Techno-economic Analysis for the Optimal Hybrid Renewable Energy based System Planning in Autonomous Islands of Aegean Sea

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Abstract

Most small and medium size Greek islands of Aegean Sea cover their electricity needs on the basis of autonomous thermal power stations consuming remarkable quantities of imported oil. Additionally, several small islands cover their needs for clean water with water imports at an extremely high cost. In this context, the current work summarizes an extended and systematic research effort spent in order to face these important and pressing problems of our islands.

More specifically, under the framework of the PHAROS (Aristia-II) research project, a comprehensive planning tool for the study of hybrid renewable energy systems (RES) to ensure meeting the demand for energy and water in the small and medium scale autonomous islands of the Aegean Sea has been developed. The newly developed software tool E.S.A. followed a methodology based on hourly basis calculations. The RES production (wind and PV actually) is compared to the energy demand of the under examination system and accordingly the needs of the required storage devices are revealed. The operational characteristics of the desalination plants are also estimated according to the annual water consumption of the island under investigation.

A preliminary economic evaluation of the whole system (Wind-PV-Battery-Diesel-Desalination) has been undertaken and a great number of possible solutions are produced under this setup. Based on the techno-economic results identified, the optimal solution for each island may be selected. According to the results obtained the proposed solution can be implemented with limited initial capital cost (e.g. for an island similar to Agios Efstratios the cost of the proposed hybrid system can be approx. 3.6 MEUR with less than 4 days per year contribution from the island's diesel plant) accepting minimum operation of the existing thermal power station. This initial capital required for the hybrid power solution may be further reduced (e.g. by 40%) assuming some additional contribution (e.g. total 10% participation) of diesel oil plant in the total annual electricity consumption of the island.

Recapitulating, the proposed solution may significantly contribute on reducing the operational cost of the existing autonomous electricity generation micro-grids improving at the same time the life quality of the local remote communities.

Keywords: hybrid system; battery; software tool, desalination, cost reduction

1. **Introduction**

The globally increasing energy consumption, the gradual depletion of conventional resources and the connection of the above with the greenhouse effect and climate change has led researchers from all around the world to implement a more sustainable and environmentally friendly way to generate electricity. The purpose of this work was to develop an environmental impact assessment methodology for hybrid systems spatial planning in autonomous islands of the Aegean Sea taking into account also techno-economic criteria. The proposed method combines the planning and the use of Geographic Information Systems (GIS) meaning a variety of criteria such as energy consumption, vegetation density, distance from roads, and other spatial constraints. Yet, the most important research output was the development of a software tool (tool E.S.A.) that techno-economically evaluates the proposed hybrid system (HS) for each island or proposes a hybrid system after optimization implemented in several Greek Islands. The islands were studied and selected: a) due to the fact that their energy system is not connected to the mainland (with no prognosis many of them to be connected in the coming years) and therefore their electricity generation cost is extremely high and b) because of the increased difficulties in planning and installing hybrid systems in intense touristic environments that involve high conflict of land use (Georgiou et al., 2011).

A methodological plan was developed focusing on determining the criteria for selecting the representative island and islands clusters and collect and prepare the required input data, in order to apply the integrated planning hybrid systems software tool (HSST). The plan (figure 1) followed was:

- ✓ Review of the scientific literature on RES and HS siting methodologies
- ✓ Building of a multicriteria decision making methodology
- ✓ Application of the tool and method to several Greek Islands

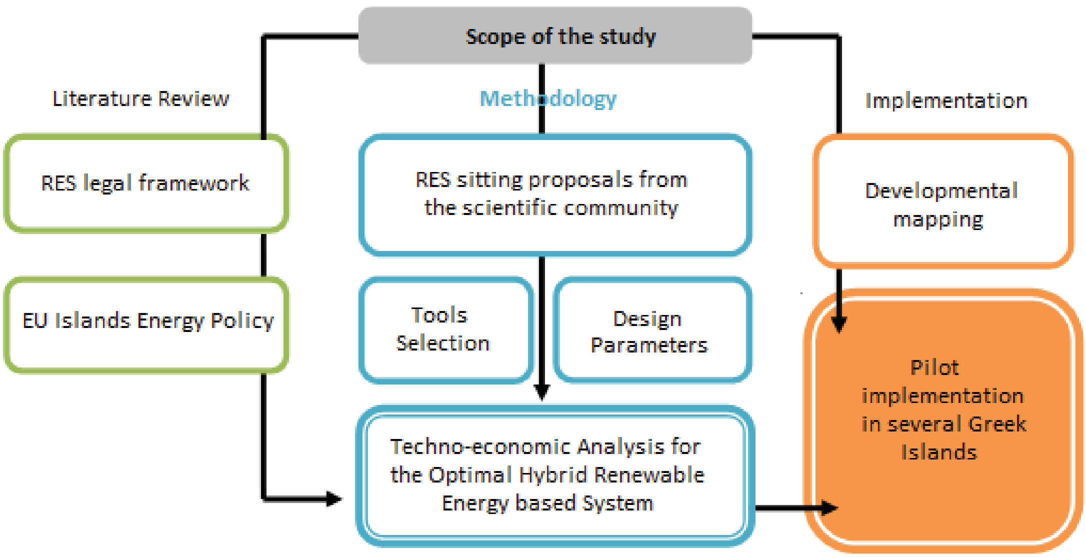

Fig. 1. Methodology Structure

Islands occupy approximately 1/6 of land's surface globally and host around 10% of global population (Island Studies, 2007). Their specific fragile and vulnerable nature makes it extremely difficult to apply sustainable (and innovative) energy policies in these (UN, 1992).

In the past decade, the issue of sustainability of island regions became bigger and bigger mainly due to high electricity generation costs and low RES shares and fossil fuels consumption (Kaldellis et al., 2009a; Gori et al., 2007).

Interconnected islands have the privilege of connecting with a large power grid and therefore carrying the possibility of 100% (or near to 100%) electricity production via renewable energy sources. Well known studies have been implemented for the Samsoe Island, Denmark (Gipe, 2006), the Pellworm Island, Germany (Koopmann et al., 2015) and Fox Island, United States (Dua, 2008).

Non-interconnected islands face the vicissitudes related to small network, such as significant frequency and voltage deviations (Notton et al., 2011). This makes RES penetration an even more difficult task, due to the fact that RES production is not continuous, and depends on the meteorological conditions. Studies on islands conventionally electrified, give a maximum RES penetration 25-35% (Papathanasiou and Boulaxis, 2006; Neves et al., 2011; Notton et al, 2011). Neves et al. analysed and presented that the most friendly hybrid system for islands with a population over 5000 inhabitants is the combination of diesel engines, wind turbines and PV systems. Similar studies integrating the local genset to the HS have been implemented in a large number of islands including the Maldives Islands (van Alphen et al, 2007), Lemnos Island, Greece (Koroneos et al., 2013) and Kutubdia Island, Bangladesh (Nandi and Ghosh, 2010). In order to achieve higher RES penetration local energy storage is of ultimate importance (Kaldellis, 2008). Some of the most popular energy storage items are batteries, pumped storage, and hydrogen storage. Each has advantages and disadvantages which need to be studied in connection each time with the local limitations of the island. A proper island system design can even reach up to 100% RES (Xydis, 2013a). In general, batteries find better application in small power systems because of their significant cost, while their comparative advantage is that it is possible to be applied everywhere, regardless of the particular geographical characteristics (Kaldellis et al., 2009b). Similar studies have been conducted for Fiji (Krumdieck and Hamm, 2009), and Corsica, France (Diaf et al., 2008).

It is worth noting that the issue of interconnection of the islands gained some attention again after the 90s because of the significant exploitability and potential of renewables in most islands.

For Greece, even though that there are studies, proposing extensive RES installations with a final installed capacity multiple of what the islands' require to meet their energy needs (Xydis, 2013b; Koroneos et al., 2005), it seems that the national target of 20% by 2020 of RES integration will not be achieved unless a major part of these studies are implemented (Mondol and Koumpetsos, 2013), which under the long lasting economic recession in the country it seems impossible.

2. Scope of the study

The scope of this work was to initiate a methodology proposing hybrid systems development in autonomous grids (islands) taking into consideration GIS and long term optimization planning. A detailed analysis in several Greek islands was implemented and detailed results are presented.

More than 17% of the Greek population lives in the islands. Among the 124 inhabited islands in the Greek territory, 36 are not connected to the national interconnected system and are defined as non-interconnected islands. The electrification of the non-interconnected islands is mainly done via autonomous thermal power stations and a very small percentage of RES in some of the islands. Under the context of PHAROS project, a comprehensive planning tool for the study of hybrid renewable energy systems was developed to ensure meeting the energy and water demand in the small and medium size autonomous islands of the Aegean Sea.

Regarding water, the management of the water resources in arid islands is following an unsustainable way. The central government, follows the costly water transport model wasting public money, while the technically mature solution of desalination remains unexploited.

Table 1. Quantities and costs of transported water per year in South Aegean

	CYCLADES			DODECANESE			TOTAL	
Year	Quantity (m^3)	Cost (€)	Specific Cost (€/m^3)	Quantity (m3)	Cost (€)	Specific Cost (€/m^3)	Quantity (m^3)	Cost (€)
1997	86.525	311.078,49	3,60	402.295	933.802,75	2,32	488.820	1.244.881,24
1998	91.050	650.755,33	7,15	484.994	1.312.419,05	2,71	576.044	1.963.174,38
1999	87.760	672.712,07	7,67	461.855	1.407.916,62	3,05	549.615	2.080.628,69
2000	145.570	1.158.370,19	7,96	555.212	2.004.234,58	3,61	700.782	3.162.604,77
2001	203.792	1.625.093,41	7,97	621.297	2.722.540,50	4,38	825.089	4.347.633,91
2002	329.343	2.561.278,36	7,78	617.745	3.109.358,65	5,03	947.088	5.670.637,01
2003	336.777	2.772.718,04	8,23	605.019	3.214.680,89	5,31	941.796	5.987.398,93
2004	338.812	2.787.235,66	8,23	759.737	4.034.203,29	5,31	1.098.549	6.821.438,95
2005	464.562	4.006.916,45	8,63	969.676	5.082.935,63	5,24	1.434.238	9.089.852,08
2006	567.719	4.677.686,54	8,24	1.005.338	4.905.044,06	4,88	1.573.057	9.582.730,60
2007	697.117	4.006.916,45	5,75	1.101.628	5.082.935,63	4,61	1.798.745	9.089.852,08
2008	687.731	5.721.922,00	8,32	1.141.724	5.765.706,00	5,05	1.829.455	11.487.628,00
2009	429.075	3.569.904,00	8,32	826.910	4.175.896,00	5,05	1.255.985	7.745.800,00
2010	306.851	3.068.076,44	10,00	413.909	4.061.370,23	9,81	720.760	7.129.446,67
2011	280.784	3.108.278,88	11,07	288.885	3.197.956,95	11,07	569.669	6.306.235,83
2012	246.581	2.729.651,67	11,07	265.164	2.935.365,48	11,07	511.745	5.665.017,15
2013	221.315	3.084.065,84	**	253.276	3.298.081,04	**	474.591	6.382.146,88
2014*	60.441	817.766,73	13,53	66.050	893.656,50	13,53	126.491	1.711.423,23
TOTAL	**5.291.477**	**43.428.594**		**10.774.664**	**53.946.366,31**		**15.821.437**	**105.468.530**

*till May 2014
**with not a fixed price throughout the year

In table 1, there is a summary of quantities and costs of transported water per year in South Aegean. The high costs for water transportation in arid islands can be confronted without the use of vessels for the transportation, but with the use of desalination. For this purpose, an alternative and integrated planning mind-set was followed by the researchers involved in the PHAROS project, in order to meet the energy and water needs at several Aegean islands, the existing experimental, hybrid RES station (small wind turbine, PV, batteries) in the Laboratory of Renewable Energy and Environmental Protection (SEALAB) of the University of Piraeus of Applied Sciences was upgraded, adding a desalination unit with reverse osmosis (Figure 2), suitable for the under scale experimental simulation of various RES hybrid (including desalination) schemes. The experimental desalination pilot unit supports the study of various energy performance parameters and substantially contributes to develop an integrated experimental RES hybrid facility including water production.

Fig. 2. SEALAB RES hybrid (including desalination) experimental unit

One of the basic needs of the integrated hybrid system studied by the experimental facility was to identify the proper way to dimension the system taking into account that the excess energy generated from RES could be utilized powering the desalination subsystem. In the experimental facility, the optimal way of the desalination operation was tested within the HS setup and was integrated to form a unified small scale HS.

3. **Methodology**

The development of an analytical database (DB) that includes detailed long-term meteorological data for many small and medium size autonomous islands of the Aegean Sea, based on the characteristics of the local RES potential, as well as information related with the environmental impact of the energy utilization was initially implemented. The transported water data were included, load, heating, and fuel consumption, all the necessary geographical information (Natura sites, protected areas, infrastructure etc) for the siting and installation of HS in the islands examined. Figure 3 (top) shows the user interface of the DB (Database-SL), which includes separate tabs (with specific information loaded) meteorological data, for South or North Aegean for different years. It also gives the opportunity to the user to compare meteorological data, to check/compare water shipments and electricity demand. It was built in such a way to offer the chance to the user to load wind speed, ambient temperature, air pressure, solar radiation, and air density data, printing out the relevant charts. Database-SL tool was built in C#.

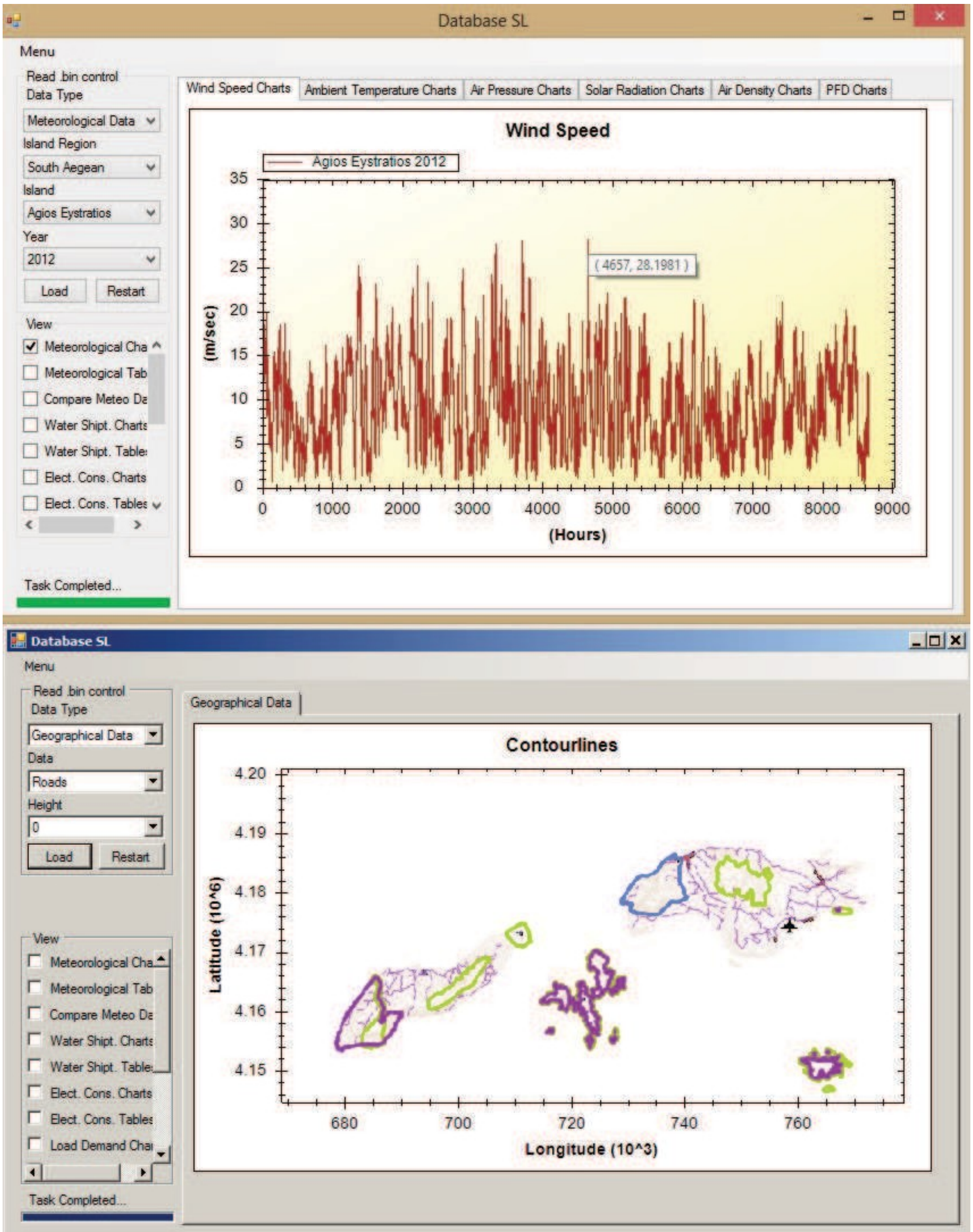

Fig. 3. DatabaseSL user interface (geographical and data interface)

In figure 3 (bottom), this simple GIS tool developed, can include all environmental and geographical constraints required to be taken into account for the initial sitting plan of the HS.

At the same time, a comprehensive simulation tool (ESA) was developed (Figure 4) for analysing every possible RES HS design to meet energy and water needs, incorporating both demand management techniques and desalination. An intensive developing process, also constructed in C# follows the necessitate and usual tool versioning for the different tool's outputs. ESA v2 is the current version, however the tool continues to be improved mainly by shrinking the required time for calculations.

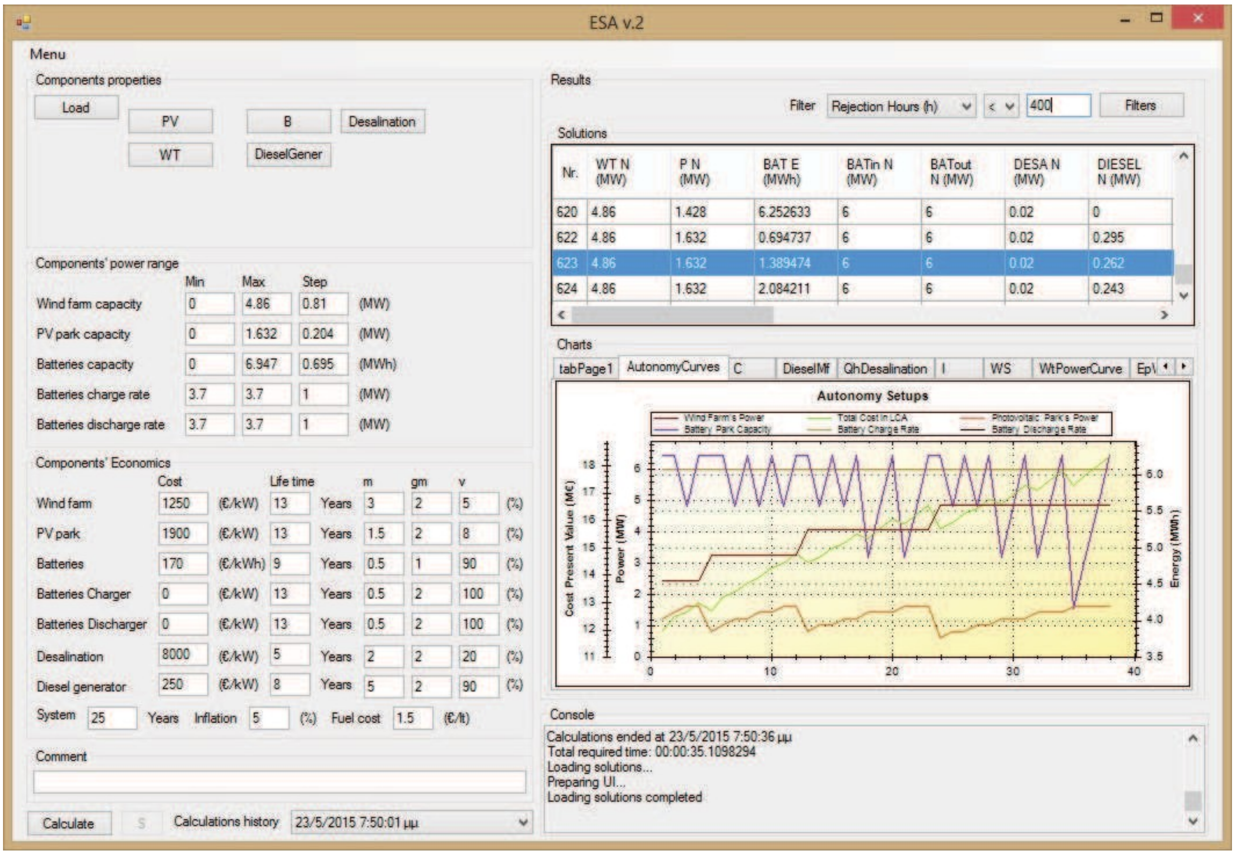

Fig. 4. ESA user interface

The methodology followed by the simulation tool starts with calculating the energy production. Calculations are made on an hourly basis. In the case of PV, based on the panel parameters, the power curve and the solar radiation, the temperature and the rated power of the park, and the energy production from the PV is estimated. This production is summed up with the wind farm electricity production which takes into account the standard power curve of each wind turbine and the wind resource of the area (based on the measurements that the user inserts to the tool). The next step is to compare the electricity generation with the demand and size the storage system (it may not be needed in all cases) under its technical constraints. The tool user takes also into account the total storage capacity, the maximum depth of discharge, the charging-discharging rate and the overall efficiency of the storage system. Regarding electricity demand, it is defined as the electrical demand is imported into the tool as a base load, adding however the electrical consumption required for the operation of the desalination plants. Desalination electricity consumption is obtained after the automatic sizing of the desalination system according to the annual water consumption that will be covered.

Last, a holistic evaluation/assessment of the total load coverage, total sizing and costing the HS, storage facility, desalination plant and the cost of the non-covered energy amounts according to the electricity deficit takes place. The methodology described is followed for different power combinations for the 1) wind farm, 2) solar park, 3) the desalination unit and 4) the maximum capacity of the storage system and its charging and discharging rate. As a part of this work and in order to cover the needs of the islands studied, the "Wind-PV-Battery-Diesel-Desalination" setup was examined using the tool. The islands Agios Efstratios and Donousa were studied for their energy behaviour having as a goal to cover part or 100% of their electricity and water demands. The reason we selected these islands was mainly the size, the data availability and the preference to test an island in North Aegean and one in South Aegean taking into account the different meteorological parameters recorded in the DB DatabaseSL. The case of Ag. Efstratios was also chosen, because there is already a national plan to become the first green island.

As described in the preceding paragraphs, calculations were broken down on an hourly basis. For the simulation with the ESA tool, the necessary input data for each island were:

- ✓ The electric load of the island
- ✓ The wind speed of the data of the National Observatory of Athens through meteo.gr existing in DatabaseSL.
- ✓ Solar radiation of the island
- ✓ The ambient temperature
- ✓ The annual water consumption

2 possible wind turbines were selected for the simulations. Enercon E-48 (800 kW) and VestasV-27 (225 kW), introducing their power curves into the tool. The PV panels (and their properties), were those which were tested in the laboratory, Kyocera LA361-K51S Panel (51 Wp). The type of battery and its characteristics of the rated load, depth of discharge (DoD), load rate, and the corresponding efficiencies were also inserted and the cost and the amount of fuel consumption in the local conventional unit.

4. **Main results**

8,500 combinations were approximately examined, leading to both technically and economically viable solutions for both islands.

4.1. Agios Efstratios Island case study

From all the solutions some are in detail described below (Table 2). The total cost was estimated for 25 years (life time), including installation, maintenance, and replacement costs of all the individual parts of the «Wind-PV-Battery-Diesel-Desalination» setup. It includes also the cost of the fuel use of the oil station when the HS is not covering 100% the demand.

Table 2: Solutions table with Enercon E-48 WT nom. power 800kW (Ag. Efstratios)

Solution	100% load demand from the HS	100% load demand from the HS and conventional station
Solution Nr.	1870	3993
WT Nominal(MW)	2.43	0.81
PV Nominal(MW)	1.12	0.41
BAT Energy(MWh)	6.25	2.08
DESA Nominal (MW)	0.02	0.02
DIESEL Nominal (MW)	0.00	0.30
WT Inst. Cost (M€)	3.04	1.01
PV Inst. Cost (M€)	2.13	0.78
BAT Inst. Cost (M€)	1.06	0.35
DESA Inst. Cost (M€)	0.16	0.16
DIESEL Inst. Cost (M€)	0.00	0.08
DIESEL Fuel Mass (tn/year)	0.00	20.63
DIESEL Fuel Mass Cost (1000€/year)	0.00	35.17
TOTAL Inst. Cost (M€)	6.39	2.38
TOTAL Cost Present Value (M€)	11.68	5.91
Annual Coverage (%)	100.00	93.95
Rejection Hours (h)	0	821

Since the analysis was done for 8760 hours on a yearly basis, it was revealed that the diesel unit operates during the summer months when there are load peaks that affect the island significantly.

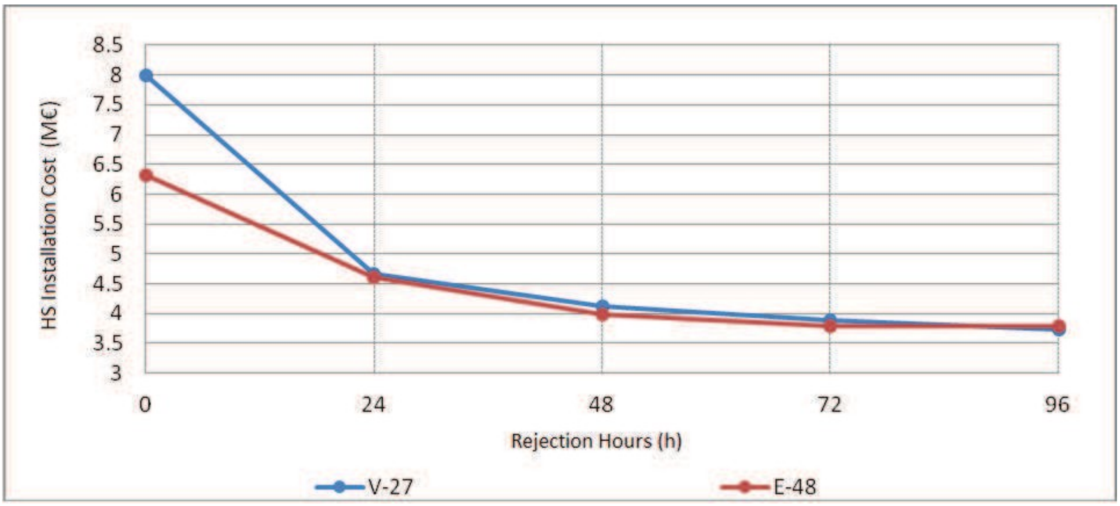

Fig. 5. HS optimal solution in relation with the rejection hours and the WT selected

Figure 5 illustrates the optimal economic solution in relation to the HS installation cost for a different number of hours of non-coverage of the electricity demand. It is noted that the wind turbine that behaves better for the whole system is Enercon E-48 in comparison with the Vestas V-27 (Table 3).

Table 3: Solutions table with Vestas V-27 WT nom. power 225kW (Ag. Efstratios)

Solution	100% load demand from the HS	100% load demand from the HS and conventional station
Solution Nr.	2738	3005
WT Nominal(MW)	1.58	0.45
PV Nominal(MW)	0.92	0.57
BAT Energy(MWh)	0.69	2.08
DESA Nominal (MW)	0.02	0.02
DIESEL Nominal (MW)	0.31	0.29
WT Inst. Cost (M€)	1.97	0.56
PV Inst. Cost (M€)	1.74	1.09
BAT Inst. Cost (M€)	0.12	0.35
DESA Inst. Cost (M€)	0.16	0.16
DIESEL Inst. Cost (M€)	0.08	0.07
DIESEL Fuel Mass (tn/year)	22.42	24.62
DIESEL Fuel Mass (1000€/year)	38.22	41.97
TOTAL Inst. Cost (M€)	4.07	2.24
TOTAL Cost Present Value (M€)	8.31	5.76
Annual Coverage (%)	93.42	92.78
Rejection Hours (h)	821	942

Based on the findings, the strategy of full coverage from RES with the use of the E-48 (if selected) is preferable as it has 1.68 M€ of total savings. The choice of the strategy of serving the needs by a small percentage via the Diesel station, it will be more economical but it always burdens the environment and the national economy. The WT V-27 could overall provide a more economical solution in the long term of 25 years, however, having 942 hours in addition with the conventional station it is something always unwanted.

4.2. Donoussa Island case study

Following the same approach, using the same tools an analysis was done for Donoussa Island. Loading all the data to the tool, e.g. wind speed (which is on average lower than the average speed Ar. Efstratios) existing in the DatabaseSL, as well as solar radiation and annual water consumption. The analysis was based as well on the two WT models used also in the case study of Ag. Efstratios, the V-27 and E-48, and were examined about 8,500 solutions. The cases presented in detail are the cases of the optimum economic solution that offers full autonomy from RES and the case of optimum economic solution with the electricity demand derived from the combination of RES and the diesel station (Tables 4 and 5).

Table 4: Solutions table with Enercon E-48 WT nom. power 800kW (Donoussa)

Solution	**100% load demand from the HS**	**100% load demand from the HS and conventional station**
Solution Nr.	1580	284
WT Nominal(MW)	1.62	0.81
PV Nominal(MW)	1.326	0.5508
BAT Energy(MWh)	6.75	2.25
DESA Nominal (MW)	0.02	0.02
DIESEL Nominal (MW)	0	0.301
WT Inst. Cost (M€)	2.025	1.012
PV Inst. Cost (M€)	2.519	1.047
BAT Inst. Cost (M€)	1.148	0.382
DESA Inst. Cost (M€)	0.16	0.16
DIESEL Inst. Cost (M€)	0	0.075
DIESEL Fuel Mass (tn/year)	0	16.713
DIESEL Fuel Mass (1000€/year)	0	28.488
TOTAL Inst. Cost (M€)	5.852	2.677
TOTAL Cost Present Value (M€)	10.672	6.114
Annual Coverage (%)	100	93.6
Rejection Hours (h)	0	629

Table 5: Solutions table with Vestas V-27 WT nom. power 225kW (Donoussa)

Solution	**100% load demand from the HS**	**100% load demand from the HS and conventional station**
Solution Nr.	4530	1624
WT Nominal(MW)	1.35	0.675
PV Nominal(MW)	1.5504	0.5916
BAT Energy(MWh)	6.75	2.25
DESA Nominal (MW)	0.02	0.02
DIESEL Nominal (MW)	0	0.318
WT Inst. Cost (M€)	1.688	0.844
PV Inst. Cost (M€)	2.946	1.124
BAT Inst. Cost (M€)	1.148	0.382
DESA Inst. Cost (M€)	0.16	0.16
DIESEL Inst. Cost (M€)	0	0.08
DIESEL Fuel Mass (tn/year)	0	20.255
DIESEL Fuel Mass (1000€/year)	0	34.526
TOTAL Inst. Cost (M€)	5.941	2.59
TOTAL Cost Present Value (M€)	10.653	6.16
Annual Coverage (%)	100	92.244
Rejection Hours (h)	0	755

Comparing the 2 wind turbines, the E-48 one is (slightly) preferable in the case where the objective is the full autonomy only via RES, because only 19,000 EUR could be saved (Figure 6).

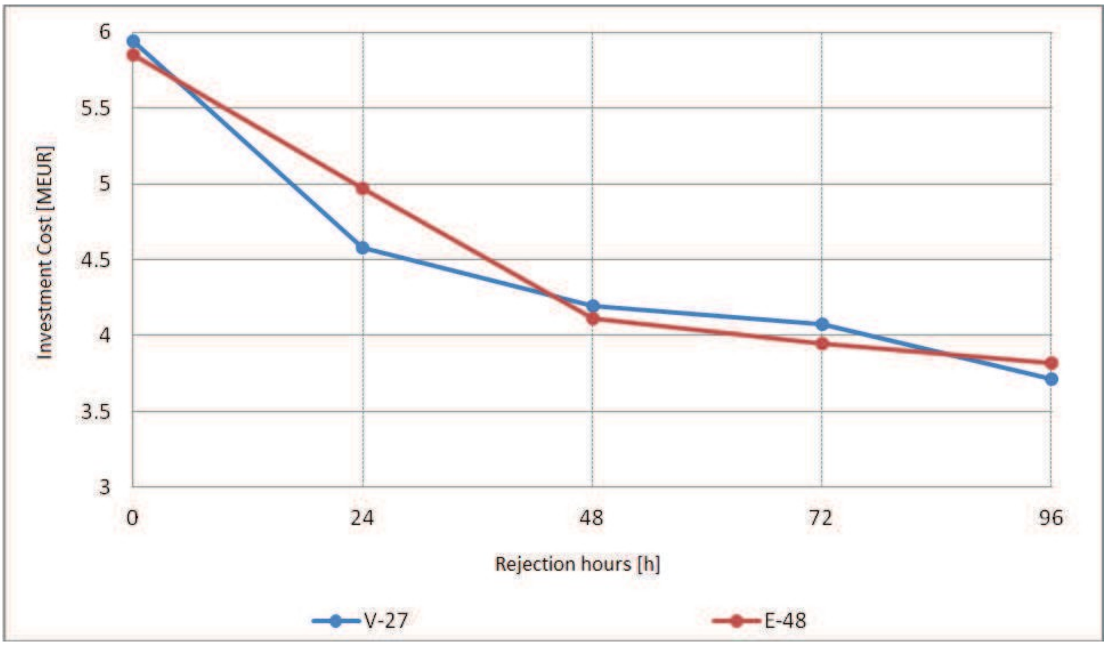

Fig. 6. HS optimal solution in relation with the rejection hours and the WT selected

It can be seen, in figure 6, that only for 0.27% (=24 hours) of the time yearly (8760 hours), the initial installation cost can be increased by 22.9% and 15.4% for the V-27 and E-48 WTs, respectively. For the 100% RES scenario the cost climbs up at approx. 6 MEUR independently of which is WTs selected (the HS with E-48 is cheaper by only 89,000 Euro). The initial setup cost is also very closely related to the installed capacity but is also connected with the mixture of energy production. The largest PV power facility is what makes it economically unviable for the WT V-27.

5. Conclusions

The need for the optimal management of energy and water demand for the small and medium (and often arid) Aegean Sea islands was the need to implement the project PHAROS in order to address and propose solutions to overcome this problem. The islands are facing continuing problems with the electricity management and with their unsuccessful and uneconomical water supply. The purpose of the PHAROS project, was to propose an alternative approach by designing hybrid systems that could confront successfully. A complete analysis was implemented for the islands of Agios Efstratios and Donoussa.

Based on the results of the 2 islands, the initial capital required for the hybrid power solution in both cases, it may be further reduced by 30 – 40%, with some more participation (up to maximum 20%) of the conventional plant in the total annual electricity demand coverage scheme of the island.

Out of the many scenarios examined, it was revealed that nearly 99% of the islands energy and water needs can be met with only a small contribution (just over 1%) from the diesel station on the island. Also, as a result of the 2 WT simulated in the tool it was revealed that ENERCON E-48 is more efficient and also more economical in comparison to VESTAS V-27. Via the concept of the design and promotion of HS and local storage it is proven that it is one of the most promising ways to confront water scarcity and repeated frequency and voltage deviations in the islands.

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