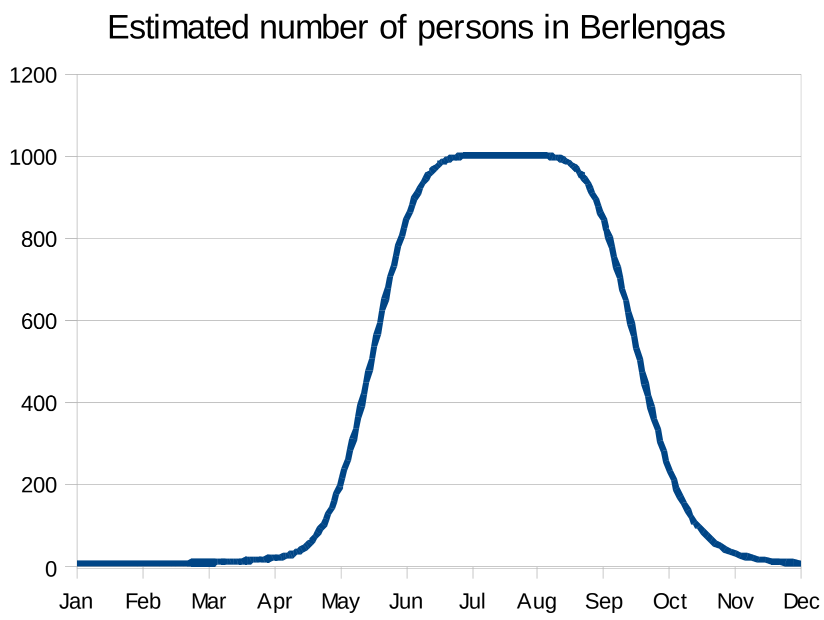
Electricity was until recently fully provided by electrical generators running on diesel. There are several problems with the existing system, besides the cost, there is risk of fuel spills and high carbon emissions associated. In summer the generators work until midnight. Recently a small photovoltaic array was installed in the islands as a pilot project and is planned to be expanded.

Camping area

Detail of Bairro dos Pescadores, the main building area besides the fort and lighthouse. The restaurant, mini-market, support buildings, water elevation equipment, rooms for renting, some private houses and public bathrooms are in this part of the Island. Below the small sear port is visible.

5.2.2 Occupation

Nowadays, the archipelago permanent population consists of two lighthouse keepers, two watchers from the Nature Conservation Institute and a few fisherman.
During the low seasons divers, nature observers and occasional tourists visit the island.
There is a considerable seasonal Summer touristic activity, with the island receiving about 1000 visitants every day.



5.2.3 Water sources and usage

All potable water has come for many years from the mainland by boat, which is still the main source of fresh water. The existing system is highly disadvantageous:

- The cost of water ascends almost to a very high 30€ per cubic meter
- Requires boat trips to the island
- The water is transported in containers. Transporting water introduces additional quality concerns.
- There are carbon emissions related to the water transport from the mainland

The transported water is distributed for several reservoirs in the island, from where it is fed to 3 collective taps managed by local operator, restaurant, camping, park facilities and some private households.

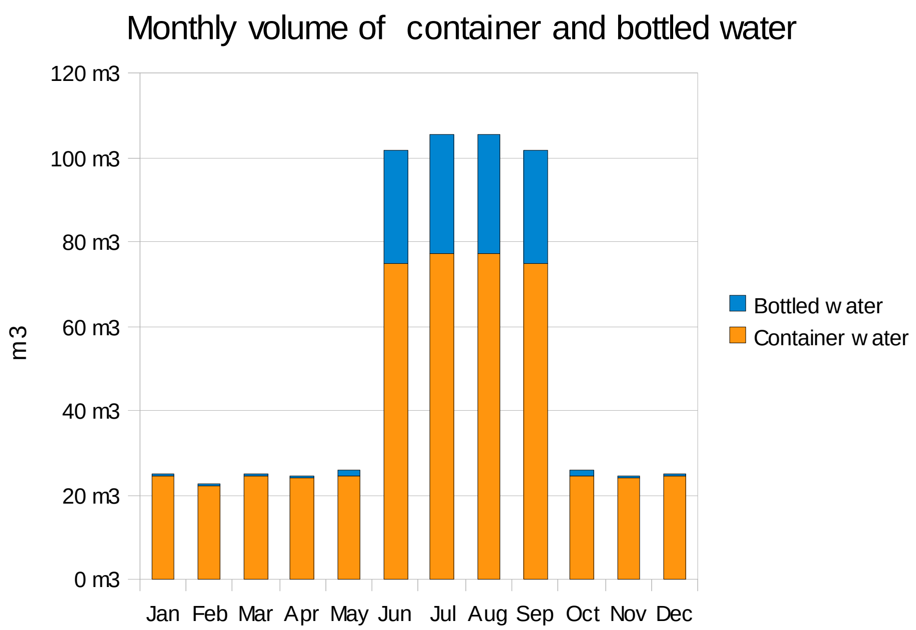
During low season some rainwater was collected, in small amounts. This practice is not done during summer, and even if it was the amount of precipitation is low.

From studies conducted on the island there is information on the amount of transported water in containers.

Besides this water there is a lot of bottled water being consumed in the island, for the comfort of the tourists and for lack of trust in the transported/collected water quality. The quantity of bottled water consumed is here estimated in a conservative way to be 1 liter per person in the island, including all bottled water for drinking or cooking (in camping).

Sea water is pumped to another set of small containers, and distributed among the infrastructures.

One or two small desalination units were assembled in the past, one of them for the fort. One unit stopped working due to poor maintenance , helped by the fact that the manufacturer of the unit had stopped activity. These units, running on electricity required reinforcement of the diesel based electrical generation capacity installed.



For bottled water 1 liter / person / day was considered.

An estimate of the high season fresh water consumption is above 3.5 m^3/day, of which 2,5 m^3/day being transported by boat in 8 m^3 containers. A total of about 630 m^3/year is consumed, around 68% of which in the high season. From this total 500 m^3/year are being transported in container by boat and 130 m^3 are bottled water.

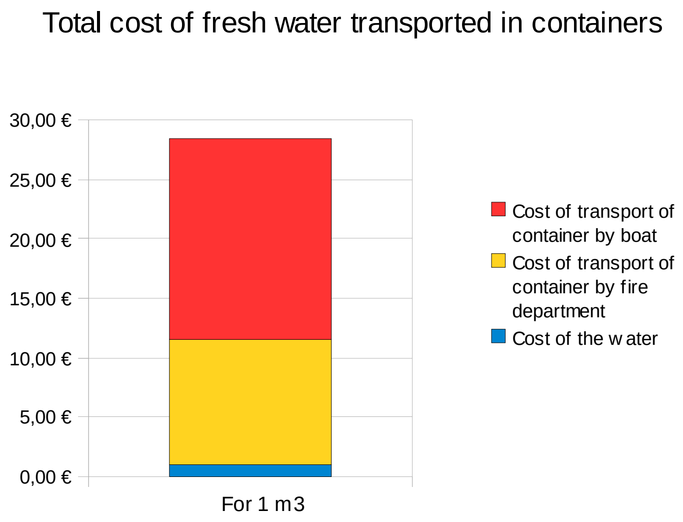
The present fresh water consumption in the island is also restricted due to poor supply. For example:

- In the available and public fresh water points the valves handles are removed during the night to prevent unauthorized utilization, and the consumption is controlled daily by a municipal worker.

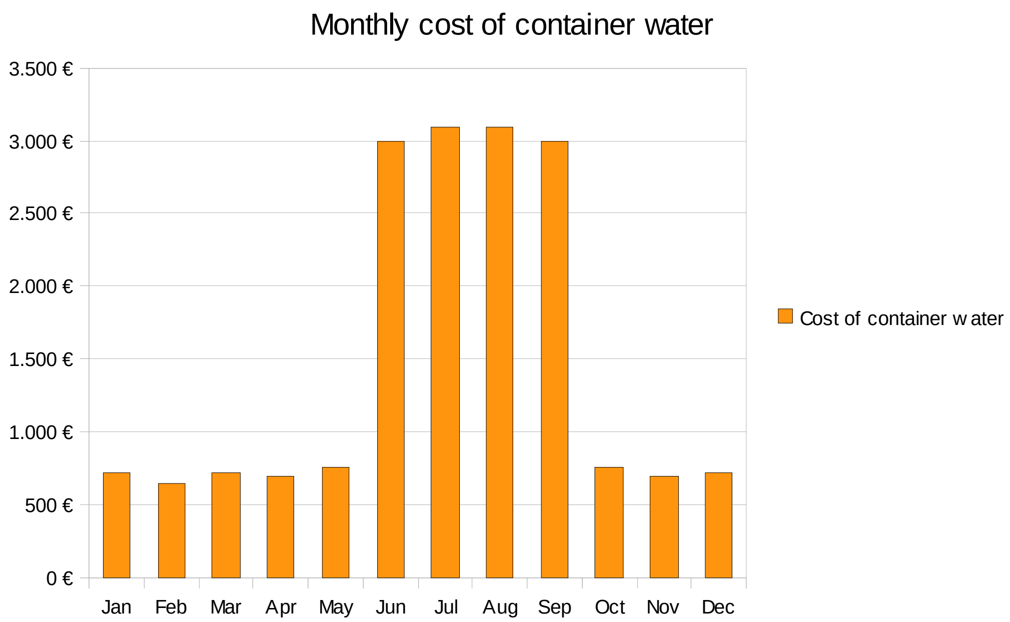
- in the camping there is a limit of fresh water made available to each camper, made available with the camping site card presentation

5.2.4 Fresh water cost

The cost of **container transported water** breaks down like this:



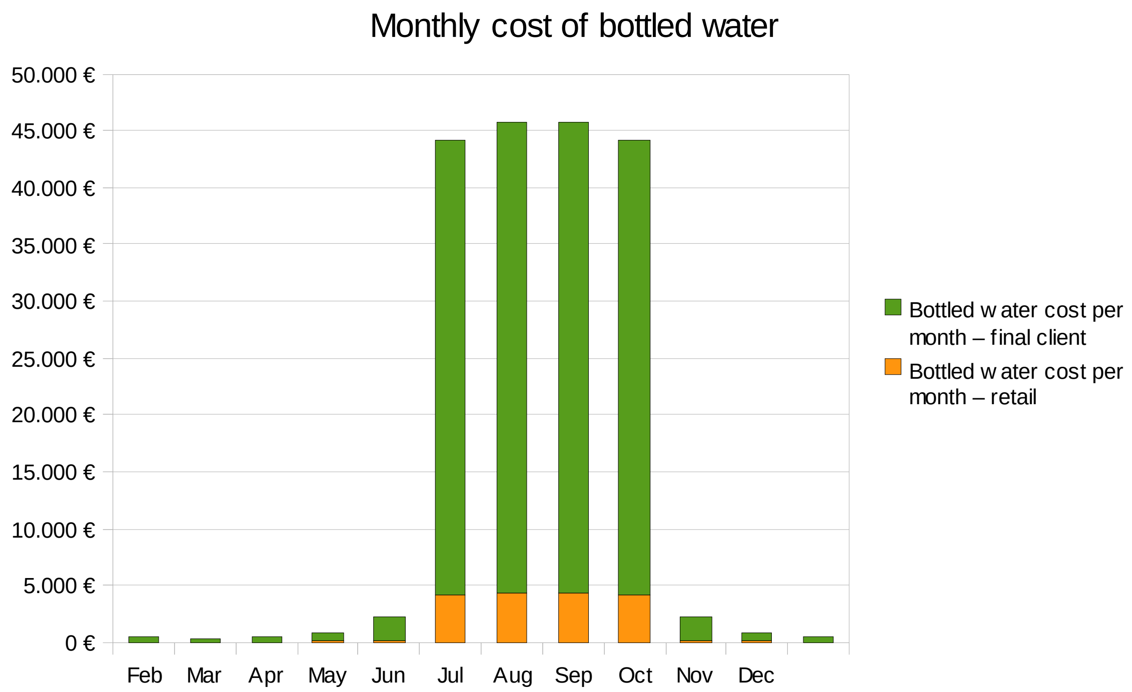
The cost associated with potable water transported in containers to the island is:



In Portugal a 5 litter of **bottled water** costs to the final consumer in a supermarket typically between 0.07 € - 0,25 € per liter, and to the retail seller about 0.07 € – 0.09 € per liter. Here 40% additional cost is considered for transport to the island. The retail cost of the water should be then around 140 €/m^3.

In general water in touristic areas is bought in smaller bottles in the restaurant or to be taken to the beach. A 1,5 liter bottle can cost around 2€ in a beach area like Berlengas, about 1.30€ - 1.50€ per liter.

So the retail and final customer cost of the bottled water sold in the island is around:



5.3 Desalination water supply strategy

The Government is interested in promoting the island as an ecological location, and is considering some investments in it. There are also some companies that may be willing to participate in a social responsibility and environmental initiative.

Two main strategies are possible:
Strategy #1 – Provide desalinated water to cover the water transported in the containers, without replacing the bottled water. In this case the desalinated water will be used mostly for washing and bathing.
Strategy #2 – Provide desalinated water to replace the container transported and partially the bottled water. In this case drinking quality would have to be ensured.

The second strategy would be a much bolder strategy for such a natural touristic location, setting an ecological example. Bottled water is being publicly contested by some ecologic movements in Portugal because of the solid waste it produces and because the piped distribution network water has good quality also.

The Municipality could adopt a program of promoting tap water drinking in Berlengas as part of the ecological plan of the islands. Of course the drinking of desalinated water instead of bottled water cannot be enforced. But with a proper motivation and campaign a good share of the bottled water consumption could be converted to desalinated water consumption. A significant reduction of plastic bottles waste could be achieved if the visitants would have the sense of contributing to maintaining the island clean and ecologic.

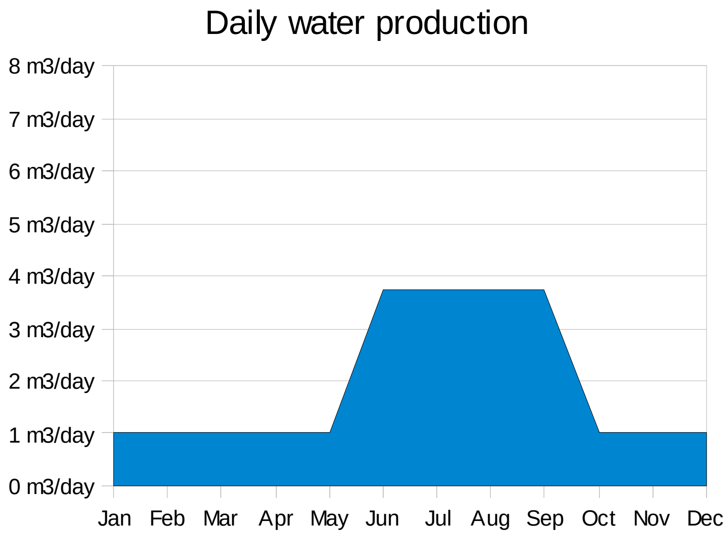
- Because most of the Portuguese population does not have any contact with drinking desalinated water a public information campaign would have to be conducted. The experience in Porto Santo with desalination could be used as a reference.
- Would be necessary to fully ensure the water quality. Regular monitoring should be conducted and results should be both made public locally and available through the internet.
- Not only solid waste reduction would be achieved but also the global carbon footprint of the island would be improved.

For restaurants and supermarkets bottled water is not a cost but a revenue. If 0,20€ profit is made when selling a 0,33 liter bottle that means 600€ profit per m^3 of water sold. Hence the commerce would continue to push bottled water selling in any case. But tap water glasses for free would be served, as is a common practice in Portugal, allowing the customers to have a choice.
For camping and room renting potable tap water freely available would be an improvement, that could allow the owners to consider increasing the room / camping prices.

5.3.1 Daily production estimate

Taking the following scenario, the below daily volumes of desalinated water production can be estimated:

- Adopting strategy #2, producing water for drinking, partially replacing the bottled water consumption.
- 60% of the bottled water consumption would be replaced by desalinated water production.
- Once the present condition of potable water relative scarcity and high cost is overcome an increase of 25% of the non-bottled fresh water consumption would take place.



So the installed capacity should be around 4-5 m^3 / day to ensure that the island can fully abandon the present boat transport of water, without risking lack of water in a peak situation.

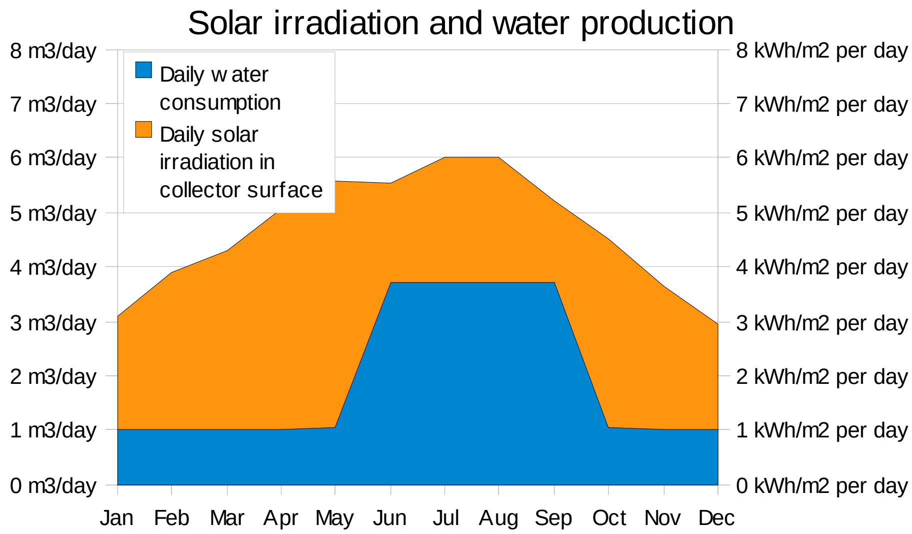
5.4 Technology selection

For this volume of daily water production the technologies in commercial stage that are suitable are:

- Solar thermal multiple effect humidification (ST-MEH)
- Photovoltaic, wind or hybrid reverse osmosis (WIND-RO)
- Photovoltaic, wind or hybrid reverse osmosis (PV-RO)

The experience in small wind desalination systems is lower in comparison with photovoltaic. For wind a good assessment of the wind potential would have to be made in the island and a proper location for a small wind unit would have to be found.
Another aspect is the short term fluctuations in the wind power supply, which pose additional challenges, in particular in the summer when the availability of water is more critical.

For solar thermal and photovoltaic technologies the renewable energy resource (solar irradiation) is maximum when the load is maximum. Below is a plot of the available daily irradiation in Peniche/Berlengas that reaches a collector field facing South and tilted to local latitude, plotted together with the daily water consumption expected.



Although investment costs are lower for PV-RO than for ST-MEH the operation and maitenance costs are normaly lower for ST-MEH. Depending on the specific installation conditions the water cost from ST-MEH can be lower than PV-RO after 4-9 years.

For this study the ST-MEH technology will be considered, with the standard modules of MAGE WATER MANAGEMENT and with high efficiency AO SOL's CPC MAXI collectors.

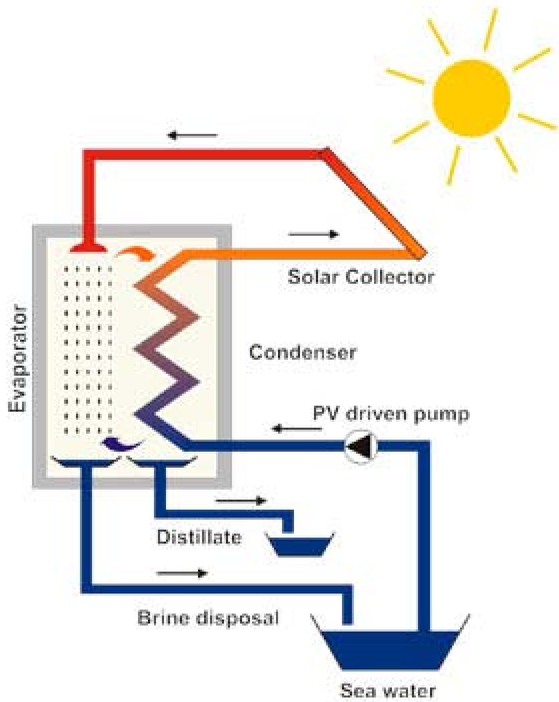
Because there is no grid electricity on the island a photovoltaic system is planned to power the desalination system. It will have a peak power of 3.5kW and a battery bank for night operation, providing solar field and desalination unit operation, control and illumination needs. Raw water pumping energy would have to be calculated depending on chosen location, and the corresponding PV additional capacity added to the calculations of this study.

5.5 Installation overview

5.5.1 Desalination unit

The MidiSal 5000 unit of MAGE has the appropriate 5 m^3/day production rate.

The MAGE WATER MANAGEMENT's SAL-MEH desalination process is based on the evaporation of sea water and the subsequent condensation of the generated steam.



The steam is completely clear and does not carry any solvents. Following condensation, the unit yields clear, healthy and distilled fresh water.

Sea water is heated by the sun or by waste heat – transferred by superbly corrosion protected heat exchangers. The sea water enters an evaporation chamber made from high-grade, anticorrosive materials – very important for reliable long term operation. Here the sea water evaporates off of efficient
antibacterial fleece surfaces.

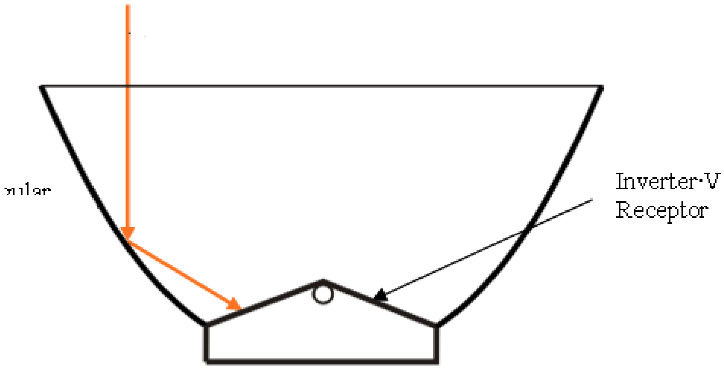
The unit is shipped in a 20’ CSC container, with base area of 2.44 m x 6.06 m.

Midisal installed in solar driven desalination system in the south of Jeddah, KSA

5.5.2 Solar thermal collectors

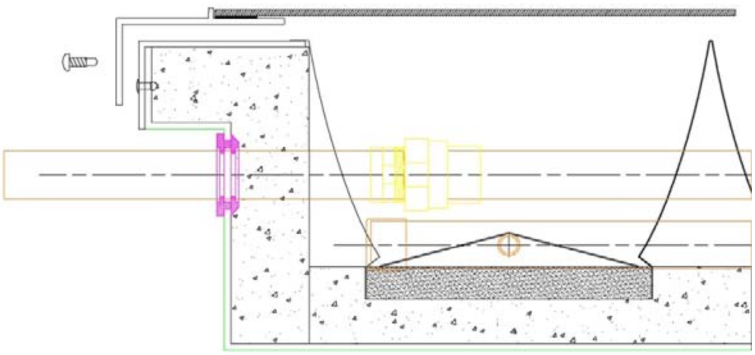
The solar collectors considered are AO SOL's high efficiency solar thermal stationary concentrator CPC MAXI.

AO SOL's CPC collector use patented optimal non-imaging optics to concentrate the solar radiation that reaches the collector in a smaller absorber plate. By reducing the hot surface to a smaller absorber the collector has lower thermal losses, especially in temperatures that are above normal domestic hot water applications. The optimal optical design, based on non-imaging optics and the quality of the materials make AO SOL CPC a first class solar collector.



CPC MAXI reflectors and absorber principle

AO SOL's CPC MAXI collector has about 5.5 m2. This large collection area make it ideal for easy assembly of large collector fields, in less time and with less accessories. It has a concentration factor of 1.5x. and has two different configurations: with or without an internal anti-convection barrier (TIM).
The optical efficieny is 0.77 and the loss coeficient is 3 $W/(m^2.K)$ (without TIM) or 2.3 $W/(m^2.K)$ (with TIM).



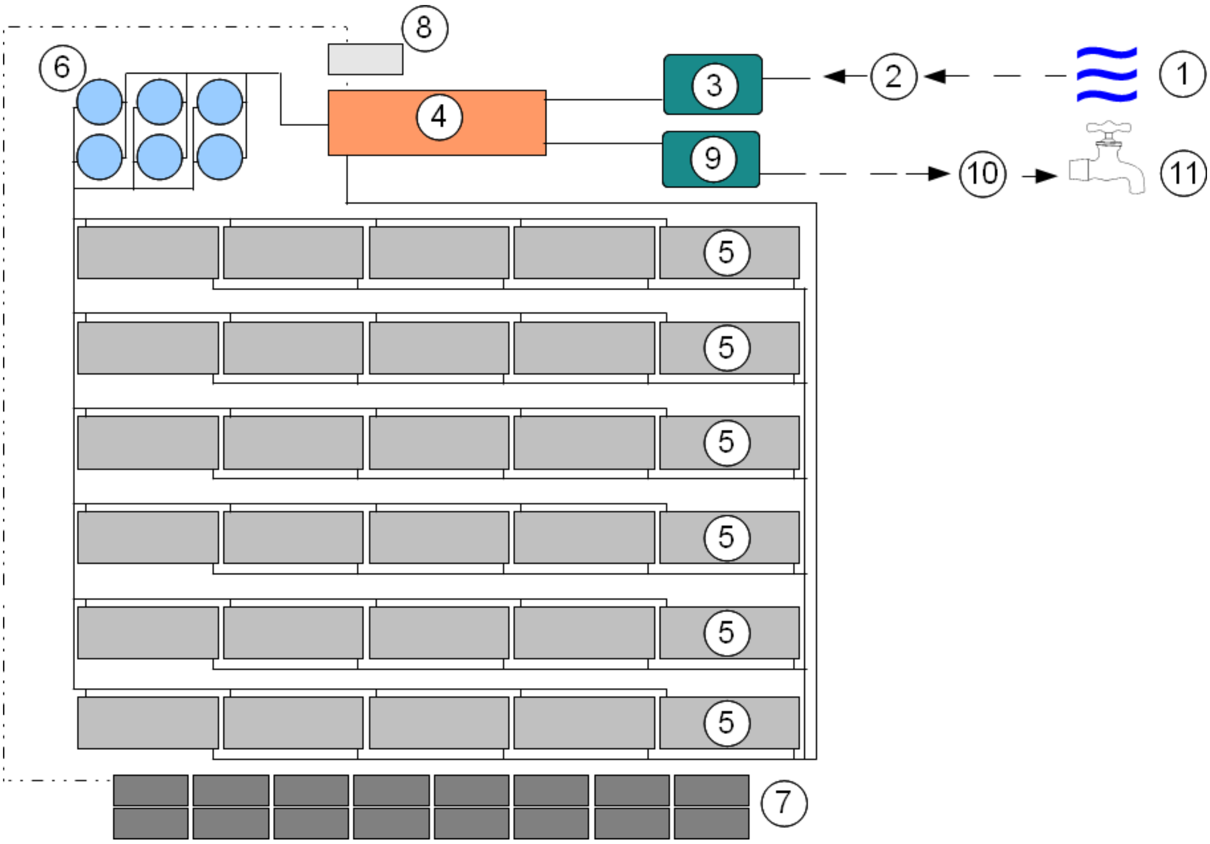
CPC MAXI's section

MAXI (5.5m2 area) and AO SOL's standard product CPC 3E (2m2 area). Being tested in AO SOL's factory test bench.

100 m2 MAXI collector field installed in a demonstration desalination plant in Carboneras, Spain (project MEDESOL)

5.6 Basic layout

The basic layout for the proposed system is :



The plant is basically composed of:

1. Raw water source
2. Raw water pumping station
3. Raw water tank
4. Desalination multiple effect humidification unit MIDISAL, with heat exchanger to separate the desalination unit loop from the solar collector hot hater loop
5. High efficiency solar thermal stationary concentrator CPC MAXI collector field
6. Thermal energy storage for night operation
7. Photovoltaic array to cover the electrical consumption
8. Inverters, batteries and control
9. Distilled water tank
10. Drinking water conservation kits with UV and mineralization
11. Potable water consumption

5.7 System Sizing

5.7.1Monthly thermal needs of the desalination unit

The desalination unit MidiSal can be operated 24h/day with solar collectors, which is in fact recommend for the economic optimization of the desalination unit. During the day the solar collector field hot water is directly fed into the desalination unit. For night operation the solar field is increased and the thermal energy is partially stored in hot water tanks to be used in the night.

From the MidiSal datasheet can be seen that:

- 20 kW thermal power delivered at 85ºC (or up to 98°C) are required for nominal operation of the unit
- It produces 5 m^3/day = 0.21 m^3/h

Hence, assuming 10% losses thermal storage:

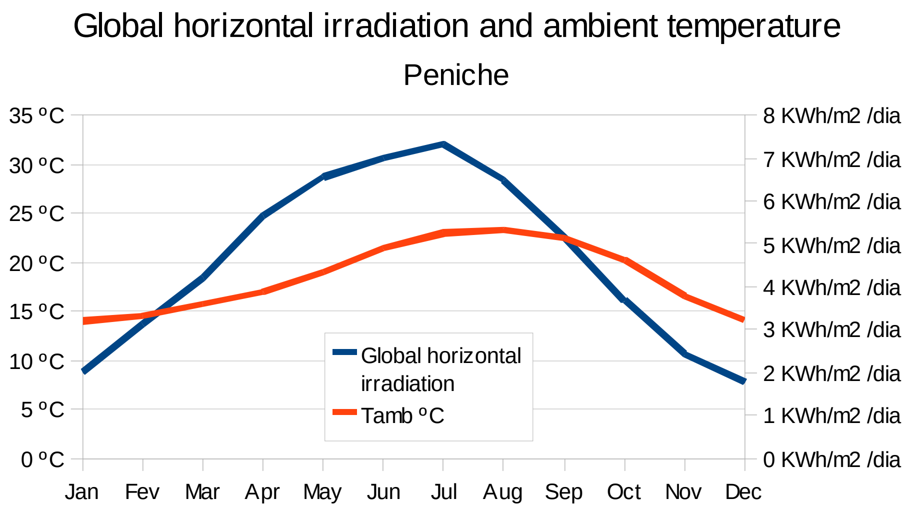
	Direct use of solar energy (day operation)	**Indirect use of solar energy (night operation)**
Losses	Piping and heat exchanger efficiency	Piping, heat exchange efficiency and storage heat losses (10%)
Nominal thermal power required by desalination unit	20 kW thermal	20 kW thermal
Additional thermal power to cover storage losses		2,22 kW thermal
Thermal power required (total)	20 kW thermal	22,22 kW thermal
Energy required per m3	96 kWh thermal /m3	106,67 kWh thermal /m3

With this and the water demand (already presented) the monthly energy needs of the desalination unit can be calculated.

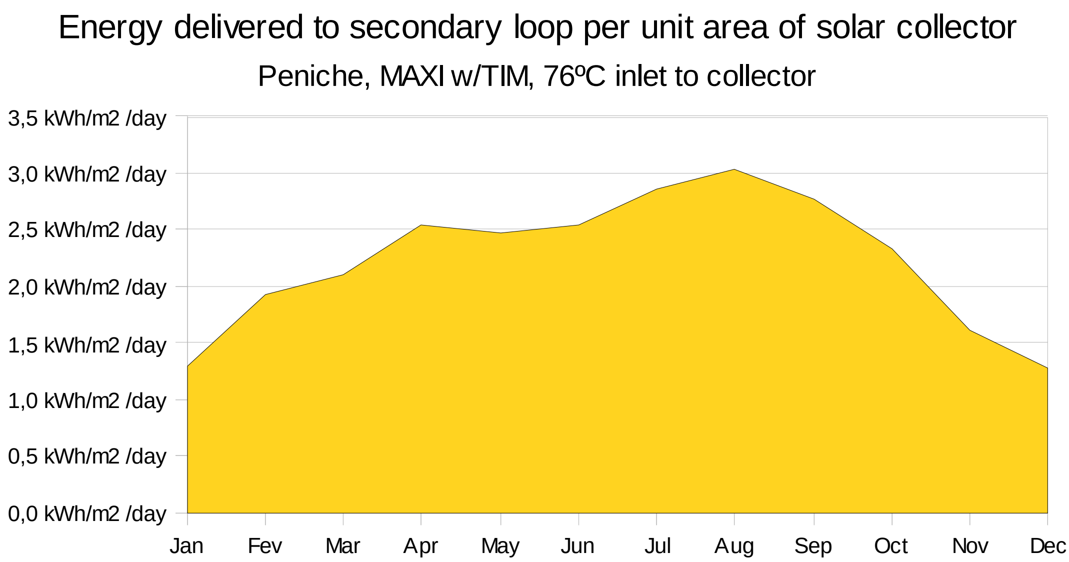
5.7.2 Monthly energy that can be produced per unit of collector area

The energy that the CPC MAXI (with TIM) solar collectors can provide at the MidiSal nominal temperature range of 84ºC /76ºC can be calculated with the collector characteristics and the usability method.

The climatic data are the following:



The resultant energy delivered by the collectors to a secondary loop through an heat exchanger with 75% efficiency , with 40 kg/h per m2, and inlet temperature to the collectors of 76ºC is:

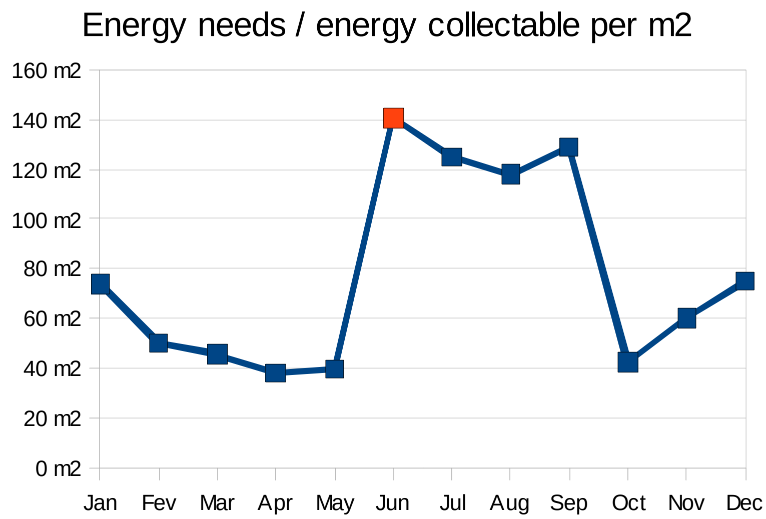


5.7.3 Critical month

The ratio:

$$\frac{\text{monthly thermal energy desalination needs}}{\text{monthly collector energy harvest per m}^2\text{ of solar collector}}$$

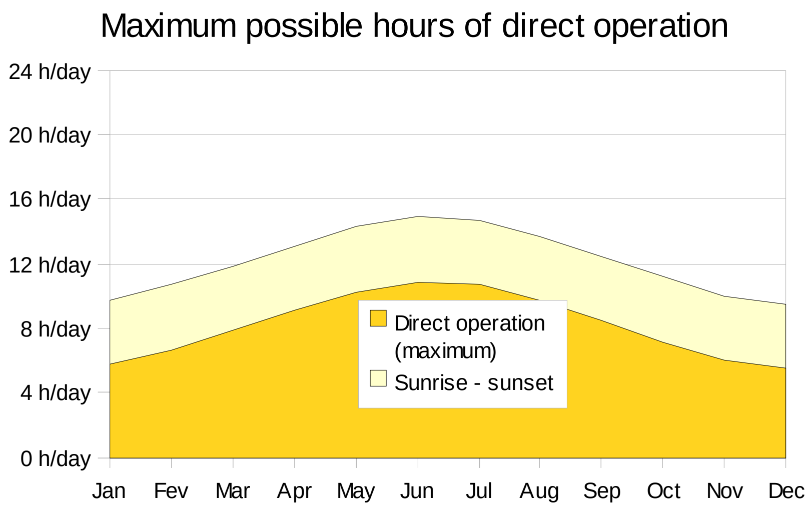
when calculated for direct operation (no storage) gives the area of collectors needed for each month if was possible to meet the water demand with 100% of daytime operation:



From this the most critical month is identified to be June. The reason is because it combines a high affluence to the island with still low ambient temperature.

5.7.4 Load matching in critical month

In June there are almost 15h of sun per day. Considering that in average there are 4 of these hours of sun during which there is not enough solar radiation collected in the solar field to operate the plant without the storage, a total of almost 11h of direct operation is considered.



From the available amount of direct operation time and the direct operation parameters presented the data in the "Direct use" column can be calculated. The the required "Indirect use" daily water production can be calculated, to meet the water demand in this month. A safety margin of 15% over the estimated consumption is considered, resulting in about 4 m^3/day.

Critical month: June	Direct use (day operation)	Indirect use (night operation)	Total (24h operation)
Number of hours per day	10,9 h	8,4 h	19,3 h
Daily thermal energy required	218 kWh thermal per day	187,11 kWh thermal per day	405,11 kWh thermal per day
Daily water production	2,27 m3 per day	1,75 m3 per day	4,03 m3 per day

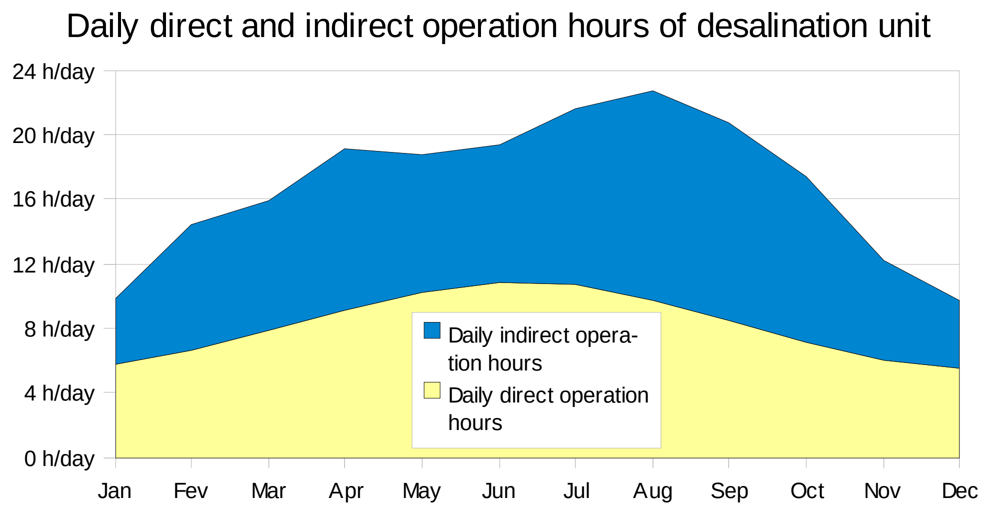
5.7.5 Collector field area calculation

From the daily thermal energy required for the solar collectors for direct + indirect operation and the collector monthly energy harvest (already presented) the collector area can be calculated to be about 160 m2.

5.7.6 Direct and indirect operation hours of the desalination unit

With the collector field area and the energy yield per m2 already presented the total daily energy collection can be calculated. According to the number of direct operation hours the direct utilization of this energy can be determined. The remaining energy can be stored and used in indirect operation.

The result number of hours of operation of the desalination unit is in this way estimated to be:



5.7.7 Thermal storage for night operation

According to the number of indirect operation hours calculated the maximum number of hours of operation based on storaged thermal energy is almost 13 h.

But a bigger storage, enough to cover one full day of production in peak summer water demand, will be dimensioned. From the previously presented energy needs of the system can be seen that for the production of 3,73 m^3 of water (peak day value) will be necessary to store about 397 kWh of thermal energy.

The water should reach the heat exchanger for the desalinatin unit at 84ºC. For a practical volume of storage tank water should be stored above 100ºC, 110ºC will be considered. The water volume be calculated from:

$$m_{water} = \frac{E_{stored}}{C_{P(water)} \times \Delta T_{water}}$$

Hot water usage temperature	84 ºC
Maximum design storage temperature	110 ºC
Temperature delta	26 ºC
Energy to store	397,33 kWh
Necessary water volume	13,16 m3

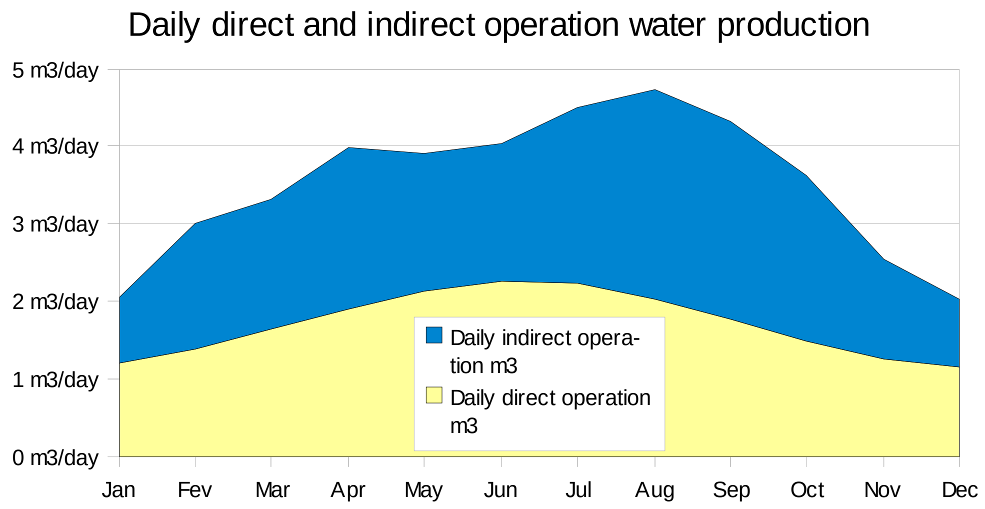
14 cubic meters willbe considered.

5.7.8 Drinking water buffer

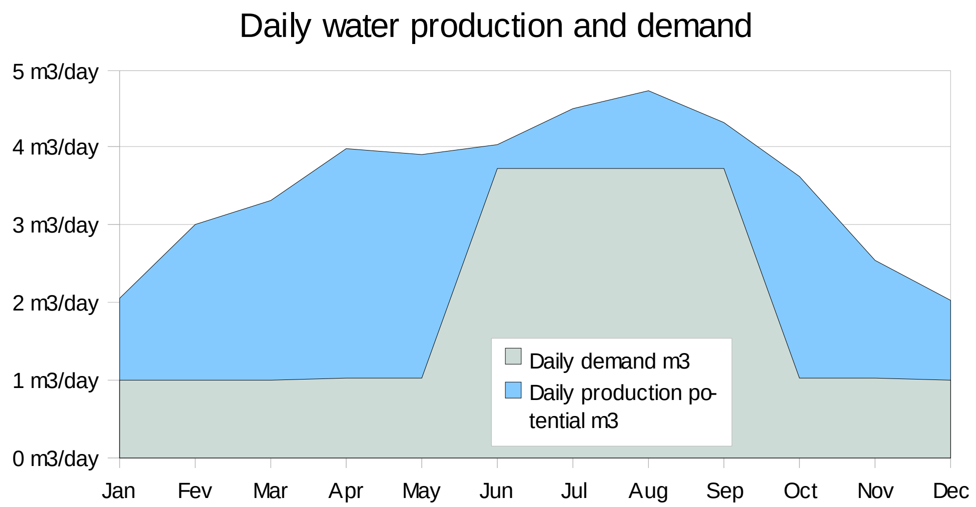
A drinking water buffer for 4 days of peak consumption will be considered. This corresponds to 15 m3 of drinking water storage.

5.8 Water production

From the previous section the water production can be plotted:



And can be verified that the load is met, with a safety margin:



5.9 Economic Evaluation

5.9.1 Installation costs

The installation costs considered are the following:

Item	Cost	Notes
Concrete slab	10.000,00 €	
Desalination unit cost	60.000,00 €	MidiSal
Solar thermal field	47.725,62 €	159 m2 of CPC MAXI w/TIM collectors at 300€/m2 (installation included)
PV system	21.000,00 €	3.5 Kw_peak (with installation),includes battery bank for night time operation
Storage for raw water	1.200,00 €	5 m3 non insulated, atmospheric, installed
Storage for hot water	6.720,00 €	14 m3 insulated, pressurized, installed
Drinking water tanks	2.773,00 €	15 m3 potable water tank in high density PE, for human water consumption
Drinking water kit(s)	2.250,00 €	Supplier recommends re-mineralization and disinfection devices with UV when water is for drinking and needs to be stored
Transport of equipments to the island	7.500,00 €	By boat and on the island
Engineering and supervision	36.000,00 €	
Total initial investment	**195.168,62 €**	

5.9.2 Operation and maintenance costs

Regarding operation and maintenance costs the following should be taken into account:

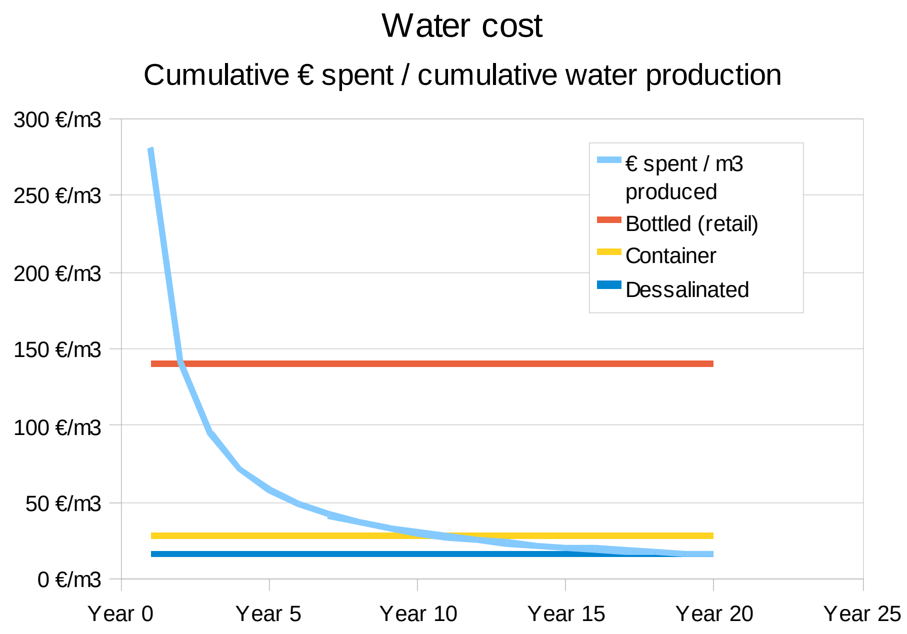
- Pump maintenance and replacement
- Evaporation sheets replacement
- General maintenance
- Water mineralization consumables
- Boat travel of maintenance personnel to the island, and accommodation in the island facilities

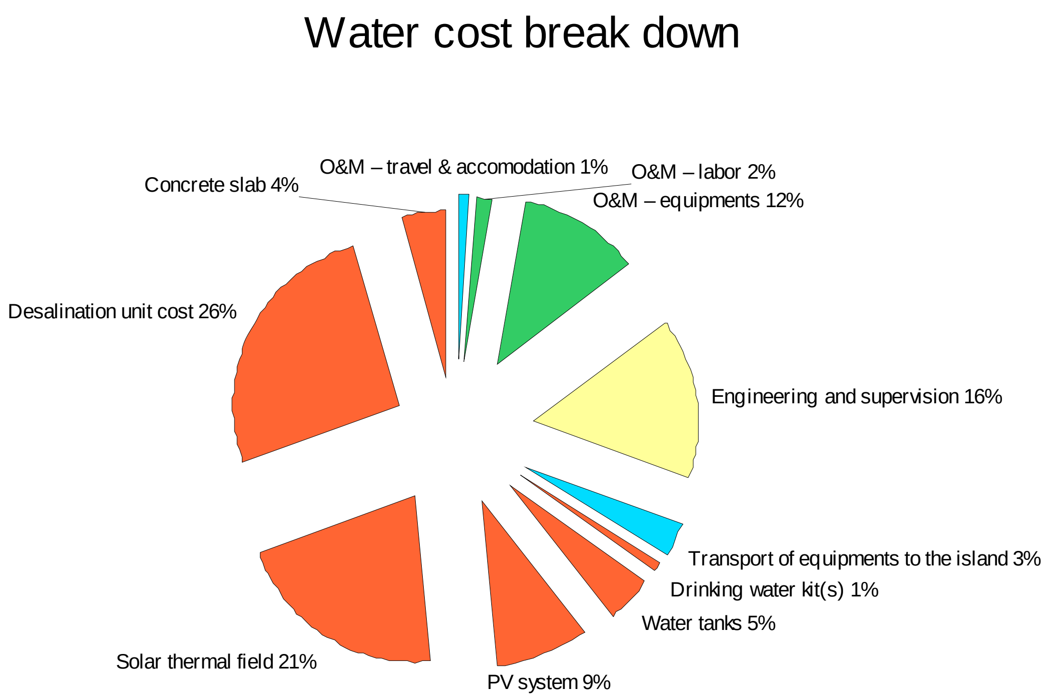
Resulting in the following estimated O&M costs, over 20 years of operation:

Item	Yearly costs
Parts and equipments	1.358,33 €
Labor costs	185,00 €
Maintenance personnel travel and accomodation in the island	141,67 €
Total yearly O&M costs	**1.685,00 €**

5.9.3 Water cost

A water cost over 20 years of about 16-17 €/ m^3 of water should be attainable. It is plotted in chart below,as well as the much more costly options of the present transported container water tanks water and bottled water:





The water cost breakdown shows that the initial cost of equipments and infrastructure represents about 66% of the water cost (red in the pie chart). Site specific additional costs of transportation of equipments to the island and maintenance personal travel and accomodation represent 5% (light blue). Operation and maitainance represent 13% of the total cost of the water (green). And engineering and supervision 16% (yellow).

From the desalination unit side this is a sub-optimal setup, since the dessalination unit is not operating 24h per day. But is this case seems to be more economical configuration, because the desalination unit capacity is higher that the load.

If the water demand was higher, even keeping the same solar collector field, utilizing all the available energy to produce water the water cost would be around 8-9€ /m^3 (20 years).

In case of a green light to promote such a system on the island, more detailed calculations would be made, with the goal of making a final optimization which might still reduce costs. For instance the relationship collector area/hot storage volume can and should be optimized, likely resulting in a reduced hot storage volume, etc.

Also the estimates of transport costs and the cost of local work and materials can and should be refined, with specific consultations and offers, something which is clearly beyond the scope of this study, for which known average values were used.

It is interesting to note that the cost of this system is still such that it provides a cheaper alternative to present day water, not to mention a much larger availability of it.

5.10 Conclusions

The installation of a solar thermal multiple effect humidification in the Berlenga Island proves to be a cost effective solution, providing water around 43% less costly than of the current boat transported water used for bathing and washing. It would also provide 8-9 times less costly water for drinking than the present bottled water solution (retail price).

The installation of such a system would reduce the ecologic footprint of the island very significantly, namely:

- Eliminating boat transport of washing fresh water
- Reducing to half the bottled water consumption
- Reducing solid waste production resultant from bottled water consumption
- Not introducing any additional fuel consumption (electricity is generated in photovoltaic)

In terms of comfort of living for the residents, campers and hotel rooms there would be a significant improvement, with quality controlled potable water network permanently available and less restrictions in water use.

For tourism operation, the main island income, there would be two advantages. On one hand there would be an improvement of tourist basic infrastructure with a good, controlled, potable water network. On the other hand an additional attraction of an ecological desalination system driven by renewable energies would be added to the natural richness of the island.

Annex: List of references

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