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Creating the electric energy mix in a non-connected island

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Abstract

As the electric energy in the non-connected islands is mainly produced by oil-fueled power plants, the unit cost is extremely high due to import cost. The integration of renewable resources in the energy mix is essential for reducing the financial and environmental cost. In this work, various energy resources (renewable and fossil fuels) are evaluated using technical, environmental and economic criteria with an emphasis to biomass, pumped hydro storage and replacement of oil power plants. Finally, a synthesis is presented as a toy-model in an Aegean island that satisfies the electric energy demand including base and peak electric loads.

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Keywords: renewable energy resources; stochastic simulation; Hurst parameter; hybrid energy system

1. Introduction

Most of the Greek islands are not connected to the electricity network of the mainland. The production of electric energy relies on local oil fuel plants, which have a high cost due to the import cost of oil (compared to the import and distribution cost on the mainland and the import-free use of renewable energy resources) and also, a high environmental impact. During the last years, there has been a significant effort to replace the energy produced from oil fuel with renewable resources either partly or entirely. The continuous advances in renewable energy resources technology along with the gradual installation-cost reductions pave the way towards a wider adaptation of renewable energy resources worldwide.

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Since the late 1970s, the idea of a so called Hybrid Energy System (HES) that combines wind, solar and diesel generators, as well as battery tanks, has been developed. In recent years, the integration of other renewable resources, such as pumped hydro storage, wave energy and biomass, is also evolving. According to [1] combining HES with wave energy converters to create the energy mix of a non-connected island could lead to a much higher renewable fraction. However, so far, the combination of all renewables towards an autonomous grid is still at an early stage [1]. In this work, all six renewable resources are examined (solar, wind, marine, hydropower, biomass and geothermal) in order to create the energy mix for a non-connected island. In this respect, we note that the uncertainty that dominates the associated natural processes and the energy demand is considerable and requires the use of a stochastic approach in order to achieve effective planning of the energy system.

For our case study the selected the area for the toy-model analysis is Astypalaia, which is a Greek island, part of Dodecanese, an archipelago of twelve major islands in the south-eastern Aegean Sea (Figure 1). The island has about 1300 inhabitants and it extends in an area of 97 km^2. Astypalaia has more than 20 000 visitors per year which makes tourism the main industry.

Fig. 1. Location of Astypalaia (36◦5390N 26◦3131E).

Today the electric energy demand is satisfied by an oil-fuelled thermal station because the island is not connected to the electricity system of the mainland and there are no renewable energy sources installations in the area.

According to records from 2014 to 2015, the island's mean annual demand was 6250 MWh. The peak hourly demand was 2.2 MWh (occurred on 14/08/2015 at 21.00) and the minimum was 0.23 MWh. In Figure 2, the hourly energy demand of Astypalaia for the 2014-2015 period is shown. As expected, it exhibits high values during the summer touristic period and low values during the rest of the year.

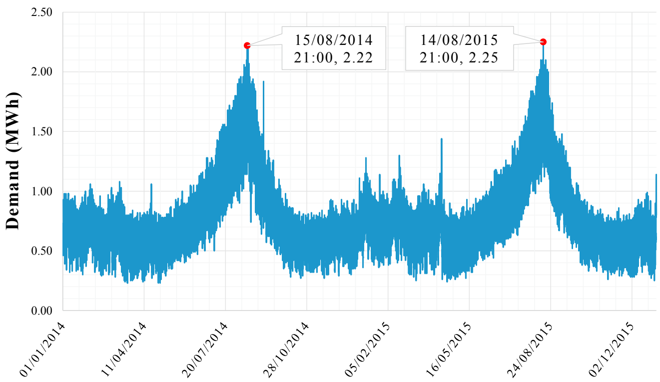


Fig. 2. Historical 2014-2015 hourly electric energy demand (MWh).

2. Data

2.1. Existing data for renewable energy resources

First, the possibility of hydropower production in the island is examined. The mean annual precipitation in Astypalaia is estimated as 680 mm/yr. According to hydrological modelling of the only water basin in the island (Livadi), the mean annual runoff is estimated to be 100 mm/yr. The existing dam located downstream of the Livadi basin area (8 km^2) has a storage capacity of 875 000 m^3 and receives approximately 800 000 m^3/yr inflows on a yearly basis. The dam is 32 m high. Today, the reservoir serves only domestic and agricultural water uses.

Furthermore, the potential of deploying the agricultural field residues (remains) in order to produce energy from a biomass station is investigated. The agricultural residues of the island are 105 tonnes, 40% of which are oat crops, 21% barley crops, 17% wheat crops, 6% corn crops, 6% trees (pruning), 9% olive trees and 1% vineyards. Considering mean calorific value of 18.5 MJ/kg according to [2] and the efficiency of the power plant as 0.35, the expected electric energy production is 190 MWh/yr. There is a potential to cultivate energy crops with low irrigation demands that can cover a maximum area of 500 ha.

Taking into account that Astypalaia is located at the Volcanic Arc of southern Aegean Sea, the potential of using geothermal energy is also considered. Although no measurements have been implemented, we assume that there is exploitable geothermal energy of a minimum of 0.5 MW. For reference, according to [3], in the Aegean islands of Milos and Nisyros units of 2 MW and 3 MW respectively have the potential to be installed.

Since there is a high wind, solar and wave energy potential in the island, the installation of wind turbines, solar panels and wave energy converter is encouraged. In Figure 3, the histogram of wind speed at 75 m height and wave height are shown, as well as the monthly distribution of solar radiation in the island.

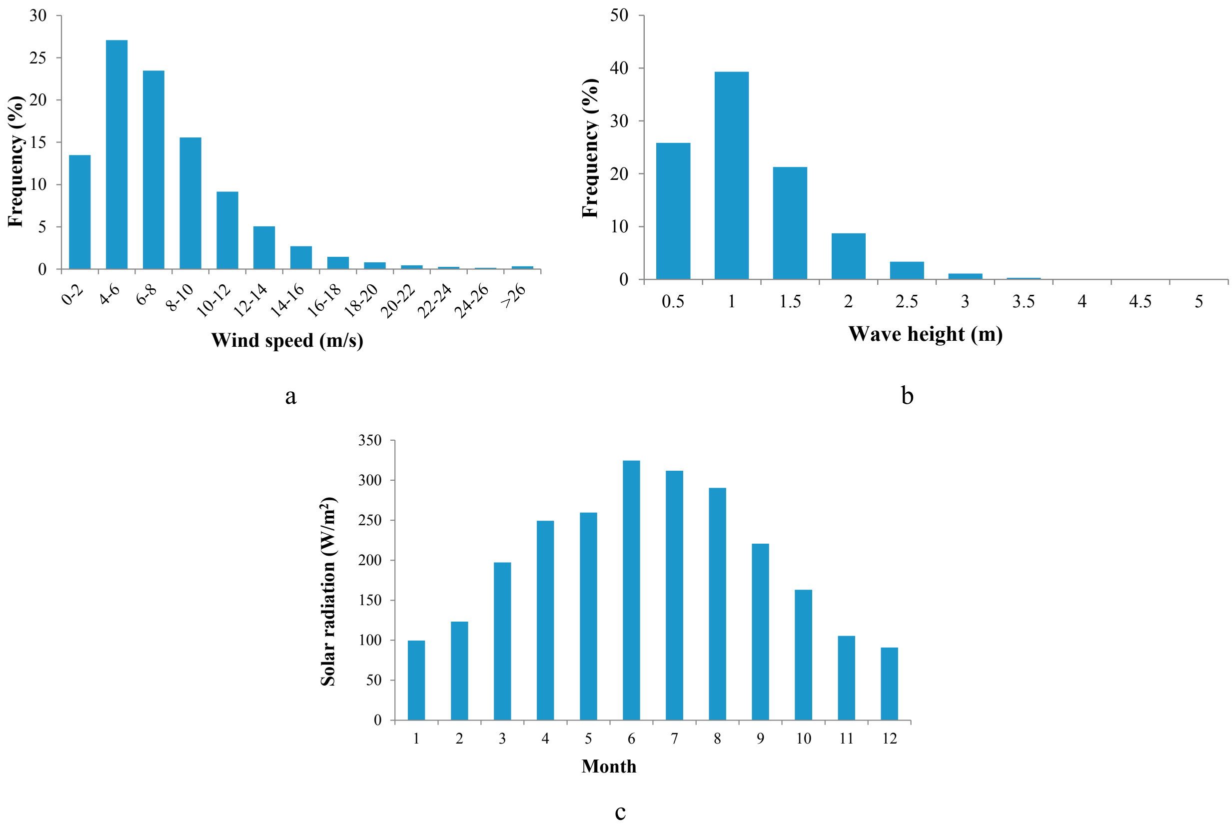


Fig. 3. Histogram of (a) wind speed at 75 m height; (b) wave height; (c) monthly solar radiation.

2.2. Generation of synthetic data for energy production simulation

Considering the electric energy demand simulation implemented in [4], a synthetic time series of hourly electric demand is produced and evaluated for a 100 year period using the measurements from 2014 to 2015 as seen in Figure 2. The resulting synthetic demand time series shows that the annual demand is 6265 MWh/yr and the peak demand is 2.6 MWh/yr.

Regarding the hydroclimatic conditions presented in [5], 100 years of rainfall data and mean monthly temperature are generated. The time series produced are based on historic hydrometeorological data from June 2009 to February 2017. The hourly synthetic data are generated through Castalia model [6]. The model preserves the essential statistical characteristics (marginal and joint distributions) of historical data at three time scales (annual, monthly, daily), as well as the long-term persistence (Hurst-Kolmogorov dynamics), periodicity and rainfall intermittency.

As for the solar, wind and wave data, the mean-hourly synthetic time series for 100 years are produced using the methodology developed by [7] which is suitable for double periodic processes. Particularly, this methodology preserves the double cyclostationarity (i.e. diurnal and seasonal) of a process though the hourly-monthly marginal distributions, including intermittent characteristics such as probability zero values, as well as the dependence structure of the processes through the climacogram (variance of scaled process) rather than the autocovariance or the power spectrum [8]. For the dependence structure we apply a Hurst-Kolmogorov model based on the empirical climacogram of each process. Finally, for the generation scheme we use the CSAR algorithm (cyclostationary sum of finite independent AR(1) processes according to [9]) capable of generating any length time series following an Hurst-Kolmogorov, or various other processes, and with arbitrary distributions of each internal stationary process of the double cyclostationarity process. The methodology for producing the wind and wave time series is detailed in [10], for the solar irradiance time series in [11] and for the cross-correlations between several involved hydroclimatic processes (temperature, dew-point, precipitation and wind speed) in [12].

More detailed information on the timeseries generation can be found at the provided references. All timeseries reproduce exceptionally well the essential characteristics of the marginal distribution and the dependence structure of each process. Although the methodologies do not explicitly focus on reproducing the extremes behavior, they exhibit a satisfactory reproduction of the extremes by preserving the skewness in all cases, or even the kurtosis as well, as in timeseries produced according to [7]. However, we note that the design and simulation of the energy system is not particularly sensitive to the extreme events of each timeseries due to technical limitations of the infrastructure, e.g. when exceeding the reservoir capacity leads to spilling.

3. Simulation of energy system

3.1. Suggested infrastructure

Given the existing and the synthetic data for our case study, possible infrastructure for the exploitation of each energy resource is suggested below.

An upgrade of the existing dam into a hydroelectric dam is the basis of the proposed solution. A turbine of 0.08 MW is proposed in order to produce 25 MWh per year [5].

Regarding the marine energy, using the 100 years of hourly wave height (and produced energy) synthetic time series, overtopping wave energy converters are proposed to produce energy collecting the incoming waves through overtopping and wave run-up into deposit reservoirs, and feeding the water to a low head Kaplan turbine of 0.3 MW with a capacity factor of 0.32. According to this scenario, 835 MWh per year are produced [10].

With regard to the solar power, the features of the proposed photovoltaic park are presented in Table1.

Table 1. Proposed photovoltaic park.

Power (MW)	Total area of panels (m^2)	Total area of park (m^2)	Panel efficiency (%)	Expected energy production per park(MWh/yr)	Capacity factor
0.1	754	11 000	13.4	162	0.16

The proposed wind turbine of 0.5 MW has total height of 75 m and diameter of 54 m. The cut-in and cut-out wind speed is 2.5 m/s and 25 m/s respectively [13] and assuming a capacity factor of 0.5, 2 233 MWh per year are produced.

The features of the proposed biomass station [13] are summarized in Table 2.

Table 2. Energy produced from biomass power station.

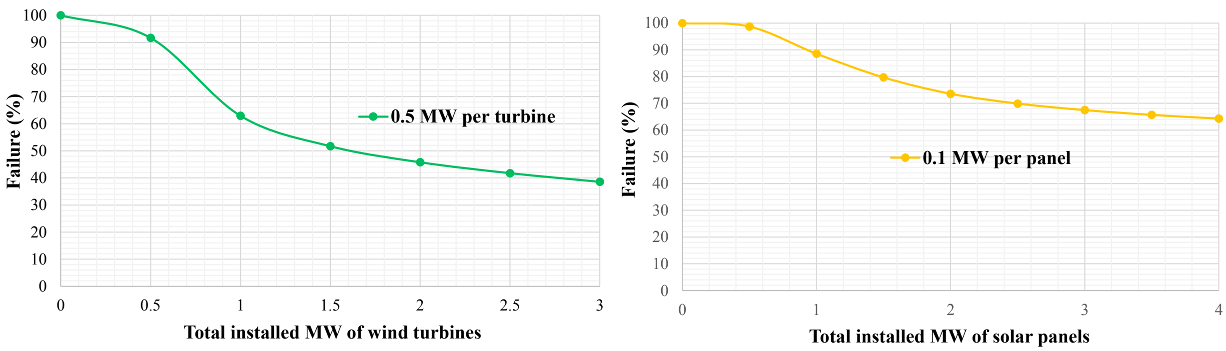
	Area (ha)	Calorific value (MJ/kg)	Production (t/yr)	Expected energy production (MWh/yr)	Power (MW)	Capacity factor
Existing crops	50	18.5	100	190	1	0.35
Cultivated energy crops	100	18	1 000	1 750		

With regard to the infrastructure suggested, several possible energy mix scenarios are simulated below and their performance is evaluated in terms of providing adequately the energy needed at all times (i.e., total energy production, hourly failure, mean annual surplus and deficit).

More detailed information on the suggested infrastructure can be found at the provided references.

3.2. Weather-related renewable energy resources

As a first step to create the energy mix, we explore the possibility of designing an energy system based only on weather-related renewable energy resources. However, as shown in Figure 4 the weather-related renewable resources cannot reach the peak demand. For energy autonomy, using only wind turbines, we estimate a high percentage of failure (38 % in 3 MW installed capacity) in an hourly scale (Figure 4a). Using only solar panels (Figure 4b) leads to a higher percentage of failure than the wind-only scenario (65% in 3 MW installed capacity). Finally, combining wind and solar energy (Figure 4e) results in a quite smaller percentage of failure (40% in a 3 MW installed capacity of which 2 MW is wind power and 1 MW is solar power). A great amount of energy surplus is produced in all cases which cannot be used and controlled because it is not synchronized with the energy demand (Figure 4c, 4d, 4f).



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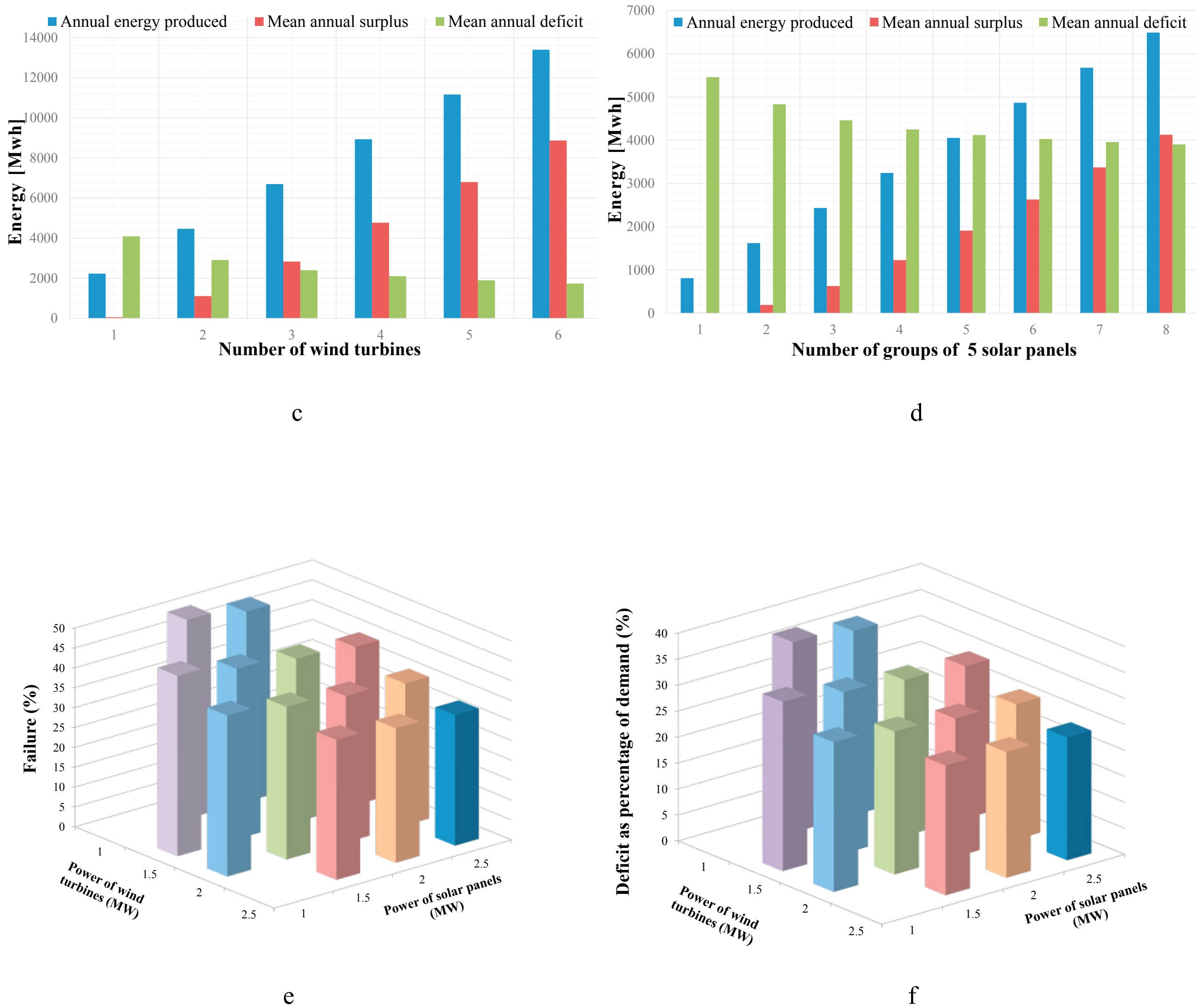


Fig. 4. Evaluation of weather related renewable: (a) wind probability of failure (%); (b) solar probability of failure (%); (c) wind mean annual surplus-deficit (MWh); (d) solar mean annual surplus-deficit (MWh); (e) wind-solar probability failure (%); (f) wind-solar deficit of demand (%).

As shown in Figure 4, wind and solar energy cannot provide sufficient energy to satisfy the peak demand. Therefore, marine and hydro are added in order to examine their contribution to the energy mix. The energy system is simulated at an hourly scale for a 100 years period. Several scenarios with combinations of renewable resources are examined in Table 3.

For each energy mix scenario, we calculate the probability of failure when satisfying the peak hourly energy demand, the mean annual deficit of energy and the mean annual surplus of energy, as shown in Figure 5. All seven scenarios present an hourly failure between 30% and 53% (Figure 5a). Taking into cosideration that the installed capacity in each successive scenario increases, the propability of failure decreases but the the produced surplus increases (Figure 5b). Both at the hourly (Figure 5c) and annual (Figure 5d) scale, high energy deficit and surplus are produced.

Table 3. Proposed scenarios of combined renewable resources.

Scenarios	Hydro (MW)	Solar (MW)	Wind (MW)	Marine (MW)	Installed capacity (MW)
1	0.08	0.5	1.0	0.3	1.9
2	0.08	0.5	1.5	0.3	2.4
3	0.08	1.0	1.0	0.6	2.7
4	0.08	1.0	1.5	0.6	3.2
5	0.08	1.5	1.5	0.6	3.7
6	0.08	1.5	1.5	0.9	4.0
7	0.08	2.0	1.5	0.6	4.2

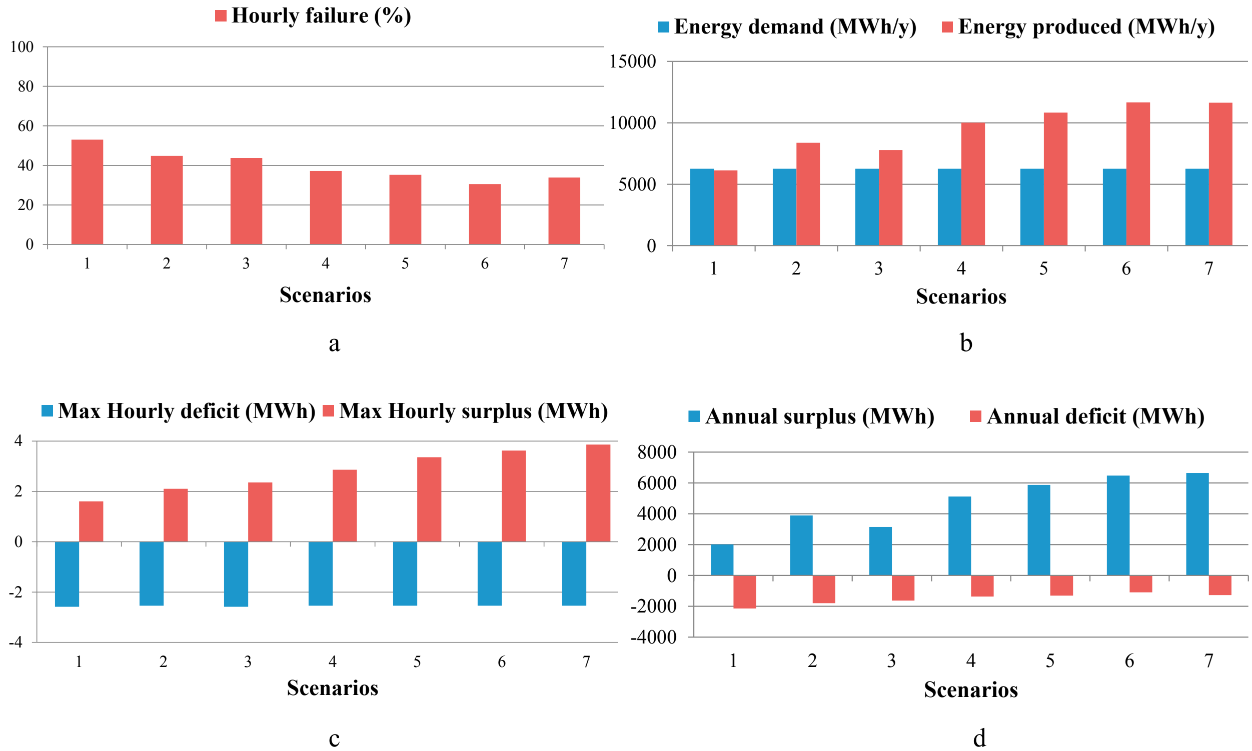


Fig. 5. Weather related energy mix scenarios: (a) Hourly failure (%); (b) Energy produced and energy demand (MWh/yr); (c) Max hourly deficit-surplus (MWh); (d) Annual surplus-deficit (MWh/yr).

3.3. *Adding governable energy resources*

Governable renewables (i.e., biomass, geothermal, pumped-storage system) are added to the energy mix in order to provide an installed capacity equal to 2.6 MW, to satisfy the peak hourly deficit, cover the annual deficits (1-2 GWh/yr) and manage the energy surplus (2-6 GWh/yr).

In case a geothermal process exists (capable of electric energy production), it is expected to operate with a small capacity factor as indicated from relevant cases in neighboring islands. Regarding the energy produced from biomass, all available agricultural residues will be deployed and cultivated energy plants will be used to cover the remaining deficit.

The use of governable renewable resources could satisfy the peak hourly and the annual deficit, but the amount of surplus energy is still significant. Hence, a pumped-storage system could be used to store electric energy surplus, as well as to satisfy the peak deficits.

4. Towards an energy mix

Considering all the above analysis (governable and weather related-renewables), we analyze two proposed scenarios with the following installed power (Table 4).

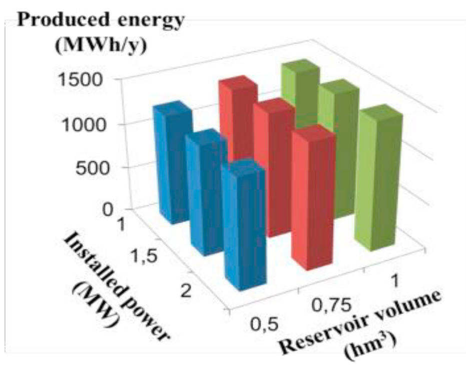
Table 4. Proposed scenarios.

Source	Power (MW)	
	Case 1	Case 2
Wind turbine	1	1
Solar panels	0.5	0.5
Hydroelectric dam	0.08	0.08
Wave energy converters	0.3	0.6
Geothermal power station	0.5	-
Pump storage system	-	1
Biomass power station	2.1	1.6
Total	4.5	4.8

In both cases there is a requirement for cultivation of energy plants which cover about 20 ha.

A pumped-storage system, that uses sea water to store energy, is considered. For the Case 2 scenario the reservoir volume and the installed power of the hydro-turbine will be determined after the optimization of the system's performance. The available net head is 400 m (Figure 6a) and the efficiency of pumped-storage cycle is assumed to be 75%.

a



b

Fig. 6. Pump strorage system: (a) location; (b) installed power-produced energy-reservoir volume.

The pumped storage system is simulated to calculate the energy production for various upper reservoir volumes and installed hydro turbines. All the proposed combinations (Figure 6b) produce about the same amount of energy, therefore the combination requiring the minimum installed power and reservoir volume is selected. A scheme of 1 MW hydro-turbine and a 0.5 hm^3 upper reservoir volume will produce 1245 MW/yr (70% of the surplus) but there will still be a deficit of 513 MWh/yr. The use of pumped-storage is a convenient way to store electric energy surplus from other sources. The existence of a reservoir also contributes to the satisfaction of peak deficits.

5. Discussion

In this study, all six renewable energy sources are examined to create the electric energy mix of a non-connected small island. The common advantage of the six resources is the free and renewable fuel and the fact that there is no need for fuel import. The energy production from weather-related sources (i.e., wind, sun, sea, water) is completely uncontrollable and does not synchronize with the demand, resulting in high values of energy deficit and surplus. In the case of hydropower, the use of reservoirs can control the production and can additionally store the surplus energy from other sources through pumped-storage facilities. The other two sources (i.e., biomass, geothermal) are governable and therefore, capable of satisfying the peak electric energy demand when needed. Combining all the above, could result in a sufficient energy mix for a small island or a larger area.

In recent years, a considerable number of wind turbines and solar power plants have been installed in many Greek islands as a result of the financial aid provided by the European Union and the benefits of the 'green' energy autonomy. Hydroelectric dams are broadly used in the mainland and their technology could be easily adjusted to small island reservoirs. The installation of biomass, geothermal and wave energy power stations is at an early stage but attracts a lot of scientific and technological interest regarding near future installations.

However, the use of renewable energy sources is not free of obstacles. We note that in the case of the biomass, the fuel must be thoroughly collected and transported before its use whereas, in the case of the geothermal process, the corresponding fields with a high exploitable -for electricity production- enthalpy are located in a few places around the world. The implementation of a renewable energy mix results in a high installed capacity -as the installed power of each renewable does not always synchronize with the demand- and a rather high installation cost especially for small islands (regarding the current situation of the renewable infrastructure). For example, the Case 2 scenario includes two wind turbines of 75 m height, 3800 m^2 of photovoltaic panels, two wave converter installations, a small hydro turbine to the existing dam, a biomass installation that must be fed with 180 t/yr of cultivated biomass, and a pumped storage system that includes a reservoir with a 0.5 hm^3 volume, a 2 km penstock and a hydro turbine installation. The total installed power of the system will be 4.8 MW (while the peak demand is 2.6 MW) and the total cost will be much more than 10 M€ according to estimated costs for each energy unit as shown in Table 5.

Table 5. Economic analysis.

Source	Estimated cost (M€/MW)	Power (MW)	
		Case 1	Case 2
Wind turbine	1.5-2	1	1
Solar panels	2-3	0.5	0.5
Hydroelectric dam	1	0.08	0.08
Wave energy converters	3-4	0.3	0.6
Geothermal power station	1-2	0.5	-
Pump storage system	1.5-2	-	1
Biomass power station	2-3	2.1	1.6
Total		4.5	4.8

On the other hand, the energy demand (peak and annual) of the island could be easily covered by a common thermal station [14] with installed power less than 3 MW. The quantity of fossil fuel required to cover the annual electric energy demand is estimated to be approximately 1 300 toe (tonnes of oil equivalents) per year. In case that the fuel is oil, the estimated annual cost is about 0.5 M€, considering high import cost but low installation and operational cost.

The decision for the energy mix must be taken after considering financial, environmental and societal issues. Additionally, the examined solutions still have a high implementation and maintenance cost, and therefore, it is reasonable that the thermal stations fed with transported oil are broadly used in non-connected islands. In the near future, it is expected that the cost of renewable resources will be further reduced and the proposed solutions will be more attractive from a financial, societal as well as environmental point of view.

References

[1] Friedrich D., Lavidas G. (2015) Combining offshore and onshore renewables with energy storage and diesel generators in a stand-alone Hybrid Energy System, *Offshore Energy & Storage Symposium 2015*, Edinburgh, Scotland

[2] Gravalos I., Xyradakis P., Kateris D., Gialamas T., Bartzialis D. Giannoulis K. (2016) An Experimental Determination of Gross Calorific Value of Different Agroforestry Species and Bio-Based Industry Residues, *Natural Resources*, 7, 57-68

[3] Papachristou M., Mendrinos D., Dalampakis P., Arvanitis A., Karytsas C., Andritsos N. (2016) Geothermal Energy Use, Country Update for Greece (2013-2016), *European Geothermal Congress 2016*, Strasbourg, France

[4] Hadjimitsis E., Demetriou E., Sakellari K., Tyralis H., Dimitriadis P., Iliopoulou T., and Koutsoyiannis D. (2017) Investigation of the stochastic nature of temperature and humidity for energy management, European Geosciences Union General Assembly 2017, *Geophysical Research Abstracts*, Vol. 19, Vienna, 19, EGU2017-10164-5, European Geosciences Union.

[5] Papoulakos K., Pollakis G., Moustakis Y., Markopoulos A., Iliopoulou T., Dimitriadis P., Koutsoyiannis D., and Efstratiadis A. (2017) Simulation of water-energy fluxes through small-scale reservoir systems under limited data availability, European Geosciences Union General Assembly 2017, *Geophysical Research Abstracts*, Vol. 19, Vienna, 19, EGU2017-10334-4, European Geosciences Union.

[6] Efstratiadis A., Dialynas Y., Kozanis S., & Koutsoyiannis D. (2014) A multivariate stochastic model for the generation of synthetic time series at multiple time scales reproducing long-term persistence, *Environmental Modelling & Software*, 62, 139–152, doi:10.1016/j.envsoft.2014.08.017

[7] Dimitriadis P., and Koutsoyiannis D. (2015) Application of stochastic methods to double cyclostationary processes for hourly wind speed simulation, *Energy Procedia*, 76, 406–411, doi:10.1016/j.egypro.2015.07.851

[8] Dimitriadis P., and Koutsoyiannis D. (2015) Climacogram versus autocovariance and power spectrum in stochastic modelling for Markovian and Hurst–Kolmogorov processes, *Stochastic Environmental Research & Risk Assessment*, 29 (6), 1649–1669, doi:10.1007/s00477-015-1023-7

[9] Deligiannis E., Tyrogiannis V., Daskalou O., Dimitriadis P., Markonis Y., Iliopoulou T., and Koutsoyiannis D. (2016) Stochastic investigation of wind process for climatic variability identification, European Geosciences Union General Assembly 2016, *Geophysical Research Abstracts*, Vol. 18, Vienna, EGU2016-14946-6, European Geosciences Union, doi:10.13140/RG.2.2.26681.36969

[10] Moschos E., Manou G., Georganta C., Dimitriadis P., Iliopoulou T., Tyralis H., Koutsoyiannis D., and Tsoukala V. (2017) Investigation of the stochastic nature of wave processes for renewable resources management: a pilot application in a remote island in the Aegean Sea, European Geosciences Union General Assembly 2017, *Geophysical Research Abstracts*, Vol. 19, Vienna, 19, EGU2017-10225-3, European Geosciences Union, doi:10.13140/RG.2.2.30226.66245

[11]Koudouris G., Dimitriadis P., Iliopoulou T., Mamassis N., and Koutsoyiannis D. (2017) Investigation of the stochastic nature of solar radiation for renewable resources management, European Geosciences Union General Assembly 2017, *Geophysical Research Abstracts*, Vol. 19, Vienna, 19, EGU2017-10189-4, European Geosciences Union, doi:10.13140/RG.2.2.16215.06564

[12]Koskinas A., Zacharopoulou E., Pouliasis G., Engonopoulos I., Mavroyeoryos K., Deligiannis E., Karakatsanis G., Dimitriadis P., Iliopoulou T., Koutsoyiannis D., and Tyralis H. (2017) Simulation of electricity demand in a remote island for optimal planning of a hybrid renewable energy system, European Geosciences Union General Assembly 2017, *Geophysical Research Abstracts*, Vol. 19, Vienna, 19, EGU2017-10495-4, European Geosciences Union, doi:10.13140/RG.2.2.10529.81767

[13]Stamou P., Karali S., Chalakatevaki M., Daniil V., Tzouka K., Dimitriadis P., Iliopoulou T., Papanicolaou P., Koutsoyiannis D., and Mamassis N. (2017) Creating the electric energy mix of a non-connected Aegean island, European Geosciences Union General Assembly 2017, *Geophysical Research Abstracts*, Vol. 19, Vienna, 19, EGU2017-10130-10, European Geosciences Union, doi:10.13140/RG.2.2.36537.77927

[14]Roussis D., Parara I., Gournari N., Moustakis Y., Dimitriadis P., Iliopoulou T., Koutsoyiannis D., and Karakatsanis G. (2017) Energy, variability and weather finance engineering, European Geosciences Union General Assembly 2017, *Geophysical Research Abstracts*, Vol. 19, Vienna, 19, EGU2017-16919, European Geosciences Union.