OPTIMIZATION OF A SUSTAINABLE ELECTRICITY SUPPLY SYSTEM FOR THE MEDITERRANEAN ISLANDS

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ABSTRACT

The study focuses on the optimization of the RES electricity system of Ios island in Greece, based on solar PV and wind, developed in a previous paper under the title "Distributed or centralised renewable energy systems? Meeting the demands of the Mediterranean islands". Investigation on alternative scenarios with different requirements and constraints has been carried out for the improvement of the electricity system. The optimal scenario has been extracted and further improved. It is concluded that by exploiting the existing infrastructure, the external energy supply from the neighbouring island of Paros to Ios partly for two summer months, while Ios exports green energy from RES back to Paros for nine months constitutes the optimal solution. Ios Island could then act as an exemplar of sustainable development for similar initiatives in other islands of the Mediterranean.

INTRODUCTION

Buildings are the most energy-consuming sector, while at the same time they offer a great potential for the application of energy efficiency techniques and technologies. The environmental challenges that buildings currently face call for immediate action and particularly those, which are located in insular communities, are the most vulnerable ones. Therefore, the introduction of the appropriate sustainable energy systems to the insular communities through the exploitation of the local natural energy resources can contribute to face local environmental and global warming issues, the security of energy supply and volatile energy prices, achieving a stable, self-sufficient and sustainable development (EC 2009).

The paper is divided into three sections; presentation of the material, discussion and analysis and conclusions. In the first section the aim and the methodology of the current study as well as the exploration of the alternative scenarios for the electricity sector are presented. The second section begins with the presentation of the optimal scenario, an investigation of the potential for further improvements and the specification of the systems' size, while the arrangement of the RES electricity systems on the island for the optimal solution follows. This section closes with the description of the electrical energy storage scheme. The concluding remarks of the investigation are presented in the end.

PRESENTATION OF THE MATERIAL

Aim and methodology

The principal aim of the study is the optimization of the RES electricity system of Ios island, developed in a previous paper, so as to power both the building and the transport sectors in the next ten years (Chatzivasileiadi 2011b). Further objective to this end is the design of a sustainable energy system of zero emissions that will require the introduction of a capacity of RES systems as low as possible to cover the energy demands of the island all the year round and will generate the least surplus energy.

The methodology includes the investigation of alternative scenarios through the use of linear programming (Dantzig and Thapa 2003). A tool based on Excel was developed for this reason. Considering the minimum RES installed capacity, the maximum annual capacity factor of the system and the specific power generation per kW installed (Masters 2004), the most preferable power system design solution is extracted. The study carries on with the arrangement of the systems, according to their sizing, which takes into account technical, social, environmental and aesthetic parameters.

Exploration of alternative scenarios for the electricity sector

Having as starting point the basic scenario presented in the previous paper, 17 scenarios have been explored in total (Chatzivasileiadi 2011a). By defining different constraints and requirements for each scenario, different outputs as regards the solar and wind installed capacity and the surplus energy produced have been extracted. Energy savings in July and/or August, external energy supply from the island of Paros, storage losses and cost assumptions for solar and wind energy have been considered in different ways for each scenario. The total minimum installed capacity is what we sought for in any case. The results are presented in Table 1 and the ranking of the most promising scenarios according to Table 1 is shown in Table 2.

NO -S-	SCENARIOS	SOLAR INST. CAPACITY (kWp), ENERGY (kWh/y)	WIND INST. CAPACITY (kW), ENERGY (kWh/y)	TOTAL CAP.(kW), SURPLUS ENERGY (kWh/y)	ENERGY FOR COMPENSATION (kWh/y)
1	Only solar PV	28,064 40,692,800	0	28,064 17,382,800	-
2	Only wind	0 0	24,101 68,687,850	24,101 45,377,850	-
3	Min. surplus energy (results as in S1)	28,064 40,692,800	0 0	28,064 17,382,800	-
4	Min. installed capacity	6,207 9,000,150	12,375 35,268,750	18,582 20,958,900	-
5	10% energy saving in August (+scenario 4)	7,409 10,743,050	10,106 28,802,100	17,515 16,715,050	-
6	20% energy saving in Aug +10% in July (+s4)	8,610 12,484,500	7,837 22,335,450	16,447 12,903,850	-
7	40% external supply in July - August (+s4)	12,210 17,704.500	3,448 9,826,800	15,658 7,877,300	3,656,000

8	50% external supply in July - August (+s4)	11,100 16,095,000	3,134 9,102,900	14,234 6,457,900	4,570,000
9	Economics, min (a.W+2a.S)[1], kWh (+s4)	6,207 9,000,150	12,375 35,268,750	18,582 20,958,900	-
10	With storage losses: 110% (+scenario 4)	6,828 9,900,600	13,614 38,799,900	20,442 23,059,500	-
11	With storage losses: 115% (+scenario 4)	7,139 10,351,550	14,232 40,561,200	21,371 24,106,250	-
12	With storage losses: 110% (+scenario 5)	8,150 11,817,500	11,117 31,683,450	19,267 18,387,840	-
13	With storage losses: 110% (scenario 6)	9,471 13,732,950	8,621 24,569,850	18,092 14,055,700	-
14	With storage losses: 110% (+scenario 7)	12,114 17,565,300	3,628 10,339,800	15,742 6,285,700	4,021,600
15	With storage losses: 110% (+scenario 8)	12,210 17,704,500	3,448 9,826,800	15,658 6,917,300	5,027,000
16	With storage losses: 110% (+scenario 9)	6,828 9,900,600	13,614 38,799,900	20,442 23,059,500	-
17	min (a.W+2a.S)[1], kWh (+s15)	12,210 17,704,500	3,448 9,826,800	15,658 6,917,300	5,027,000

Table 1 Investigation of various scenarios and results

WITH STORAGE LOSSES	**WITHOUT STORAGE LOSSES**
S15/S17	S8
S14	S7
S13	S6
S12	S5
S10 (basic)	S4 (basic)

Table 2 Ranking according to the minimum installed capacity (from lower to higher)

A graphical presentation of the 17 scenarios is depicted in Figure 1.

[1] The cost of the energy produced by solar PV is assumed to be twice the cost of the wind energy. “a” is used in this case as a coefficient to illustrate this assumption, while “W” and “S” relate to wind and solar energy correspondingly.

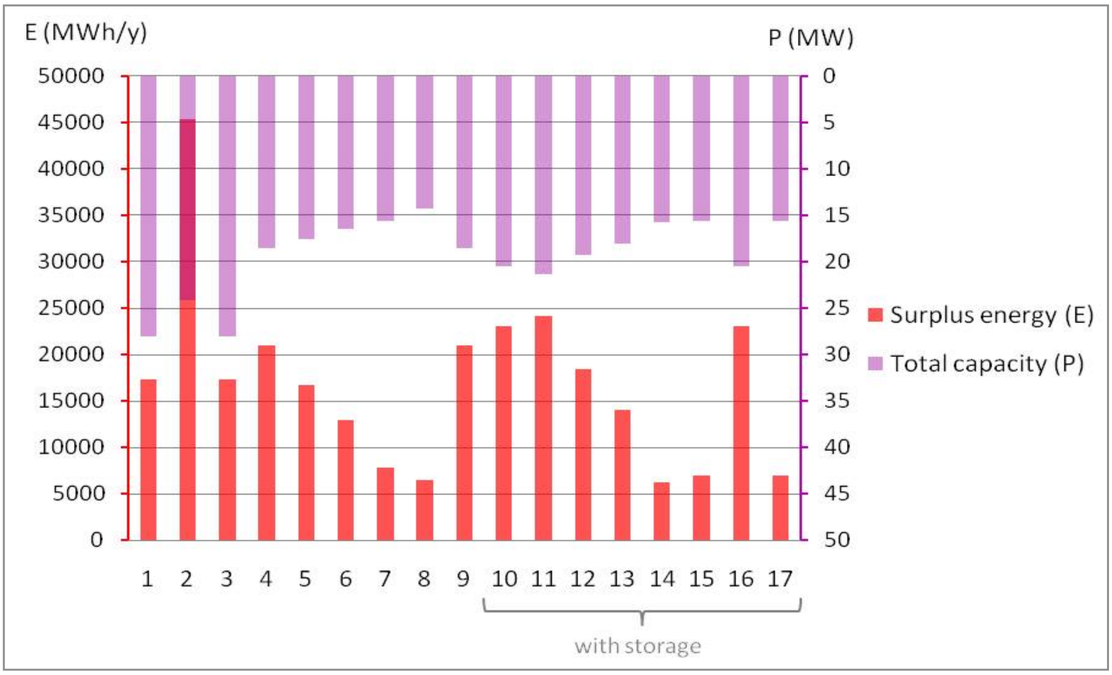

Figure 1 Graphical presentation of the 17 scenarios

Based on Figure 1, an attempt has been made to estimate the profitability of each scenario. This factor takes into account the arithmetical sum of the total installed capacity and the surplus energy. This arithmetical sum should be as small as possible. Hence, to produce Figure 2, the space between each red and purple column that corresponds to one scenario has been shifted to the horizontal axis and coloured blue. So, the higher the blue column is the higher the profitability.

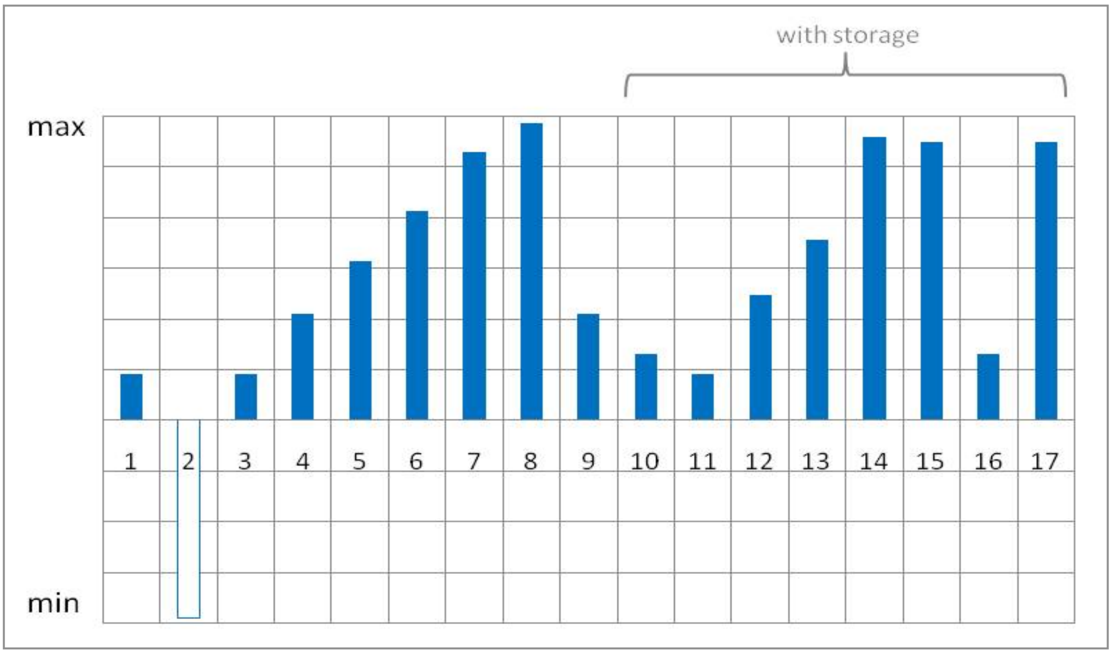

Figure 2 Profitability of each scenario, based on Figure 1

In line with the criterion of the minimum installed capacity, another qualitative and quantitative parameter, which should be considered in order to choose the optimal scenario, is the annual capacity factor of the system and the specific power generation per kW installed (Masters 2004). In Table 3, the derived results are presented.

SCENARIOS WITHOUT STORAGE LOSSES				
	INST. CAPACITY (kW)	ANNUAL ENERGY (kWh)	kWh/kW	CAPACITY FACTOR
S5	17,515	39,545,150	2,258	25.8%
S6	16,447	34,819,950	2,117	24.2%
S7	15,658	27,531,300	1,758	20.1%
S8	14,234	25,197,900	1,770	20,2%
SCENARIOS WITH 10% STORAGE LOSSES				
S12	19,267	43,500,950	2,258	25.8%
S13	18,092	39,302,800	2,172	24.8%
S14	15,742	27,905,100	1,773	20.2%
S15/S17	15,658	27,531,300	1,758	20.1%

Table 3 Capacity factor of the systems for the selected scenarios

Comparing S14 and S15/S17 which have very similar installed capacity figures, it seems that S14 is better, although the installed capacity is slightly higher than S15/S17. This is consistent with the indications of Figure 2 and is graphically presented in Figure 3 below. It should be noted that S6, S5, S13 and S12 render Ios completely autonomous and independent on energy imports throughout the year.

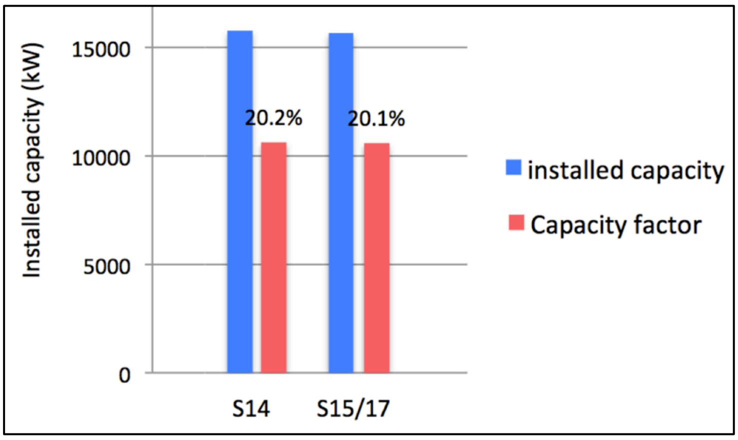

Figure 3 Capacity factor of the systems for the promising scenarios

From all the scenarios investigated for Ios' energy demand profile, it seems that solar energy, compared to wind energy, corresponds in a better way to the load profile of the island. In addition, the adoption of a scenario that includes energy storage is inevitable, as storage facilities are definitely required for such system.

DISCUSSION AND ANALYSIS

Optimal solution, further improvements and specification of the systems' size

On the basis of the above evaluation, considering 10% storage losses, it seems that the scenario 14 with 15,742kW total installed capacity constitutes the optimal solution. 40% of the load during July and August should be supplied by Paros' power station, while the surplus zero-emission energy from Ios' RES system should be supplied to the neighbouring islands Sikinos, Folegandros and Paros during the rest 10 months of the year. It should be pointed out that in this way, a net zero energy requirement from the grid for Ios is achieved. The characteristics of the dominant scenario S14 which is adopted for further investigation are presented in Table 4.

SCENARIO 14: 40% EXTERNAL SUPPLY IN JULY-AUGUST, STORAGE LOSSES 10%	
Total installed capacity • Solar PV installed capacity • Wind installed capacity	15,742 kW • 12,114 kWp (77%) • 3,628 kW (23%)
Total annual production by solar PV and wind • Annual power production by solar PV • Annual power production by wind	27,905,100kWh/y • 17,565,300kWh/y (63%) • 10,339,800kWh/y (37%)
Surplus energy produced by RES per year	6,285,700 kWh >> 5,658,000 kWh
Imported energy from Paros per year	4,021,600 kWh >> 3,393,800 kWh
Total solar PV area (min./horizontal)	72,684 / 145,368 m^2
New wind turbines (existing capacity 1.2MW)	4 units of 600kW each

Table 4 Characteristics of S14 and improved figures of surplus and imported energy

Further analysis shows that there is room for improvement of the figures in scenario 14. In July, there is surplus energy production and instead of 40% import, as the scenario suggests, it could be reduced to about 27%, so the surplus energy for July is zero. Therefore, during July and August, the total import from Paros is 3,393.8MWh/y and the surplus energy is 5,658MWh/y. Monthly data are presented in Figure 4, where the surplus energy for export is indicated. In June, the amount for export is zero and in December very little, while in the rest eight months there is a considerable capacity for export.

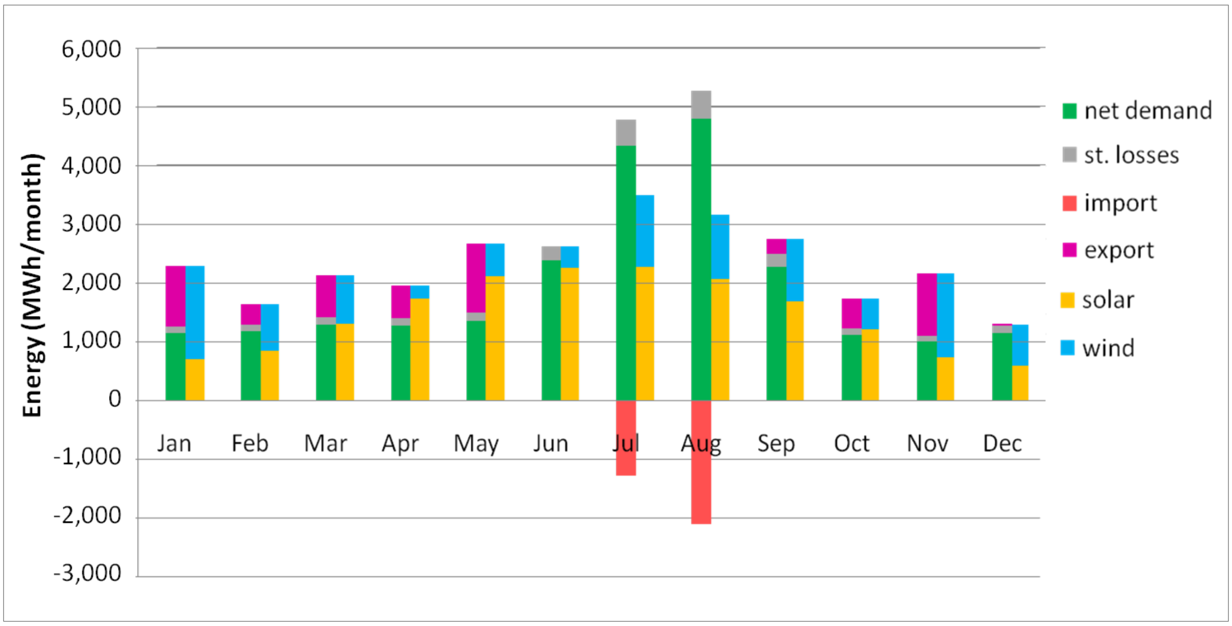

Figure 4 Monthly data of energy demand, production by solar PV and wind, imports and exports for the island of Ios

Arrangement of the RES electricity systems (optimal scenario)

The arrangement of the systems takes into account technical, social, economic, environmental and aesthetic parameters, as presented in the previous paper. Four medium size wind turbines of nominal capacity 600kW each, with 46m high masts and of advanced technology (variable speed, pitch control, power electronic system) have been selected for installation. They will be installed close to the existing one on the mountainous site called "Pyrgos", where a significant wind potential, as well as the infrastructure for connection to the grid, exist. They should face towards the direction of the prevailing winds, due NNE-NE. The wind park is far from Chora and other settlements and no visual disturbance or noise is expected to be caused. Offshore or micro wind turbines are not suggested for technical, economic, environmental, legal and aesthetic reasons (EWEA 2011).

As regards the PV modules, they should be distributed in dispersed PV systems in the urban environment and three centralised PV systems on the ground. This will result to higher reliability and lower aesthetic impact. Considering the special conditions of the traditional settlements and the percentage of the owners who would be interested in installing RES systems on their houses, a capacity of 1,440kWp in 360 households and 1,200kWp in 100 commercial buildings is estimated for integration by 2021. An additional capacity of about 300kWp is estimated for integration in Municipal buildings and facilities. The remaining PV capacity of 9,174kWp will be planted on sloped mountainous areas with south orientation in the southern part of the island. The PV plants require a sloped area of about 55,000m^2 and will be placed at a distance of about 1m from the ground, so that they serve stock-raising activities at the same time. In this way, they will not be cancelling the existing land use, minimisizing the impact on the island's ecosystem. The color of the PV modules and the supporting structures is suggested to be cobalt blue, like the color of the window frames, the shutters, the doors of the buildings and the sea. Thus, polycrystalline silicon PV modules are suggested.

The suggested arrangement of the renewable energy technologies is presented in figure 5. The calculations showed that the PV plants will occupy an area of about 0.05% of the total area of Ios Island, while all the RES applications are expected to occupy less that 0.01% of the island. Therefore, the proportion of the RES systems against the total area of the island is quite remarkable, bearing in mind that the island is fully powered to meet 100% of its energy demands over the year.

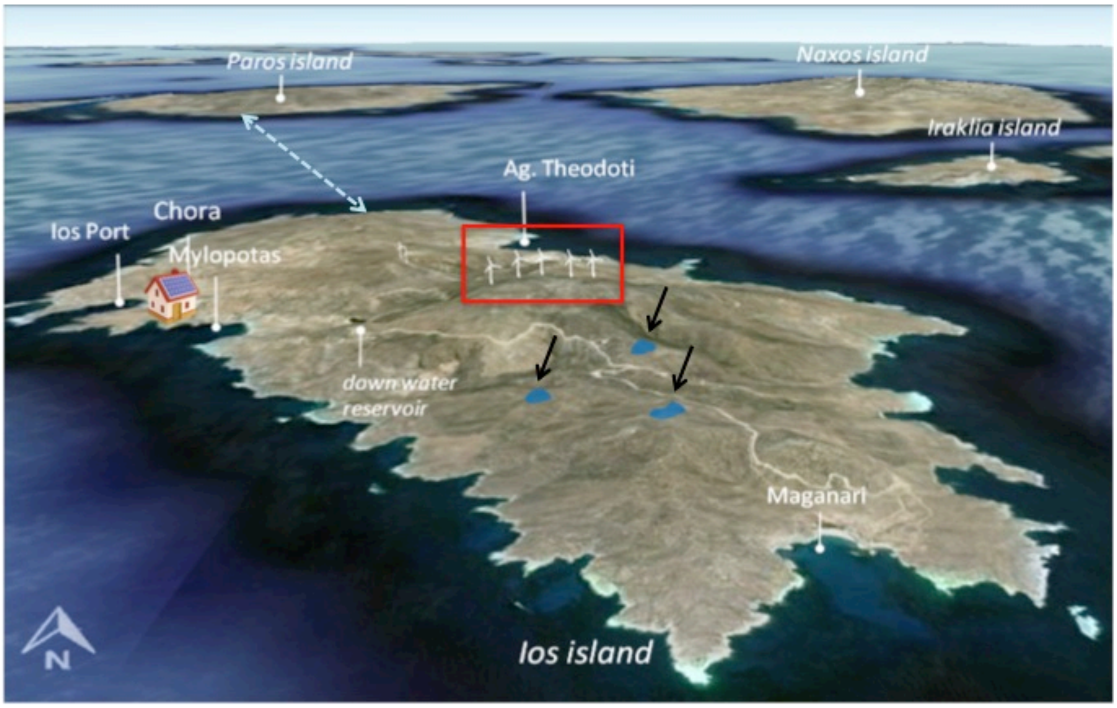

Figure 5 Overview of wind and solar PV (blue) applications in Ios (optimal scenario)

Electrical energy storage scheme

A central storage facility of advanced technology -chemical or pump storage- and distributed storage systems with batteries in each household or by using the battery pack of the electric cars (Emandi 2011) seems to be the best combination for the electricity system. Both types of distributed storage systems can be managed by advanced control strategies based on Smart Grids, which are expected to be playing a more and more important role in the future. The flexibility of the demand and forecasting weather models are also necessary for an efficient system management.

A schematic presentation of the concept of solar energy storage is illustrated in Figure 6. It depicts the daily load curve for a summer day in the middle of August, when the maximum demand occurs. The load (MW) values are cumulative and wind energy is distributed during day and night, acting as base load. As most of the energy is produced by solar energy, the challenge is to manage a huge amount of solar energy for a few hours during the day through the use of storage facilities. The round trip storage losses are distributed to 24 hours because the system is active continuously as storage or supply facility. In adittion, the import from the neighbouring island of Paros is mainly scheduled for the early morning and night hours, when solar energy is decreased to zero.

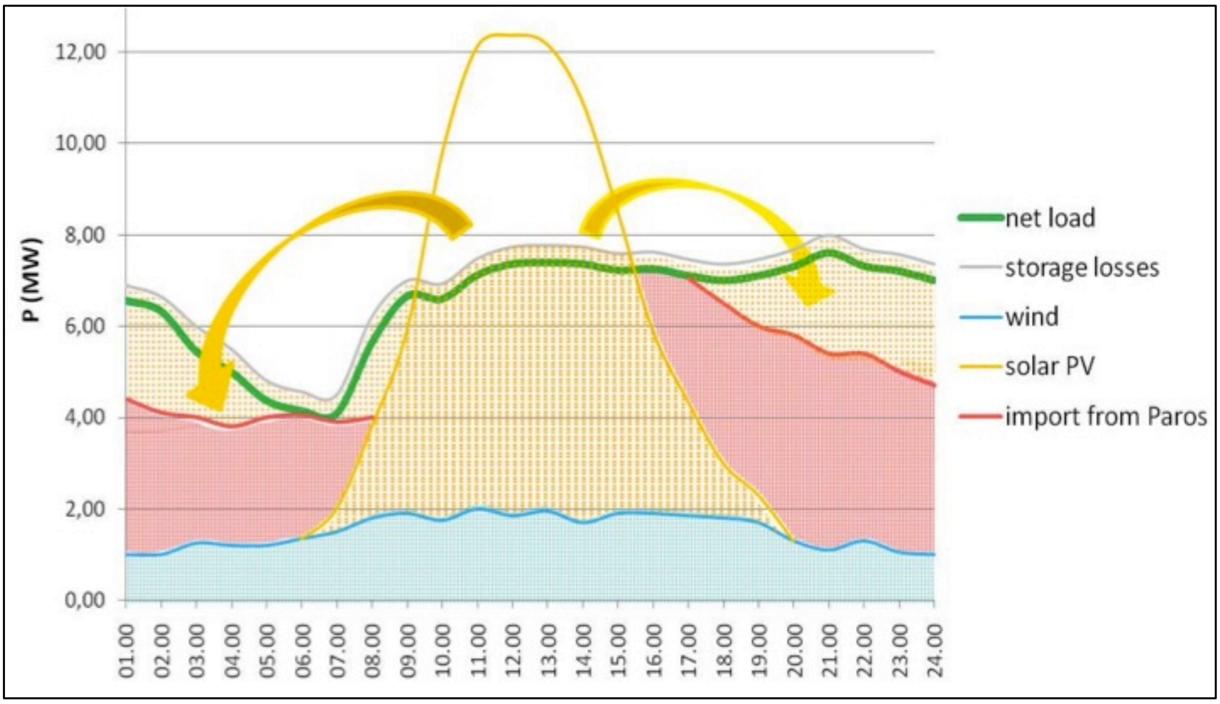

Figure 6 Daily load curve for a summer day in the middle of August

CONCLUSION

The undertaken research achieves the goal of establishing sustainability through the introduction of RES in an island of the Mediterranean in a very focused manner. The RES potential of Ios is not over-exploited, resulting to the minimal effect on the island's ecosystem, while the island has a net zero energy requirement and zero CO_2 emissions at the same time. In the household sector, the direct interaction of the occupants with the solar thermal collectors, the solar PV and the storage system could also raise social awareness and alert the local community. Summing up, Ios could be the pioneering island that would act as an exemplar, outlining the way towards sustainable development of the islands.

NOMENCLATURE

RES	Renewable Energy Sources
PV	Photovoltaics
W, kW	Watt, kilo-Watt
kWp	kilo-Watt$_{peak}$
kWh, MWh	kilo-Watt-hour, mega-Watt-hour
y	year

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