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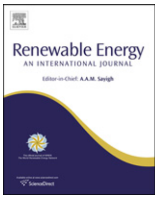

A comparative feasibility study of stand-alone and grid connected RES-based systems in several Greek Islands

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ABSTRACT

This paper deals with the feasibility of RES-based systems for electricity supply in four different Greek Islands. Three specific typical loads were selected to be covered, where the grid connection was considered as optional. An optimization procedure in terms of energy efficiency and economical feasibility has also been applied, using the HOMER software for the energy part and a hand-made calculation procedure for the financial aspects. It is found that an off-grid project is not economically feasible and the grid connection is necessary only for the sale of excess electricity (not as a backup source). Finally, the relationship between environmental potential and produced energy is found to be linear, with almost constant behaviour for solar systems.

1. Introduction

Global warming is at a worrying level and the use of fossil fuels (mainly carbon-based) seems to be very expensive for an individual consumer in terms of both economy and environment. Renewable Energy Sources (RES) give the impression of a significant energy alternative, thus many researchers work on RES-based systems from many scientific aspects. Special effort has been given to the optimization of stand-alone hybrid systems in terms of both energy and economy [1,2].

One major problem is the selection of optimal components which should be established for energy coverage in combination with the most efficient economical performance. Furthermore, a serious problem is the high overall cost for the continuous supply of the electrical load by grid connection, especially in isolated areas such as the Greek Islands. Another rigorous situation that isolated Greek Islands face, is the outage of electric power when the region is dominated by unfavorable climatic conditions, especially during winter with very strong wind potential. Under these conditions, much damage occurs to the national grid and some islands remain without electricity for several days each year. Therefore, the optimization for continuous operation of an RES-based unit established in an isolated area is crucial.

It is possible to overcome the above drawbacks by suitably designing an autonomous power plant, whereas the selection of the appropriate technologies has to done in accordance with the climatic conditions [3]. Several studies have shown that renewable resources influence the behavior and economics of power systems and these must be economically feasible in combination with the energetic optimization (see Ref. [4]). Towards such a solution, this work has taken into account three different typical loads (one for a typical house, one for a typical country house with limited load demands, and one for a typical small enterprise), all established on four Greek Islands with different climatic conditions (sun-ray, wind potential). Different scenarios were created and optimized in terms of energy efficiency and economical feasibility. Each case was assumed to utilize solar and wind energy, either separately or simultaneously. For plant energy storage, a stack of batteries was used.

2. Theory

2.1. Technological aspects

The structure and characteristics of the sun determine the nature of the solar energy transmitted to earth. Photovoltaic panels (PV) constitute the technological achievements that take advantage of the energy being incorporated into the solar radiation and transform it into DC load. The electric power produced by a typical photovoltaic array is given as [5,6]:

$$P_{\mathrm{solar}} = P_{\mathrm{STC}} f_{\mathrm{PV}} \left(\frac{\overline{G}_{\mathrm{T}}}{\overline{G}_{\mathrm{STC}}} \right) \left[1 + a_{\mathrm{P}} \left(T_{\mathrm{C}} - T_{\mathrm{C,STC}} \right) \right] \tag{1}$$

where P_{STC} is the output power of the panels in standard test conditions, f_{PV} is the derating factor, $\overline{G}_T$ is the solar radiation

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incident and $\overline{G}_{STC}$ is the radiation in standard test conditions (1000 W/m^2). The last brackets represent the performance of the PV cells which is influenced by the temperature, T_C, under which the photovoltaic array is exposed, in real time conditions.

The critical parameters for the conversion of solar energy to electricity are f_{PV}, T_C, and the orientation factor which is covered in the numeration $\overline{G}_T$ of the ratio of solar radiation, as shown in the first parenthesis of eq. (1). It is obvious that all these factors compromise the input variables of a typical solar system and moreover they are considered as constants for a specific location of the photovoltaic arrangement. The orientation of the photovoltaic panels, β, which is referred above as hidden in the numerator of the parenthesis of eq. (1), is used in the next expression through which the solar radiation incident on the photovoltaic array is calculated [6]:

$$\overline{G}_T = (\overline{G}_b + \overline{G}_d A_i) R_b + \overline{G}_d (1 - A_i) \left(\frac{1 + \cos\beta}{2} \right) \left[1 + f_{PV} \sin^3 \left(\frac{\beta}{2} \right) \right] + \overline{G} r_g \left(\frac{1 - \cos\beta}{2} \right) \tag{2}$$

where $\overline{G}_b$ and $\overline{G}_d$ are the beam radiation of the incident and the diffuse radiation correspondingly, A_i is the anisotropy index of the solar radiation and r_g is the ground reflectance. Therefore, choosing the correct factors is very important for the power output of the established panels. More precisely the slope under which the panels must be established is one of the most important steps for the appropriate simulation of a system based on photovoltaic arrays.

Wind turbines take advantage of the kinetic energy of the wind converting it into electrical power. The wind energy depends on wind speed (wind potential) and the height of the turbine's hub, since wind speed varies with height following the Weibull distribution [7]. The energy stored in the wind potential is given as [7,8]:

$$E_{\text{kinetic}} = 0.5\, m\, u^2 \tag{3}$$

where m is the air mass and u is the wind speed in real time conditions. By using the mass flow-rate instead of the mass, the wind power can be obtained as [9]:

$$P_{\text{wind}} = 0.5\, A^2\, \rho\, u^3 \tag{4}$$

where A is the swept area of the turbine's rotor and ρ is the density of the air, supposed to be constant.

The critical parameter for the power produced is the size of the blowing area, which is represented by the rotor swept area of the wind turbine. It must be stressed that approximately only 30–40% of the wind power in eq. (4) can be transformed to electrical energy at the horizontal axis turbines because of the mechanical losses of the construction [9]. This percentage is not an arbitrary parameter but is involved through the power coefficient which is unique for every wind turbine and is provided by the manufacturers. Another crucial factor is air density, which although varies with height, is considered here as constant because the elevation of the project area from the sea is not very high.

For stand-alone systems the existence of a stack of batteries or an ICE (Internal Combustion Engine) is crucial for continuous operation. These are not used only as backup energy systems but they replace the power characteristics of the grid. The apparatus operate under assessed specifications (220 V, 50 Hz). Therefore, a unit controller is necessary to receive these parameters from each source, construct the unit's local grid, and adapt the energy from the RES components under these points. In the present study, Zebra batteries are used exclusively as the cost of fuel used in ICE-systems, increases the number of abbreviation years. On the other hand, one of the main objectives is the integration of zero emissions systems [10].

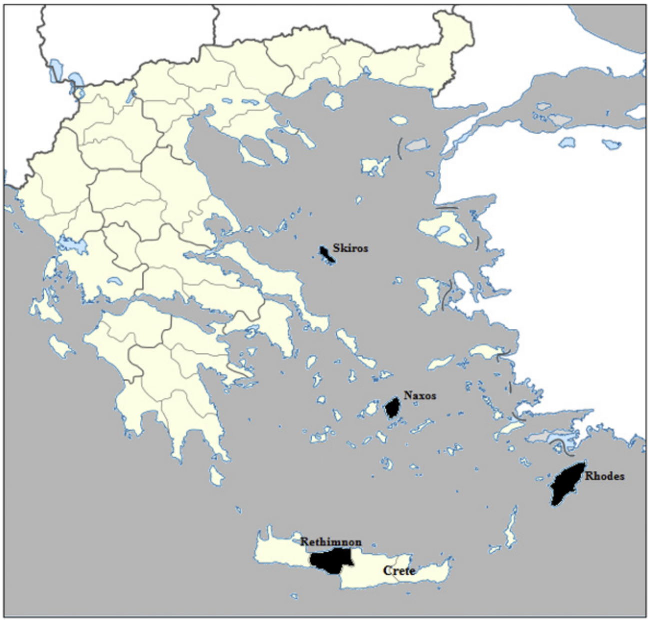

Fig. 1. Location of the four Greek Islands.

2.2. Economical aspects

The performance analysis of a system alone is insufficient to consider its optimal design for desirable load coverage, as economic issues must be taken into account when selecting components during the design stage. Note that the initial and operational costs

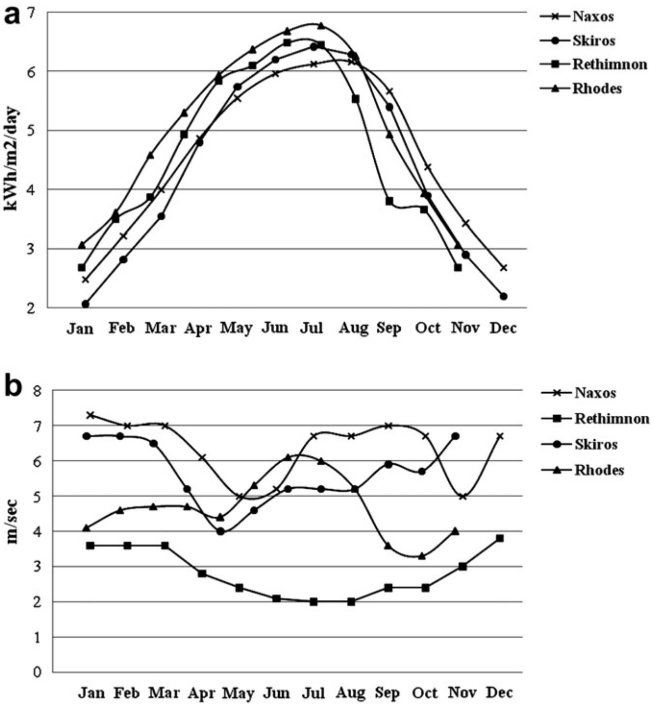

Fig. 2. Solar (a) and wind (b) potential for each island.

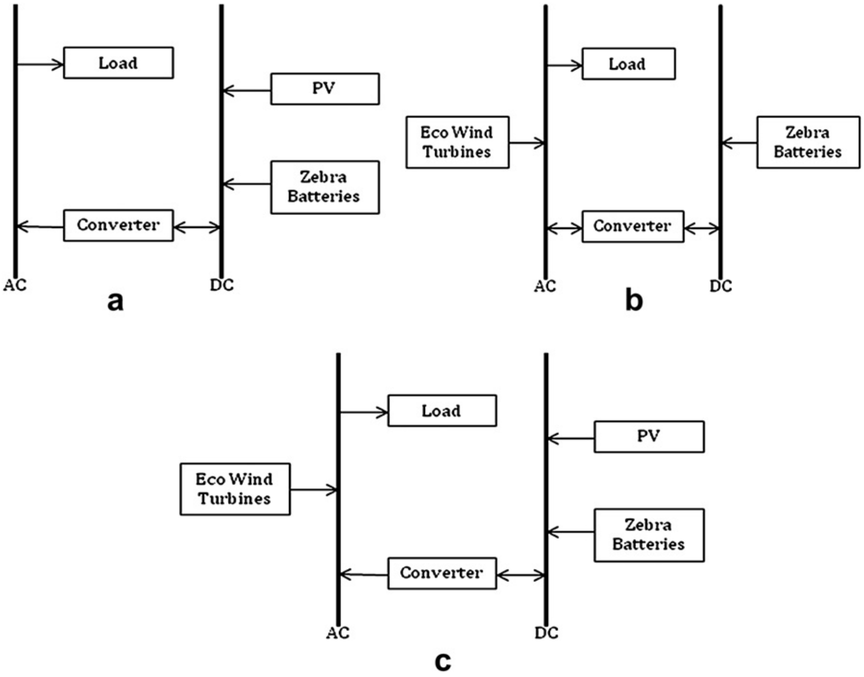

Fig. 3. Components for a single photovoltaic (a), a single wind (b) and a hybrid photovoltaic-wind (c) system.

of an RES-based system are quite high and constitute one of the most crucial parameters for a system's design. In this study, the economical analysis will be finalized by the depreciation of the system's capital costs through time. Initially, the years for depreciation will be estimated for stand-alone (off-grid) systems as:

$$Y = \frac{C_{cap.} - C_{gridcap.}}{C_{ygrid} - C_{oper.}} \tag{5}$$

where $C_{cap.}$ is the capital cost of the RES components, $C_{gridcap.}$ is the capital cost for the grid connection, C_{ygrid} is the annual cost for the usage of the grid and $C_{oper.}$ is the operational cost of the stand stand-alone (off-grid) system. A second step in the above calculation is the introduction of profit from the sale of excess electricity to the grid, thus the number of years of the systems' depreciation will be calculated through the expression:

$$Y = \frac{C_{cap.} - C_{gridcap.}}{C_{ygrid} - \left(C_{oper.} - E_{excess}0.45\right)} \tag{6}$$

where E_{excess} is the excess electrical load which is produced by RES and will be sold to the grid, while the selling price for the Greek Power Company is fixed at 0.45 €/kWh for the next 20 years, under Greek legislation.

The new concept introduced into this study is the cost of emissions that must be paid by the Greek Power Company because of coal use. Although the Kyoto protocol has incorporated a small adjustment in the price per ton of CO_2 with the emitted amounts, this cost is considered as constant in the present study. From the emissions of CO_2 per MW supplied by the grid, the augmentation for grid use can be calculated as follows:

$$C_{emissions} = E_{desload}\ \text{Emissions}\ C_{perton} \tag{7}$$

where $C_{emissions}$ is the total cost of the produced emissions if the desirable load was covered by the grid, $E_{desload}$ is the load which is appropriate for the incessant operation of the established unit, Emissions are the pollutant elements from the grid in tons, and C_{perton} is the cost of emissions per ton.

As none of the hybrid systems in this study use diesel or LPG generators as alternative sources, the operating costs given by eqs. (5) and (6) are equal to annualized replacement costs. These costs are different for each component and are given by [10]:

$$C_{arep.} = C_{totrep} f_{rep.} SFF\left(i, N_{comp.}\right) - S\ \left(i, N_{proj.}\right) \tag{8}$$

where $C_{arep.}$ is the annual replacement costs, C_{totrep} is the total replacement costs for every component at the end of their lifetime, $N_{comp.}$ and $N_{proj.}$ is the lifetime in years for a whole project. For the scopes of the present work, the second term of the above expression (8) is equal to zero because the salvage value S is zero at the end of every component's lifetime. Furthermore, f_{rep} in the first factor in eq. (8) is equal to the unit, since the end of the project is in reality the replacement of the component which the above expression refers to. Finally, the sinking factor, SFF, a ratio used to show the future value of cash flows, is calculated by [10]:

$$\text{SFF}\left(i, N_{comp.}\right) = \frac{i}{(1+i)^{N_{comp.}} - 1} \tag{9}$$

3. Simulations

For the present study, four different Greek Islands were chosen, namely Crete (Rethimnon), Rhodes, Skiros and Naxos (Fig. 1). Meteorological data for each island were acquired from local meteorological stations available online [11–14]. This selection was done by extensively studying the meteorological data, the average monthly solar radiation, the average monthly wind speed, and the whole environmental potential in general. The main criterion for the selection of these four islands was the number of solar-biased months, wind-biased months and even months. These criteria will reveal the primary environmental energy source of each island and

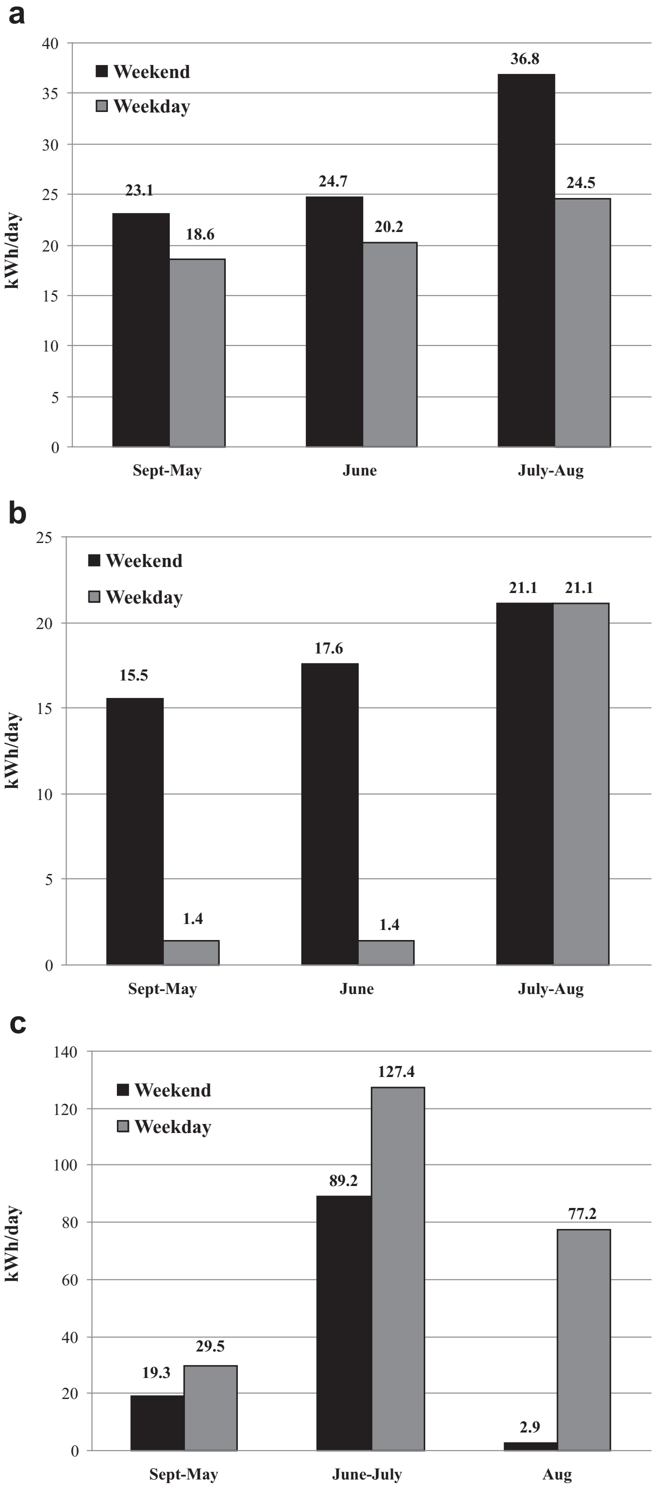

Fig. 4. Load needs for a typical house (a), a typical country house (b), and a typical small enterprise (c).

will allow the selection of the best value for money RES system in each case. The solar and wind potential per island are shown in Fig. 2a and b, respectively.

The first step of this study was the construction of three different systems (a single photovoltaic, a single wind and a hybrid photovoltaic-wind system) as shown in Fig. 3a–c. It is essential to note that batteries are used in all systems not only to backup energy but also to replace the characteristics of the local grid which is necessary to use the energy produced. All these systems were used to cover three different desirable loads, one corresponding to a typical house, one for a typical country house and one for a small company established in a small building. Through the software tool HOMER [15], the researcher has the opportunity to select the desirable load at an hourly basis separately for each month during the year. In this study a typical year was separated into three periods and for each simulated period the days were also separated into two categories: weekend and weekday, while the sum of these loads for a weekend and a weekday for each case is presented in Fig. 4a–c. Selection of the three different loads was made using the energy consumed on an hourly basis during a typical year. The relative calculations were complicated because several different parameters must be taken into account such as the air-conditioning during summer months and the devices which operate normally or in a standby mode during the whole year. In this respect, the optimization of these scenarios, in any location, would underline if the use of a stand-alone system is economically feasible for a small individual consumer.

The second step was again the design of the same systems as in step 1 but with two external limitations: the area available for the installation of the systems has been fixed to 5000 m^2 in each case, while the capital costs for the components must not exceed 100,000 €, a sum considered a feasible investment for a small consumer. In this respect, the desirable load had to be covered and the excess electricity will be sold to the grid, to reduce the years of the systems' abbreviation. It is important to note that the grid connection for every system was always one-way: the systems can offer electricity to the grid but can never buy load from it.

As the last step, the island with the highest energy environmental potential was selected to place the optimal system to cover the desirable load for a typical house under three different combinations of RES components: a single photovoltaic system, a single wind system and a hybrid photovoltaic-wind system, all used Zebra batteries to store excess electricity. This scenario with the same components was simulated under the meteorological data of all areas to identify some relation between the energy received by the environment and the total energy produced by the components of the RES-based systems.

Concerning the optimal ratio of energy load that can be obtained from several combinations of photovoltaic panels and wind turbines, it is necessary for a researcher to choose the optimal components for each system for a given specific area. For this reason, all the scenarios use multi-crystalline panels [6] with approx. 15% performance in real time conditions. Furthermore, wind velocity varies greatly during the year, so it is appropriate to find specific wind turbines which will start their operation for relatively low velocity ($\approx$2.5 m/s) in combination with an affordable cost for an individual consumer. Eco Wind Turbines [16] of 5 and 10 kW fulfill the exact requirements of this study. Finally, Zebra batteries are used as storage units for the excess electrical load, as they have high operating hours compared to competitive technologies. For the wind turbines and Zebra batteries, all the necessary parameters have been taken from the manufacturers' manuals [16].

For the needs of this work, the real interest rate is considered as standard and equal to 5%. There is not an assessed lifetime project because this is the desirable aim of the research and, moreover, the factor $N_{\text{comp.}}$ in eqs. (8) and (9) is the lifetime of each component and not the lifetime the RES-project is designed for. These are calculated separately for each component and summed for the total annual replacement costs.

Table 1
Optimal scenarios for each location.

	desload (kW)	Crete (Rethimnon)			Rhodes			Skiros			Naxos		
		PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)	PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)	PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)	PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)
pv_bat	7775	7	–	1	6	–	1	7	–	1	7	–	1
	2982	5	–	1	5	–	1	5	–	1	5	–	1
	16097	28	–	2	25	–	4	25	–	3	25	–	4
wind_bat	7775	–	4 × 10	4	–	2 × 10	1	–	1 × 5	1	–	1 × 5	1
	2982	–	2 × 5	5	–	1 × 5	1	–	1 × 5	1	–	1 × 5	1
	16097	–	14 × 10	18	–	2 × 10	3	–	3 × 10	1	–	2 × 10	4
pv_wind_bat	7775	6	1 × 5	1	3	1 × 5	1	1	1 × 5	1	1	1 × 5	1
	2982	3	1 × 5	2	1	1 × 5	1	1	1 × 5	1	1	1 × 5	1
	16097	25	1 × 5	4	19	1 × 5	2	19	2 × 5	1	21	1 × 5	2

4. Results and discussion

All the possible scenarios were designed using the software tool HOMER. The energy part of this project is based on HOMER but the economical study is differentiated in three ways to compute the systems' abbreviation in years: a) the cost of the emissions is calculated, b) the amount of money gained from the trading of excess electricity is included in the calculations, and c) the lifetime project is not considered as standard but the annual replacement costs are estimated separately for each component. Clearly the meteorological data play the most important role in the above calculations and the grid connection contributes for the sale of the excess electricity.

In accordance with the above, the scenarios were designed as presented in Table 1. It is obvious that the hybrid photovoltaic-wind systems can operate under different combinations of components but the most economically feasible solutions have been selected, as described above. The same conditions also stand for the second step of this study. The scenarios with the constraint of investment costs (100,000 €) are presented in Table 2. The systems not mentioned further cannot be designed under the limitation of the capital costs and thus, they do not participate in the present abbreviation years research. Finally, the three different optimum systems for the coverage of the load of a typical house, which is established on Naxos Island, are presented in Table 3. The latter has been selected because Naxos is the island with the largest environmental potential and the typical house is a characteristic load for an individual consumer.

Table 2
Scenarios per location under the investment limitation.

	desload (kW)	Crete (Rethimnon)			Rhodes			Skiros			Naxos		
		PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)	PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)	PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)	PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)
pv_bat	7775	35	–	1	35	–	1	35	–	1	35	–	1
	2982	35	–	1	35	–	1	35	–	1	35	–	1
	16097	35	–	1	35	–	1	35	–	1	35	–	1
wind_bat	7775	–	2 × 10	1	–	2 × 10	1	–	2 × 10	1	–	2 × 10	1
	2982	–	2 × 10	1	–	2 × 10	1	–	2 × 10	1	–	2 × 10	1
	16097	–	–	–	–	–	–	–	–	–	–	–	–
pv_wind_bat	7775	25	1 × 5	1	25	1 × 5	1	25	1 × 5	1	25	1 × 5	1
	2982	25	1 × 5	1	25	1 × 5	1	25	1 × 5	1	25	1 × 5	1
	16097	–	–	–	25	1 × 5	1	25	1 × 5	1	25	1 × 5	1

Table 3
Optimal systems for Naxos Island.

Systems	Typical house (7775 kWh/year)		
	PV (kW)	Wind (kW)	Battery (Zebra, 20 kW each)
pv_bat	6	–	1
wind_bat	–	1 × 5	1
pv_wind_bat	1	1 × 5	1

Table 4
Abbreviation of the systems in years.

	desload (kW)	Crete (Rethimnon)		Rhodes		Skiros		Naxos	
		Years		Years		Years		Years	
		No grid	Grid	No grid	Grid	No grid	Grid	No grid	Grid
pv_bat	7775	25.7	14.1	64.1	22.2	86.2	23.6	25.7	14.0
	2982	822.5	12.1	Never	12.8	Never	17.1	822.5	12.0
	16097	40.6	6.7	Never	10.5	Never	10.2	93.9	9.4
wind_bat	7775	Never	Never	Never	8.8	203.8	14.8	203.8	9.4
	2982	Never	Never	Never	20.5	Never	10.1	Never	7.3
	16097	Never	Never	Never	16.4	Never	4.7	Never	6.1
pv_wind_bat	7775	Never	28.4	Never	20.3	Never	15.3	254.4	8.6
	2982	Never	109.7	Never	16.0	Never	9.1	Never	6.9
	16097	1294.8	12.1	Never	9.0	146.0	6.0	75.7	6.4

Table 5
Abbreviation of the systems in years under investment limitation.

	desload (kW)	Crete (Rethimnon)		Rhodes		Skiros		Naxos	
		Years		Years		Years		Years	
		No grid	Grid	No grid	Grid	No grid	Grid	No grid	Grid
pv_bat	7775	745.9	4.7	745.9	4.1	745.9	4.7	745.9	4.4
	2982	Never	4.4	Never	3.9	Never	4.5	Never	4.4
	16097	37.5	5.1	37.5	4.4	37.5	4.9	37.5	5.1
wind_bat	7775	–	–	Never	8.8	Never	4.9	Never	3.6
	2982	–	–	Never	7.9	Never	4.6	Never	4.4
	16097	–	–	–	–	–	–	–	–
pv_wind_bat	7775	Never	6.8	Never	5.0	Never	5.2	Never	4.4
	2982	Never	6.3	Never	5.2	Never	4.9	Never	4.4
	16097	–	–	56.4	5.6	56.4	5.5	56.4	5.2

Table 4 shows that a stand-alone (off-grid) system is not financially profitable because the components are very expensive regarding to their performance and the over sizing for the continuous operation of the system is necessary. The grid connection dramatically changes the above results, as shown in Table 4, because the consumer takes advantage of the excess electrical load through over sizing and an important amount of money is earned from the trade of the energy packages. The systems that exclusively use wind energy have the largest failure percentage for the abbreviation of capital costs over time. This is because the wind constitutes a very unstable energy source because of the high fluctuations in combination with the high capital cost of these technologies. Finally, it is obvious that the grid is essential for an established system to sell the excess electricity from the RES components and, overall, Naxos is the island where the systems present the shortest periods of the abbreviation (for a typical house the average stack of years is 10.67 years, for a typical country house is 8.73 years and 7.3 years for a small company). This is because Naxos Island has the greatest environmental potential and as the desirable load increases, the excess electricity also increases due to the over sizing of the components.

The design of the systems will be finalized under the area and investment limitations. The results in Table 5 show that the stand-alone systems cannot be abbreviated during a logical period of time because the over sizing is much bigger than the needs of the systems. On the other hand, when the same systems are connected to grid, the average time of abbreviation is limited to five years or less. In this respect, an individual consumer is better to partially act as a small businessman whether or not the over sizing is inevitable. The single wind systems again present unpredictable behavior for the same reasons as mentioned above.

Finally, the relationship between produced energy and environmental potential supposed to satisfy the desirable load of a typical house is depicted in Fig. 5 for the three scenarios. In general, the produced electricity increases linearly with the environmental potential, presenting relatively high slopes, except in the case of the pv_bat system. In the latter case, an almost constant behavior is observed with a relatively low inclination of 0.36. This is because the solar energy is generally stable without significant fluctuations due to location and area, especially for a Mediterranean country such as Greece. However, systems that take advantage of the wind, depend on the area they will be established, thus underlining that an environmental study on meteorological data is very important.

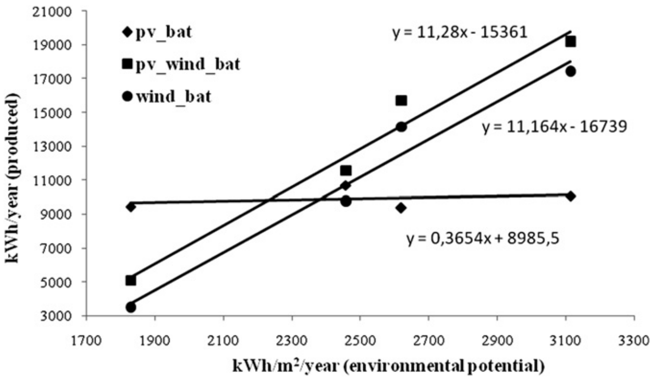

Fig. 5. The produced electricity as a function of the environmental potential.

5. Conclusion

In the present study, three different scenarios in four Greek Islands, which are based on RES technologies, are studied for the coverage of three different typical desirable loads. The simulations took place under a modified calculation system based on HOMER software. The years for the abbreviation of a system seem to be a very important parameter for investment of money that an individual consumer has available. The grid connection is found to be necessary not for energy backup but only for trading of the excess electricity arising from RES components. A system which is established in an area with large environmental potential, namely Naxos Island, has a fairly low period of abbreviation (less than 10 years). Moreover, it is observed that a hybrid photovoltaic-wind system is more profitable than a single photovoltaic or a single wind system for a unit, which needs more energy packages than a typical house. The lowest number of abbreviation years is achieved when small over sizing takes place. This allows feeding of the established unit regardless of the local environmental potential. Finally, the relationship between produced energy and environmental potential reveals the necessity of an environmental study on the meteorological data before the investment.

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Nomenclature

Latin symbols
A: surface area (m^2)
C: cost (€)
E: energy (kWh)
Emissions: emissions from the grid
f: derating factor
G: solar radiation (W/m^2)
i: real interest rate
m: mass (kg)
N: number of lifetime years for every component
P: power (W)
R: ratio of beam radiation
r: reflectance of the ground
S: salvage value (€)
SFF: sinking factor
T: temperature (°C)
u: velocity (m/s)
Y: number of abbreviation years

Greek symbols
A: anisotropy of the solar radiation
α: temperature coefficient (%/°C)
β: slope of the surface of pv panels
ρ: density (kg/m^3)

Subscripts
arep: annual replacement
b: beam radiation
c: photovoltaic cell
cap: capital
comp: component
d: diffuse radiation
emissions: emissions from the grid
g: ground
gridcap: capital for grid connection
i: index
kinetic: kinetic energy
oper: operational
p: power
perton: per ton of CO_2
proj: project of establishment
PV: photovoltaic
rep: replacement of components
solar: solar potential
STC: standard test conditions
totrep: total replacement
wind: wind potential
ygrid: annual for grid connection