Energy 116 (2016) 364–379

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Optimal design and techno-economic analysis of an autonomous small isolated microgrid aiming at high RES penetration

Dimitrios Thomas [a, b, *], Olivier Deblecker [a], Christos S. Ioakimidis [b]

[a] Department of Electrical Engineering, University of Mons, 7000 Bd Dolez 31, Mons, Belgium
[b] ERA Chair 'Net-Zero Energy Efficiency on City Districts', Research Institute for Energy, University of Mons, Mons, Belgium

ARTICLE INFO

Article history:
Received 13 May 2016
Received in revised form
14 September 2016
Accepted 25 September 2016

Keywords:
Solar-wind-battery system
Optimization
Isolated renewable energy system
Net present cost
Techno-economic analysis

ABSTRACT

Electrification demand in small isolated power systems is typically covered by autonomous power stations, mainly diesel-generators. The technical constraints introduced by diesel-generators along with the high cost of storage options confine the penetration of renewable energy sources (RES) in these systems. This paper examines the possibility of utilizing a RES-hybrid system for a small Greek island by exploring three different case scenarios. The first two include system configurations with gradual conventional fossil-fuel power reduction while in the third one we investigate if a nearly 100% renewable system is feasible. Techno-economic analyses ensure the technical feasibility of the systems and address their economic viability. Results showed that the conventional fossil-fuel power required for the first and the second scenario could be decreased 52% and 74% compared to the existing system and the system's overall by 17% and 26% respectively. RES-penetration reached 68% (first-scenario) and 74% (second-scenario) while the NPC value was calculated to 1.84 and 2.25 million euro respectively. A nearly 100% renewable energy system (third scenario) could be technically feasible but it would require the installation of enormous RES equipment capacity dramatically increasing the total cost. Finally, the social aspect and local acceptability of RES-projects in Greece are discussed.

1. Introduction

Electrification of remote areas and non-interconnected islands relies to a great extent on Autonomous Power Stations (APS) which mostly consume diesel or heavy oil (mazut). This is the case for most islands located in the Aegean Sea, Greece. Although there is a great potential of renewable energy sources in the islands (mainly wind and solar), the achievable level of renewable energy sources (RES) penetration is low and it is typically limited to 15–20% of the annual energy demand [1]. The main reasons behind those limitations are the constraints introduced by conventional generators [2]. The scope of this study is to examine the potential for reaching very high RES penetration levels on small island systems through the design and implementation of a hybrid system comprising photovoltaics (PVs), wind turbines (WTs) and electrical storage. Initially we investigate the operation of the hybrid renewable system in parallel to the existing APS considering in each scenario a different number of operating APS units. As a second step we examine the operational and economic feasibility of the power system with the APS considered totally absent. The main objective of this study is to consider various renewable energy technology options in combination with realistic inputs on their physical, operating and economic characteristics in order to optimally design a renewable energy microgrid and decide its operating policies aiming at very high levels of RES penetration.

Electricity generation in stand-alone hybrid power systems requires various aspects to be met. Two of the most significant aspects are reliability and cost [3]. Previous research [4,5] showed that hybrid stand-alone electricity generation systems are usually more reliable and less costly than systems depending on just a single source of energy. The economic viability of Hybrid Renewable Energy Systems (HRES), specifically in off-grid remote locations, has been addressed in past literature [6–8] with many studies highlighting the important role of the climate on the hybrid system configuration and profitability. For instance, authors in Ref. [9] conducted an economic analysis of hybrid Photovoltaic (PV)-diesel system in different climate zones and concluded that the optimum climate zone for installing a PV-diesel hybrid power

* Corresponding author. Site Epargne (56, rue de l'Epargne - n°4, B7), 7000, Mons, Belgium.
E-mail address: Dimitrios.THOMAS@umons.ac.be (D. Thomas).

http://dx.doi.org/10.1016/j.energy.2016.09.119
0360-5442/

system is the arid interior. Authors in Ref. [10] reached a similar conclusion supporting that photovoltaic hybrid systems (PV–Diesel–Battery) are ideal in areas with warm climates.

HRES consist of a combination of one or more renewable and of one or more conventional energy source that work in stand-alone or grid connected mode. It is possible that a conventional energy source is totally absent from the system but renewable is a prerequisite for HRES. The development in renewable energy technologies and power electronic converters made HRES notably popular for stand-alone power generation in isolated sites. The most significant feature of HRES is the potential combination of two or more renewable power generation technologies to make best use of their operating features and to achieve efficiencies higher than the ones attained from a single-type power source [11]. Fortuitously, remote areas are generally rich in locally available renewable energy resources. The rapidly declining cost of renewable energy technologies in combination with the increased cost and the environmental consequences caused by the use of diesel fuel have widely encouraged the utilization of renewable energy systems for off-grid power supply [12]. Research on RESs has been mostly carried out in the field of system modeling, simulation, component sizing, economic analysis, and particularly system optimization [13–16].

Design, optimization, and simulation of stand-alone HRES on islands have been of recent interest in the literature. Common configurations of HRES include PV–Wind, PV–Diesel, PV–Wind-Diesel, and Wind–Diesel with or without energy storage in batteries. The most commonly used ones include dynamic programming, probabilistic approach, multi-objective design, artificial intelligence methods, linear programming and iterative techniques [17,18]. Authors in Ref. [19] developed an energy management system for a stand-alone microgrid adopting a hierarchical control structure to tackle the different operation objectives. In Ref. [20] authors focused on energy storage to enhance increased penetration of renewables in islanded systems while Rahman et al. [21] developed a hybrid energy system for an off-grid community in Canada covering several scenarios based on renewable energy fractions. Koutroulis et al. [22] used genetic algorithms (GA) for optimal sizing of stand-alone PV/WG (Wind Generation) systems while Zhao et al. [23] presented an optimal unit sizing method for the design and development of a real microgrid system on Dongfushan Island, Zhejiang Province, China, consisting of wind turbine generators, solar panels, diesel generators and battery storage units.

Although the present study considers only electrochemical storage with its system's configuration, special attention should be given to two other widely studied storage technologies, the pumped hydroelectric energy storage (PHES) and the compressed air energy storage (CAES). An upper reservoir is used in PHES facilities into which water is pumped from another reservoir located at lower elevation, usually during periods of low electricity demand. Then, during periods where electricity demand is high, power is generated by releasing the stored water. PHES systems have been addressed thoroughly in literature [24,25], often in combination with systems utilizing wind power [26–28]. The authors in Ref. [29] proposed the installation on Gran Canaria island of an appropriately administered wind powered pumped hydro storage system. The results obtained by their optimum-sized economic model indicated an increase of RES energy by 1.93%. An economic evaluation of wind-powered PHES systems can be found in Ref. [30].

A largely equivalent storage system with PHES is CAES where instead of pumping water, ambient air is compressed and stored under pressure. When electricity is needed, the under-pressure air is heated and driven to an expansion turbine coupled with a generator for power production. In literature, CAES systems have been addressed in combination with hybrid RES systems [31,32] as well as with other forms of storage like thermal [33]. Authors in Ref. [34], as a case study, evaluated the economics of two hypothetical merchant CAES and distributed-CAES (D-CAES) facilities performing energy arbitrage in Alberta, Canada. They resulted in a superior economic and environmental performance of D-CAES leading to a negative abatement of cost. CAES have been investigated also in mobility concepts like air hybrid vehicles. More specifically, the authors in Ref. [35] proposed a novel compression strategy for air hybrid engines utilizing two storage tanks which increases the efficiency of regenerative braking of air hybrid vehicles.

2. Background information and present energy system

2.1. Electricity infrastructure and load profile

It is selected as a study case the small island of Agios Efstratios located in the North Aegean Sea, Greece (latitude 39° 27′ to 39° 34′, longitude 24° 57′ to 25° 05′) (see Fig. 1). Agios Efstratios had been selected in the past by governmental authorities to implement a "Green Island" project. Agios Efstratios covers a total area of 44 km^2 and has a population of approximately 300 people. However, this number greatly increases in summer due to tourism. The landscape is mostly rocky, with scarce and low vegetation. The economy is based on fishing, livestock breeding and tourism. The main settlement of the village is located northwest and it comprises public buildings (city hall, post office, general citizens' services, school) and inhabitants residences.

Agios Efstratios island's electricity is operated and managed by Public Power Corporation of Greece (PPC), the main electric utility in Greece. Similar to the majority of Greek islands, Agios Efstratios is not connected with undersea cables neither to the mainland grid nor to any nearby islands. The energy system of the island consists of a thermal power station and a 20 kW wind turbine which is the only RES component in the island. The thermal power plant is currently based on an APS including 3 × 220 kW and 2 × 90 kW diesel generators.

The daily load profile for the island was obtained from PPC for the year 2010. According to the obtained hourly load data, the island's annual electricity demand was 1223 MWh. The peak load was 360 kW in August and the average daily electricity consumption was 3.35 MWh, which doubles in summer months mainly due to tourism activities, indicating the high seasonal variations of demand. The load profile had been used to illustrate the seasonal electrical load behavior during each season and is illustrated in Fig. 2.

The average daily load profile for Agios Efstratios island is depicted in Fig. 3 while in Fig. 4, a typical winter and summer day are compared in terms of electricity demand highlighting the seasonal variations.

The thermal load is the demand for heat energy. Heat in general is needed for space heating, water warming or some minor industrial process. The thermal load is assumed to be 5% of the electrical load [36] and is added mainly to examine the impact of excess energy feeding the thermal load. In this work, the primary objective is to serve the thermal load by surplus electricity of the hybrid system through dump load. When this is not possible, thermal load is served by a boiler, namely a generator from which waste heat can be recovered.

2.2. Assessment criteria

The Hybrid Optimization Model for Electric Renewables (HOMER) is a powerful tool for designing and analyzing off-grid

Fig. 1. Location of Agios Efstratios Island (Source: edited from Google Maps).

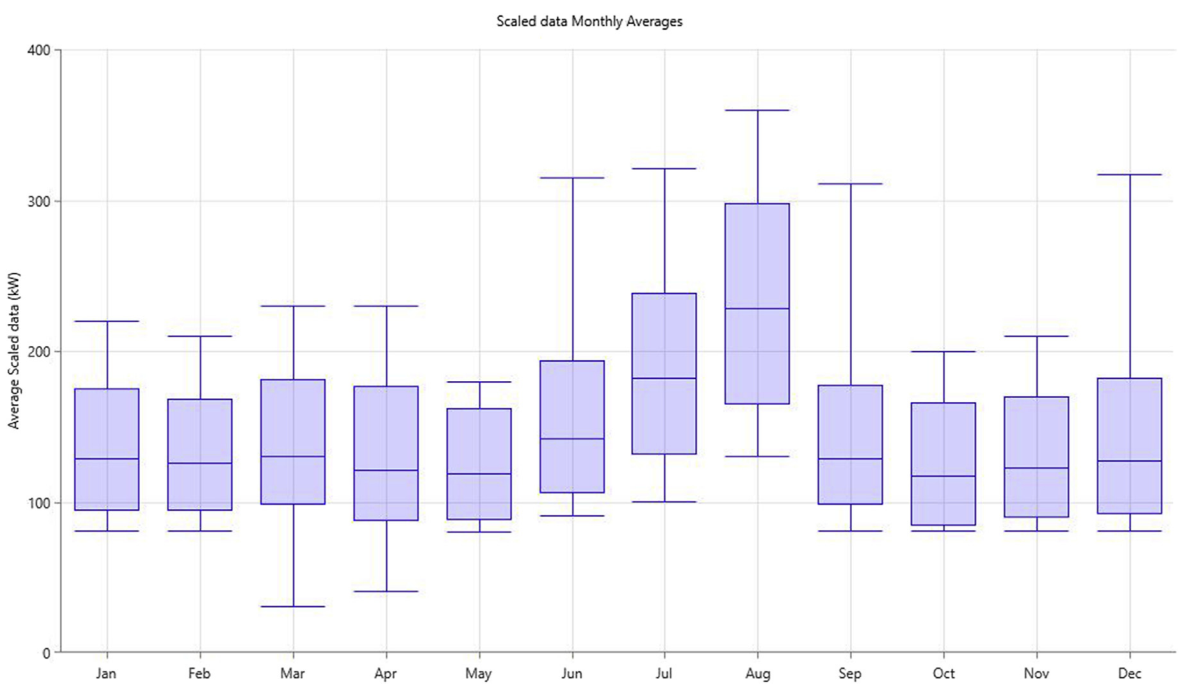

Fig. 2. Seasonal load profile during a year in Agios Efstratios (year 2010).

and grid-connected hybrid electrical power systems. The technical feasibility of the system and the load demand meet are initially assessed and afterwards the total Net Present Cost (*NPC)* of the system is calculated. The *NPC*, which is the life-cycle cost of the system, includes the initial set-up costs (*IC*), component replacement costs (*RC*), fuel costs (*FC*), and operation and maintenance costs (*O&M*). The *NPC* is calculated according to the following formula [37,38]:

$$NPC = \frac{C_{tot}}{CRF(i, T_p)} \tag{1}$$

where C_{tot} is the total annualized cost of the system (in $/year), i is the annual real interest rate (%), T_p is the project lifetime and *CRF* is the capital recovery factor. *CRF* is calculated in the following formula:

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

where n is the number of years and i is the annual interest rate. The annual real interest rate (or just interest rate) is the discount rate used to convert between one-time costs and annualized costs. The annual real interest rate is linked to the nominal interest rated according to the Eq. given below:

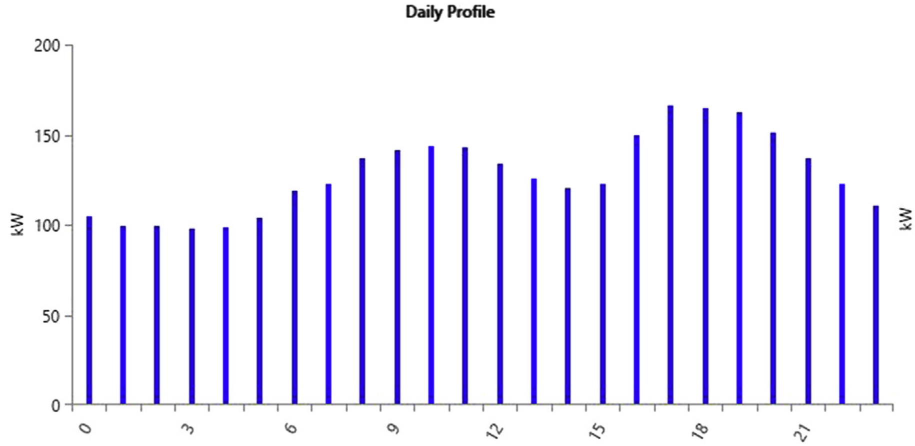

Fig. 3. Average daily load profile (year 2010).

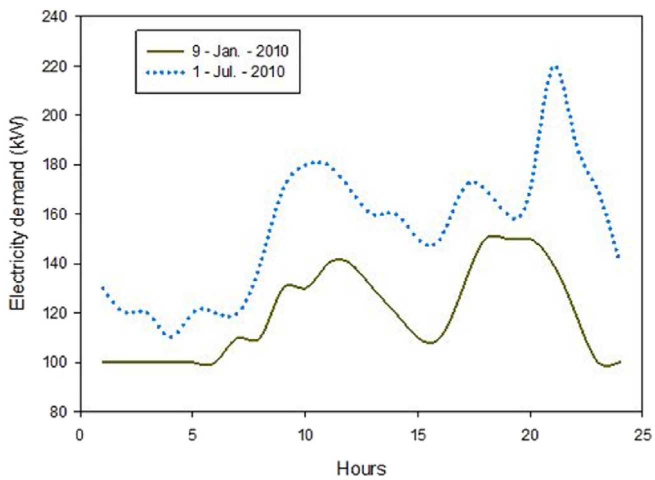

Fig. 4. Electricity demand in a typical winter and summer day (year 2010).

$$i = \frac{i' - f}{1 + f} \tag{3}$$

where i is the real interest rate, i' is the nominal interest rate and f is the annual inflation. In Greece, the nominal interest rate is 7.41% [39] (15.11.2015) and the harmonized annual inflation in 2014 was −1.4% [40]. By substituting the aforementioned values in Eq. (3) the annual real interest rate is found to be 9.66%.

The salvage costs (*SC*), namely the residual values of the system components at the end of the project lifetime, are considered in the calculation of the *NPC*. The following formula is used:

$$SC = RC\frac{T_{rem}}{T_{com}} \tag{4}$$

where T_{rem} is the remaining life of the component (year), T_{com} is the lifetime of the component (year) and *RC* is the component replacement costs as it has been stated earlier.

The levelized cost of energy (*COE*) is the average cost per kWh of useful electrical energy produced by the system. The *COE* is calculated by dividing the annualized cost of producing electricity by the total useful electric energy production. The following Eq. is used to compute the *COE*:

$$COE = \frac{C_{tot}}{E_{tot}} \tag{5}$$

where E_{tot} is the total annual electricity consumption (kWh/year).

Fig. 5 presents the operation of the algorithm and how the optimal system is selected in terms of NPC value. For each entered scenario, all possible system configurations are calculated and simulated. For all system configurations that are feasible and satisfy the user's entered constraints, their NPC value is computed. After all possible and feasible combinations are investigated; the system with the lowest NPC value is the optimal one. The operating algorithm is not affected by the different scenarios.

2.3. Local acceptability of renewable energy

Local acceptability of renewable energy in Greece relies often on the social acceptance of a project. The authors in Ref. [41] presented a detailed and comprehensive study regarding the social and economic aspects of RES projects in remote communities in Greece. Unfortunately for the further development of RES projects in Greece, the authors discovered that in several cases, applications and licenses for RES projects had been submitted without informing the local communities, neglecting the existing industrial, agricultural or domestic activities and the land properties. These acts contributed in provoking the common sense and reverting the generally positive common attribute regarding RES, recorded in Greece before 2008.

In small community structures like islands, it has been widely observed that many RES projects had to be cancelled due to local opposition. The islands of Milos, where the high geothermal potential was exploited, and Skyros, where large scale RES plants were installed are two representative examples [42]. Historically, it has been realized that local population and authorities of islands are more eager to accept small-scale RES projects that meet the island's energy demand needs, but without impacting on the community's economic interests, tourism, environment and local properties compared to large scale RES projects. The main reasons for this insistent negativity are numerous: i) potential decline in tourism and economy, ii) the aesthetic impact on landscape, iii) possible distortion of naturally preserved areas, iv) oversized RES systems could contradict with the small-scale characteristics of islands, v) concerns regarding noise levels and local health, vi) conflicting interests by investors and political parties which shape public opinion, vii) suspicion towards private investors based on previous

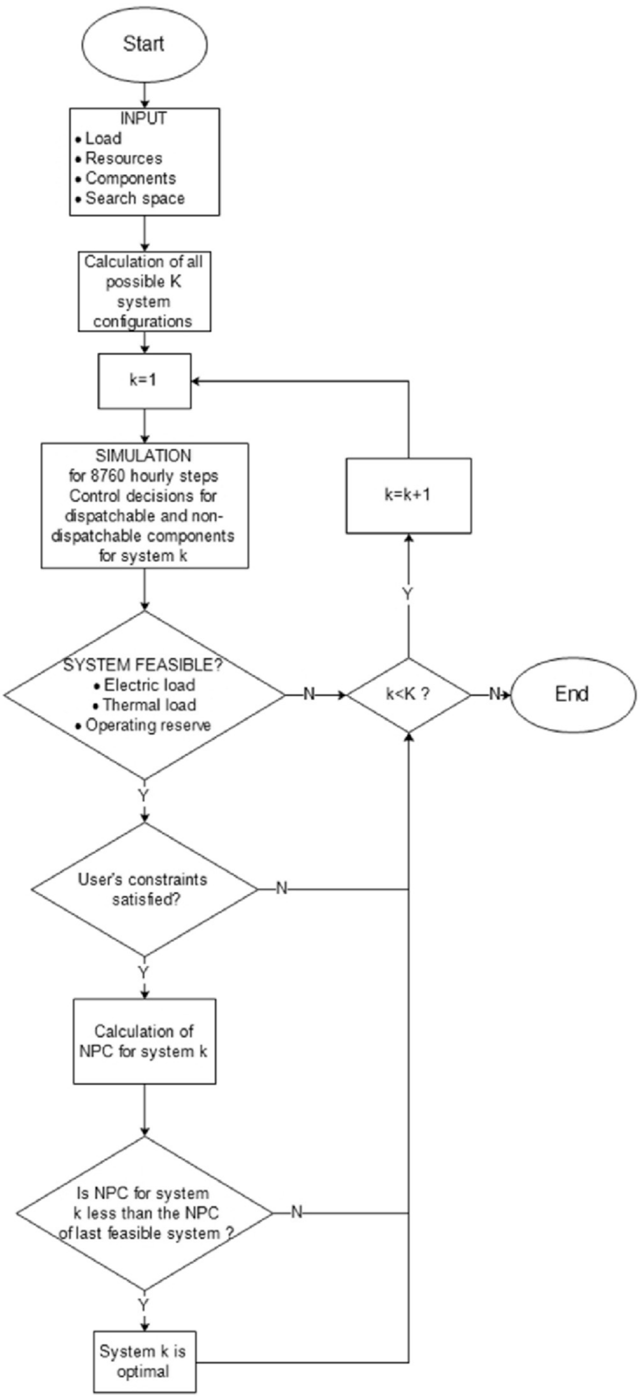

Fig. 5. Depiction of the operating algorithm.

bad experience and viii) lack of information on climate change, Greece's energy goals and the economic savings of a transition to renewable energy [43].

3. Renewable energy resource assessment

3.1. Solar irradiation

The hourly solar irradiation values are calculated using the Graham-Hollands algorithm [44]. This algorithm develops a stochastic procedure for generating synthetic sets of hourly solar irradiation values, suitable for use in solar simulation design work. This algorithm produces realistic hourly data, and requires only the latitude and the 12 monthly means ($\overline{K_t}$), as input. The annual irradiation data were obtained by the Greek Centre for Renewable Energy and Saving (CRES) but they were not sufficient for the whole yearly period studied. Monthly averages of radiation values were calculated from the daily averages to complement the sunshine data for which only monthly mean values were available. To calculate the missing values the Angstrom linear regression Eq. was used [45]:

$$\frac{Q}{Q_0} = a + b\frac{n}{N} \tag{6}$$

where Q is the monthly average daily radiation on horizontal surface (kW/m^2/day); Q_0 the monthly average daily extra-terrestrial radiation on a horizontal surface (kWh/m^2/day); N the maximum possible daily hours of bright sunshine and n is the monthly average daily number of hours of bright sunshine. Coefficients a and b are regression coefficients based on the co-ordinates of a location. In this study, the regression coefficients from the weather station of Mytiline Island (latitude 39°06′, longitude 26°33′) were used, an island very close to Agios Efstratios. The annual mean values for the regression coefficients are $a = 0.24$ and $b = 0.51$[46]. The monthly extraterrestrial radiation is computed using Eq. (7):

$$Q_0 = \frac{24 \times 3600}{\pi} G_{sc}\left[1 + 0.033\cos\left(\frac{360 n_d}{365}\right)\right] \times \left(\cos\phi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin\phi\sin\delta\right) \tag{7}$$

where n_d is the day number starting from January 1st as 1; $G_{SC} = 1367$ W/m^2, the solar constant; ϕ the latitude of the location (39° 27′); δ the declination angle (°) (see Eq. (8)) and ω_s is the Sunset hour angle (°) given by Eq. (9):

$$\delta = 23.45\sin\left(360\frac{248 + n_d}{365}\right) \tag{8}$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \tag{9}$$

The maximum duration of sunshine hours is given by:

$$N = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \tag{10}$$

The calculated solar radiation profile using the method described for a single year is shown in Fig. 6. The bars represent the daily average radiation for each month while the line depicts the clearness index.

The annual average radiation has been calculated to be 4.1 kWh/m^2/day. In order to validate the obtained results we compared the calculated irradiance data with the corresponding area data shown in Fig. 7 acquired from the U.S. National Solar Radiation Database (NSRD). The annual average radiation from the NSRD is 4.43 kWh/m^2/day, a result that confirms to a high percentage our calculations.

3.2. Assessment of wind potential

The wind speed data are very important in planning and developing a hybrid renewable energy system. In order to estimate the wind energy potential in Agios Efstratios Island, detailed information of the wind profile at the island's location is needed. Wind measurement data were provided from CRES but they did not form a complete year and the missing values had to be filled by

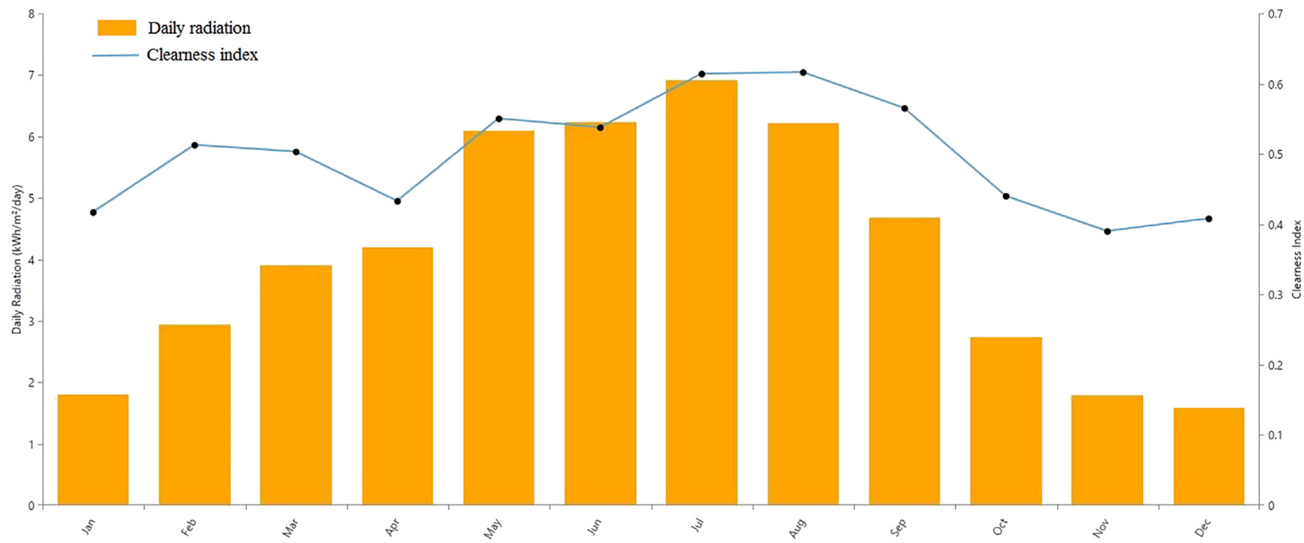

Fig. 6. Solar radiation profile for one year in Agios Efstratios.

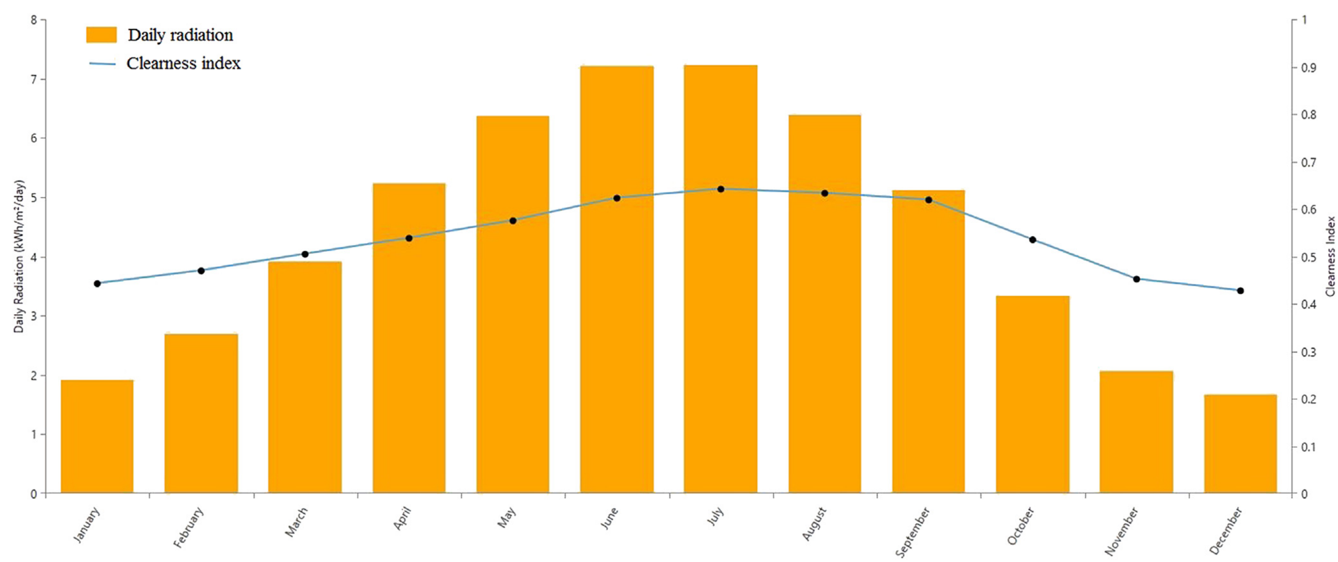

Fig. 7. Solar radiation profile for one year (NSR database).

similar previous days. Local seasonal winds affect the islands in Aegean Sea in a different way in terms of wind intensity and direction based mainly on geographical criteria. Agios Efstratios, located in the Northern Aegean Sea, records the highest average monthly wind speeds from October to February. In general, the most standard wind measurements are taken in 10 m height. Wind data had to be adjusted from the measurement height into a standard wind turbine hub height [47]. The wind power law is a frequently used tool to calculate this adjustment. The wind power law is expresses as below:

$$v(z)\ln\left(\frac{z_r}{z_0}\right) = v(z_r)\ln\left(\frac{z}{z_0}\right) \tag{11}$$

where z_r is the reference height (m); z the height for which wind speed is to be determined (m); z_0 is the surface roughness (0.1–0.25 for low and high crop land); $v(z)$ the wind speed at height of z m (m/s) and $v(z_r)$ is the wind speed at the reference height (m/s). In this study, the value of z_0 has been taken as 0.1.

The mean wind speed (V_m) and the standard deviation (σ) of the Agios Efstratios Island wind speed data were computed using the following commonly used statistics expressions where V_i represents the wind speed in time step i and N is the number of non-zero wind speed data points:

$$V_m = \frac{1}{N}\left(\sum_{i=1}^{N} V_i\right) \tag{12}$$

$$\sigma = \left(\frac{\sum_{i=1}^{N}(V_i - V_m)^2}{N-1}\right)^{1/2} \tag{13}$$

Fig. 8 shows the daily mean wind speed for Agios Efstratios island.

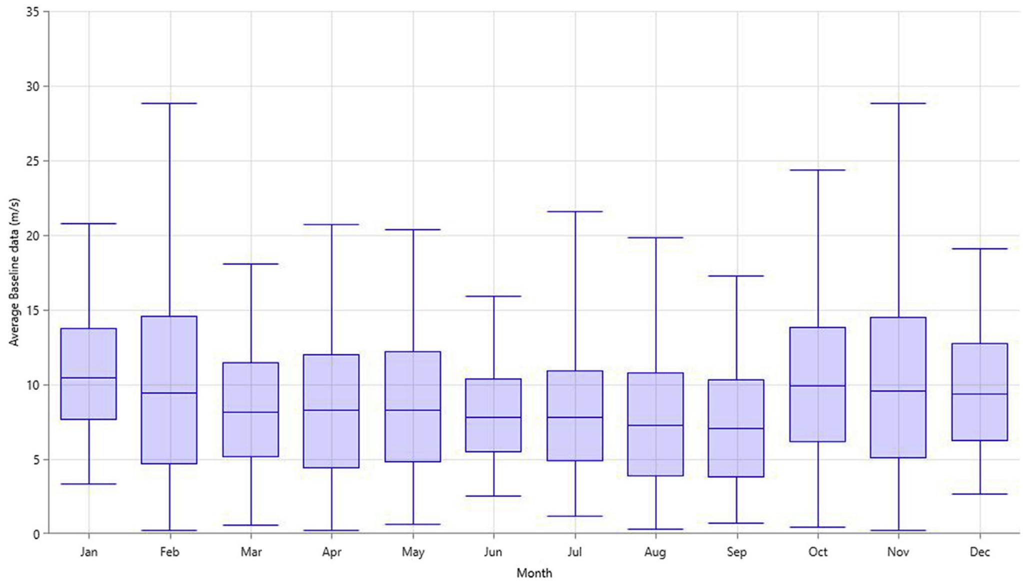

Fig. 8. Daily mean wind speed during a year in Agios Efstratios.

4. System description and components

Agios Efstratios, as well as the majority of Greek Aegean islands, are known to have abundant wind and solar potential. As islands tend to have small harbors and relatively low peak demand, shipping of only small scale equipment is considered. Thus the chosen wind turbines in the following simulations have been selected taking into consideration their size and their capability to be installed in small islands. Power quality is an essential element in energy systems, especially for autonomous grids as frequency stability and voltage control have to be kept in a certain range. Renewable energy systems, however, depend on passing clouds and wind speed variations, so energy storage can be used to eliminate intermittency problems [48].

The autonomous hybrid power system consists of five main components which includes diesel generator(s), PV modules, wind turbines, battery banks and power conversion units (converters) as shown in Fig. 9 below.

More specifically, the power conversion units include direct current DC/DC converters and alternating current rectifiers in order to connect the PV modules, the battery bank and the wind turbines to an intermediate DC bus which is then connected to the AC load and dump load through an inverter. The diesel generator(s) are also connected to the AC bus. The output power of the wind turbines and PV array can be directly used to satisfy the load demand or, in case the generated power is abundant, it is used to feed the battery bank until fully charged. In case that there is excess energy after the battery bank is charged, the surplus energy is channeled to the dump load. On the other hand, when the output power of the system is poor, the battery bank releases energy to assist the hybrid

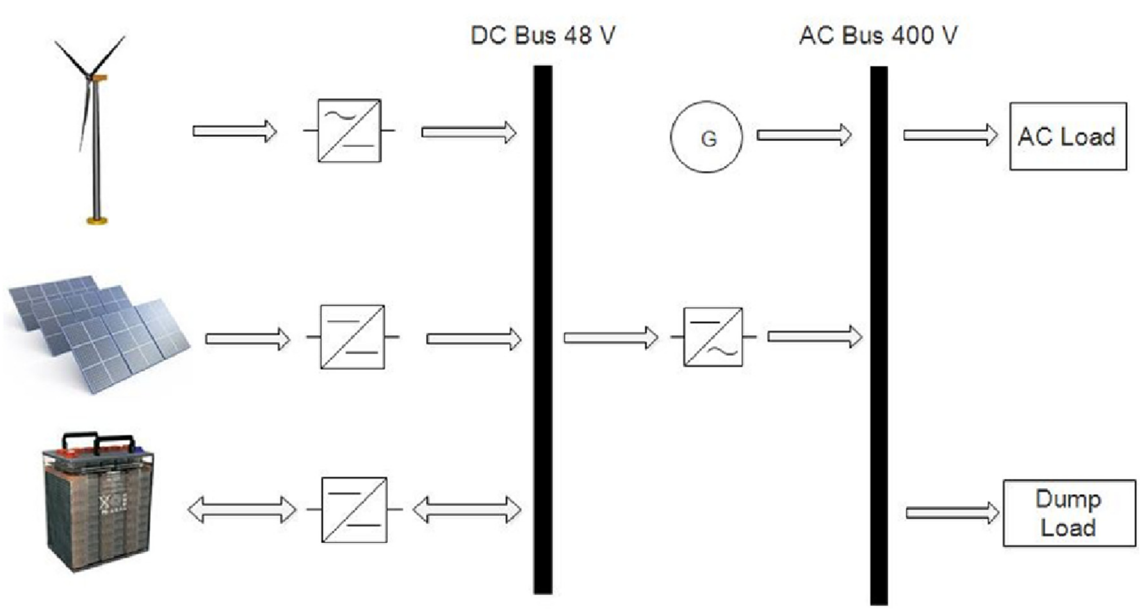

Fig. 9. A block diagram of the proposed hybrid energy system.

system meet the load demand until the battery bank is exhausted.

In addition, in order to ensure a safety margin that ensures reliable electricity supply despite the variability in the electric load and the intermittent nature of the renewable energy supply, an operating reserve has been considered according to Eq. (14):

$$\text{Operat. reserve} = (\%_L \times E_L) + (\%_{PV} \times E_{PV}) + (\%_{WT} \times E_{WT}) \quad (14)$$

where we have considered 10% of the hourly load, 25% of the solar power output the PV array output present less variability than the output of the wind turbines and 50% of the wind power output. The value of 10% of the primary load in each time step is added in the required operating reserve meaning that the system must keep enough spare capacity operating to serve a sudden 10% increase in the load. The value of 10% of the primary load is added in each time step in the required operating reserve meaning that the system must keep enough spare capacity operating to serve a sudden 10% increase in the load. Similarly, a value of 25% for the PV array output and 50% of the of the wind turbines power ensures that the system keeps enough spare capacity operating to serve the load in case of an unexpected decrease of 25% in PV power output and 50% in wind power output respectively. The reason that we have considered a smaller percentage value for the PV array output is that in most cases, the PV array output present less variability than the output of the wind turbines.

4.1. Photovoltaic system analysis

The PV array is modeled as a device that produces DC electricity in direct proportion to the global solar radiation. The power output of the PV modules when the effect of temperature is taken into account is given by the following formula [49,50]:

$$P_{pv} = W_{pv} f_{pv} \frac{G_T}{G_S} \left[1 + \kappa_p (T_C - T_{STC})\right] \quad (15)$$

where W_{pv} is the peak power output of the PV modules (kW), f_{pv} is the PV derating factor (%), G_T is the solar radiation incident on the PV module in a specific timeslot (kW/m^2), G_s is the incident radiation number under standard test conditions (1 kW/m^2), κ_p is the temperature coefficient of power (%/C), T_C is the PV module temperature in the current hour (°C), and T_{STC} is the PV module temperature under standard test conditions (25 °C). In this study, the effect of temperature on the PV array has been taken into account.

The derating factor f_{pv} is a scaling factor and it is an indication for any effects that might vary the under ideal conditions expected power of the PV module. Such effects include temperature, dust, wiring losses, shading, snow cover etc. The specifications for the chosen PV modules in this study are reported in Table 1.

Table 1
Details of the PV module.

Parameters	Value
Panel type	Flat plate
Operating temperature	47 °C
Temperature coefficient	−0.5 °C
STC efficiency	13%
Derating factor	80%
Capital cost	3000 €/kW [63]
Operating − maintenance cost	5 €-kW/year (for systems <1 MW)
Lifetime	20 years

4.2. Wind turbine analysis

Wind turbines operate by converting the kinetic energy of the wind into rotational kinetic energy in the turbine and finally into electrical energy. The main parameters affecting the converted energy are the wind velocity and the swept area of the turbine. The kinetic power content of the undisturbed upstream wind stream with velocity V and over a cross sectional area S is given by Ref. [51]:

$$W = \frac{1}{2} \rho S V^3 C_{p\max} \quad (16)$$

where W is the output power (W), ρ is the air density (kg/m^3), S is the swept area (m^2), V is the wind speed (m/s^2) and $C_{pmax} = 0.59$.

The special topology and the ground morphology of the island (rocky and mountainous) in combination with the not particularly high load demand of the island urged us to consider two substantially different capacities of wind turbines, simultaneously operating. To the existing knowledge of the authors, this is a relatively new approach which could lead to an optimal system using a combination of altered wind turbine capacities. Following this rationale, we chose on the one hand 95 kW wind turbines which can exploit the high wind potential of island substantially contributing in renewable energy and, on the other hand, 10 kW wind turbines which are smaller, more flexible regarding sitting and easier to install. The aim for these smaller capacity wind turbines is to operate in a complementary way with the higher capacity ones, contributing in load demand meet and in overall power system cost minimization. The specifications of the selected turbine models are shown in Table 2, with the power-speed characteristic curves of the proposed wind turbines in Fig. 10.

4.3. Battery analysis

Batteries can provide, among many advantages, a reliable power supply and good power quality, while reducing the fluctuations from wind and solar energy [52]. Storing electricity can be sold in a less expensive way in peak demand times and replacing fossil fuel generators with storage results in less fuel consumption, thus fewer emissions. Among the batteries storage options, Redox Flow Batteries (RFB) have gained increasing attention as promising candidates for stationary electricity storage applications [53]. Their most advantageous characteristics are the high life cycle (>12,000 [54]) and notable good round-trip efficiencies ($n_E \approx 80\%$[55]).

The battery bank is considered as a collection of one or more individual batteries. In this work, we considered the simulated battery system as a single battery which is modeled as a device able to store a specific amount of DC electricity at fixed round trip energy efficiency. In this study, a state of charge point for the batteries has been set (80%). Until this point is reached (by charging from renewable energy), batteries do not discharge. The charging and discharging capacities are calculated as following [49]:

For battery charging:

$$E(t) = E_b(t-1) \times (1-\sigma) + [E_{bh}(t) - E_{bl}(t)/\eta_{bi}) \times \eta_{bb}] \quad (17)$$

For battery discharging:

$$E_b(t) = E_b(t-1) \times (1-\sigma) - [E_{bh}(t)/\eta_{bi} - E_{bl}(t)] \quad (18)$$

where E_b is the battery energy in time interval; E_{bh} is the total energy generated by PV the array; E_{bl} is the load demand in time interval; η_{bi} is the inverter efficiency; η_{bb} is the battery charging efficiency and σ is the self-discharging factor.

The specifications of the selected battery for this study are presented in Table 3.

Table 2
Technical specifications and economic data of the selected wind turbines.

Parameters	Northern power	Aeolos
Model	120C-24	H
Rated power	95 kW	10 kW
Max power	–	13 kW
Generator voltage	400 VAC, 3 Phase, 50 Hz	300 VDC
Rated wind speed	12 m/s	10 m/s
Cut-in/out wind speed	3 m/s – 25 m/s	2.5 m/s – 45 m/s
Survival wind speed	52.5 m/s	50 m/s
Hub/tower height(s)	37 m/29 m/22 m	12 m, 18 m, 24 m, 30 m
Capital cost (per unit) [64]	200,000 €	22,500 €
Operating and maintenance cost per unit	1500€/year	400 €/year
Lifetime	20 years	20 years

The underline means that from all the available hub/tower heights for these wind turbines, in our simulation we selected the underlined values.

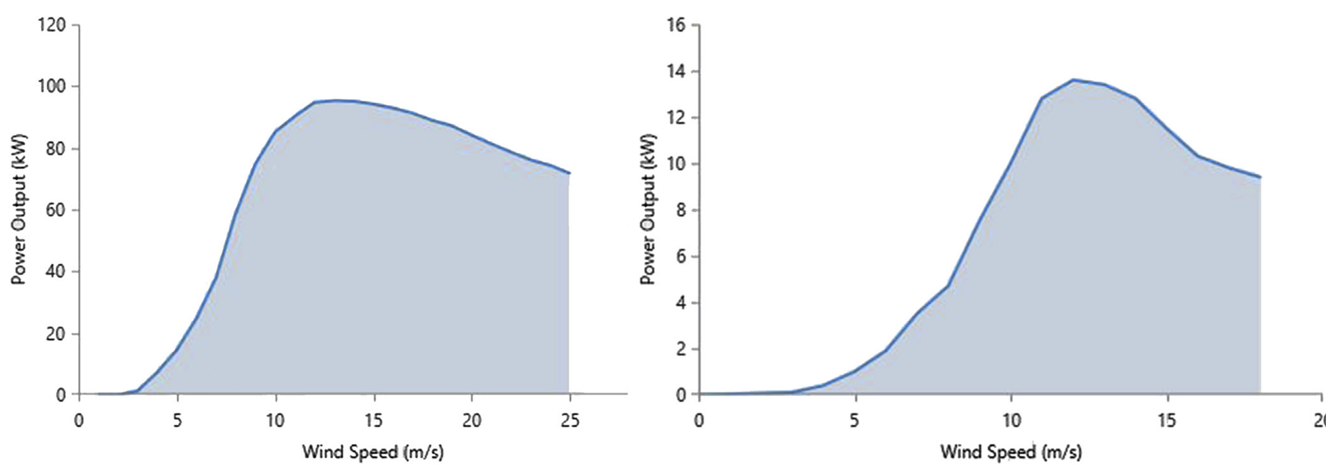

Fig. 10. The power-speed characteristic curve a) Northern Power, b) Aeolos H10.

In order to determine the search space for properly sizing the battery bank, we first perform a rough approximation based on the following methodology [56]: The total required capacity (in Ah) for the battery bank is calculated according to the following statement:

$$C_{tot\_cap} = \frac{n_{day} \cdot E_{day\_load}}{\eta_{bat} \cdot DD \cdot V_{bat}} \tag{19}$$

where n_{day} is the number of days for which we consider the battery storage bank can offer autonomy to the system; E_{day_load} is the average daily energy consumption ($\simeq 3,360$ kWh); η_{bat} is the overall battery and inverter efficiency; V_{bat} is the battery nominal voltage; and DD is the allowable depth of discharge for the batteries. For $n_{day} = 1$ day, $E_{day\_load} \simeq 3360$ kWh, $\eta_{bat} = 80\%$, $DD = 80\%$ and $V_{bat} = 48$ VDC, the total required capacity for the batteries to solely power the system is 109,375 Ah or ≈4550 Ah for an hour.

Afterwards the total number of batteries is calculated using Eq. (20):

$$n_{batteries} = \frac{C_{tot\_cap}}{C_{\sin gle}} \tag{20}$$

where C_{single} is the storage capacity for a single battery. Eq. (20) results in estimating ≈5 Cell Cube FB 20 kW/40 kWh or ≈3 Cell Cube FB 20kW/70 kWh for the system. The summation of the voltages provided by each string of batteries should be equal to the nominal system voltage of the DC bus (48V). The number of strings is calculated by:

$$n_{string} = \frac{n_{batteries}}{V_{DC\_bus}/V_B} \tag{21}$$

Since the nominal voltage of the proposed batteries is the same as the voltage of the DC Bus, only one battery per string is considered. Batteries are connected in parallel.

Table 3
Technical and economic data of the selected battery.

Parameters	Value
Manufacturer	CellCube
Model	FB 20kW/40-70 kWh
Nominal voltage	48 VDC
Nominal charge/discharge output	20 kW
Nominal capacity	40 kWh–833 Ah and 70 kWh – 1458 Ah
Round trip efficiency	up to 80%
Suggested life throughput	1,752,000 kWh
Max charge/discharge current	383 A and 599 A
Self-discharge in standby	<150 W
Capital cost	≈900 €/kWh
Operation and maintenance cost	≈50 €/battery/year

4.4. Power conversion

A power converter is necessary for the hybrid power system to control the energy flow between the DC and the AC components. When AC loads are served, then the converter works as inverter. The converter is assumed to have an efficiency of 95% [57]. The technical data of the converter selected for this study are presented in Table 4.

Table 4
Technical and economic data of the selected conversion unit.

Model	Parameters	Value
Leonics Apollo STP-219Cp	Rated power	15 kW
	Efficiency	>95%
DC side	Nominal voltage	48 VDC
	Max. charging current	200 A
	Max battery current	390 A
AC Source	Voltage	380/400/415 Vac (L-L), 220/230/240 Vac (L-N)
	Phase	Three phase
	Frequency	50/60 Hz
	Max. AC current	30 A
Economics	Capital cost	500€/kW
	Operating and maintenance cost	0 €/year
	Replacement cost	500 €/kW
	Lifetime	10 years

4.5. Diesel generator

The most important properties of a generator are its maximum electrical power output, its expected lifetime in operating hours, the type of fuel that it consumes along with the specific fuel consumption and the fuel curve that relates the quantity of fuel consumed to the electrical power produced. In this study, the fuel curve is assumed to be a straight line with a y-intercept and the generator's fuel consumption is calculated according to the following Eq. [38].:

$$F = F_0 Y_{gen} + F_1 P_{gen} \quad (22)$$

where F_0 is the fuel curve intercept coefficient, F_1 is the fuel curve slope, Y_{gen} the rated capacity of the generator (kW), and P_{gen} the electrical output of the generator (kW). For certain types of generators such as fuel cells and variable speed diesel engines, assuming the fuel curve represented by a linear function of power production may not be appropriate. But for the common, constant speed internal combustion generators, a straight-line in fuel curve's representation is a good fit [58,59].

In addition, we have set a minimum load ratio equal to 40% which prevents the generator(s) operating at very low load avoiding potential condensation in the exhaust system and increased maintenance cost. The technical data of the existing diesel generators operating in the islands are shown in Table 5. The capital cost is equal to zero because the units have been installed and have been already operating in the island.

5. Results and discussion

5.1. Definition of scenarios

As already stated, the aim of this work is to propose a renewable hybrid system to substitute the current conventional fossil fuel based operating system aiming at maximum RES penetration without causing stability problems to the system. A very important step towards this direction is the decrease of the diesel generators' operation and use. The total rated power of the 5 APS is 840 kW which is more than twice as large as the peak load (360 kW). Consequently, this can be considered as an oversized power system. In addition, peak loads appear only during a short period time (in summer). The rest of the year the average load demand is substantially smaller making the existing power system practically not useful.

To that end, we formulated several case scenarios for electrifying the island of Agios Efstratios. In the first scenario, it is only considered three out of the five APS to be operational. More specifically, we included the two 90 kW diesel generators and one 220 kW generator. In the second scenario, the operation of two further APS is dismissed and only the 220 kW diesel generator was kept operating. Finally, in the last scenario, we attempted to identify if the system can be feasible with all the APS out of operation. All the simulations were performed under both CC (cycle charging) and LF (load following) dispatch strategies and the optimal strategy was selected for each system. In load following dispatch strategy, the APS will only operate to meet the load demand. On the other hand, within the cycle charging strategy, the APS will operate in full capacity and the potential excess power will be used to charge the battery bank. The project lifetime for all the simulated scenarios has been set to 20 years.

5.2. Input parameters

All possible configurations based on the system design, specifications and input parameters are simulated in HOMER and then the optimal system configurations are decided. The search space for all the simulated scenarios is presented in Table 6.

5.3. Optimization results

The simulations have been performed using the input parameters described in the previous section. All possible system configurations that meet the load demand under the specified conditions of renewable resources for all the considered scenarios were simulated in HOMER. The number of the total simulations and

Table 5
Technical specifications and economic data of the APS units.

Parameters	Generator A (2 units)	Generator B (3 units)
Fuel	Diesel	Diesel
Rated power (kW)	90 kW	220 kW
Lifetime	15,000 h	15,000 h
Capital cost	0 €	0 €
Operating and maintenance cost	0.03 €/hour	0.03 €/hour
Specific fuel consumption (100% load)	0.2633	0.2428

Table 6
Search space for the considered scenarios.

Type	System components	Search space for scenario. 1	Search space for scenario. 2	Search space for scenario. 3
APS	Diesel gener. 90 kW	0 or 90 kW (2X)	0	0
	Diesel gener. 220 kW	0 or 220 kW	0 or 220 kW	0
PV	Flat plate collector	0–300 kW, 25 kW/step	0–350 kW, 25 kW/step	0–800 kW, 50 kW/step
Wind	NPS100C – 24	0–10 units, 1 unit/step	0–12 units, 1 unit/step	0–15 units, 1 unit/step
	Aeolos H	0–15 units, 1 unit/step	0–15 units, 1 unit/step	0–20 units, 1 unit/step
Battery	Cellcube FB 20-40	0–15 units, 1 unit/step	0–20 units, 1 unit/step	0–100 units, 5 units/step
	Cellcube FB 20-70	0	0	0–60 units, 4 units/step
Converter	Leonics	0–220 kW, 15 kW/step	0–300 kW, 15 kW/step	0–500 kW, 30 kW/step

Table 7
Optimal physical configuration systems for scenarios 1 and 2.

System components	Scenario. 1	Scenario. 2
1stAPS 90 kW (Gen 90)	90 kW	0
2ndAPS 90 kW (Gen 90 (1))	90 kW	0
APS 220 kW (Gen220)	220 kW	220 kW
Flat plate collector (PV)	0	25 kW
NPS100C – 24	3 units (285 kW)	4 units (380 kW)
Aeolos H (G10)	1 unit (10 kW)	0
Cellcube FB 20-40	3 units (120 kWh)	9 units (360 kWh)
Leonics BDI 3P	75 kW	135 kW
Dispatch strategy	CC	CC

running time varied and was between ≈500,000 and 1,500,000 runs and between ≈5 and 10 h depending on the scenario using a high speed computer, (i7, with 2.4 GHz speed, 8 GB ram).

5.3.1. *APS-hybrid energy systems*

As already stated, the aim of this work is to study the technical and economic feasibility of the electrification of the Agios Efstratios Island with the gradual reduction of the APS units' operation which would also lead to less emission and to a more environmental renewable energy approach. The configuration of the APS hybrid energy systems consisted of a combination of renewable energy sources working in parallel with the APS units. Table 7 shows the optimal (based on the total NPC) system physical configuration for the two APS – hybrid scenarios while Tables 8 and 9 present the technical and electrical characteristics of the optimal systems.

The system characteristics showed in Table 8 help us to derive a number of useful remarks regarding the first simulated scenario. Firstly, the hybrid power system including 3 APS units instead of the original 5 APS is technically feasible serving the electrification and satisfying the load demand in the island. The electricity though generated by the three APS units is lower than 15% of the total electricity production. As in most Greek islands, the high wind potential in Agios Efstratios is ideal for wind energy operation. It comes as no surprise to us that wind energy contributes to more than 80% of the total annual electricity production. The wind turbines operate almost during all time of the year. The high wind energy penetration explains the relatively high renewable energy fraction (68%) of the system as well as the high excess energy (37.1%). Excess electricity is not necessarily a sign of inadequate system design. On the contrary, it is quite often the case that it is more economical for the system to include components that produce more electricity than needed instead of investing on infrastructure for storing that excess electricity. Besides that, excess electricity can be reused in the form of heating and/or cooling load for households [60].

The substantially low hours of operation of two out of the three APS suggest that the system could cope with the electrification needs with an even lower APS installed capacity. More specifically, the 220 kW APS unit operates only 172 h/yr (mainly during August) to help meeting the (due to tourism) increased peak load. Driven by these remarks, it was decided to keep the higher capacity APS unit (220 kW) (which is the most economically detrimental for the system when not operating) to serve the base load and attempt to complement the rest of the demand by renewables. The technical and the electrical characteristics of the second simulated scenario are given in Table 9.

The rated installed capacity of the hybrid system has now been reduced to 625 kW compared to the 695 kW of the previous scenario. Most of the electricity production is still generated by wind energy. The addition of one more NPS100C – 24 wind turbines increased the electricity produced by wind energy around 7% compared to the previous system. In addition, the optimal configuration based on the total NPC for the second scenario includes now the installation of a small PV capacity. The higher installed capacity of renewable energy sources results in a higher renewable

Table 9
Technical and electrical characteristics of the optimal system based on the second scenario.

System components	Electricity production		Mean output (kW)	Hours of operation (hrs/yr)	Annual fuel consumption (L/yr)
	kWh/yr	%			
Gen220	219,356	9.05	163.33	1343	63,770
NPS100C – 24	2164.385	89.26	247.08	8585	0
PV	41,178	1.70	4.70	4386	0
Total	2,424,919	100		–	69,675

Table 8
Technical and electrical characteristics of the optimal system based on the first scenario.

System components	Electricity production		Mean output (kW)	Hours of operation (hrs/yr)	Annual fuel consumption (L/yr)
	kWh/yr	%			
Gen90	211,103	10.79	69.15	3053	61,102
Gen90 (1)	43,296	2.21	63.77	679	12,665
Gen220	34,745	1.78	202	172	9849
NPS100C - 24	1,623,289	82.94	185.31	8585	0
Aeolos H (G10)	44,663	2.28	5.10	8397	0
Total	1,957,096	100		–	87,907

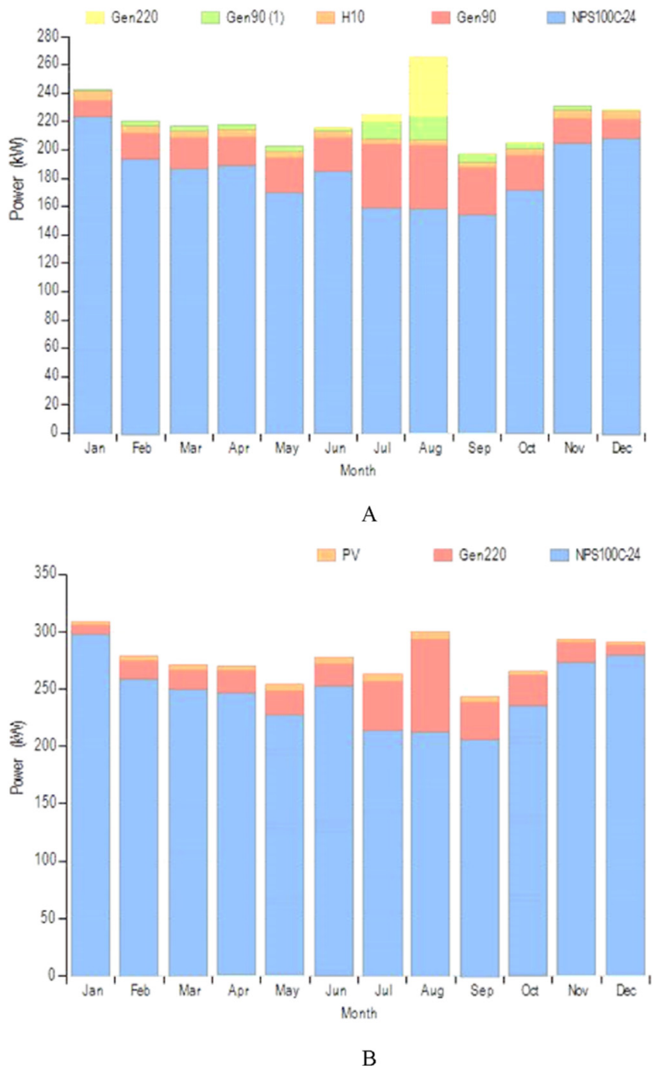

Fig. 11. Monthly average electric production for a) three APS–hybrid system, b) one APS–hybrid system.

energy fraction (74.3%) and higher excess electricity (48.1%) for this system, even if the battery bank capacity has been tripled (360 kWh instead of 120 kWh). The only considered APS in this simulation (the 220 kW unit) operates almost 800% more time during the year compared to the previous scenario but within significantly lower than the rated mean output power. Among the positives remarks is that the annual fuel consumption in the second scenario decreased around 20% resulting in equally less pollutant emissions (Table 9). The total annual fuel consumption is slightly different than the sum of the individual fuel consumption components because in the total value, the fuel consumption of the generic boiler has been counted in. As already explained in Section 2.1, the generic boiler is a backup source of heat that can serve any amount of (only) thermal load whenever necessary. Fig. 11 shows the monthly average electric production for the two APS-hybrid simulated scenarios.

The high reliance of both APS-hybrid systems on wind energy is highlighted in Fig. 12 where it can be seen that the wind turbines significantly contribute in covering energy demand by operating almost all year round.

The combustion process of the fuel which takes place during the operation of the APS is responsible for the production not only of CO_2 but also of other pollutants and greenhouse gases. Table 10 shows the most important emission pollutants produced by the APS operation.

The main economic aspects for the two simulated scenarios are presented in Table 11.

The results obtained have been calculated based on the current (November 2015) price of diesel in Greece (≈1€/L) for a total project duration of 20 years. We can see that the first system has a lower total NPC and a lower average cost per kWh of useful electrical energy produced by the system (L.C.O.E). Although the first system has higher replacement, operating and fuel cost, it is the most economical system mainly for two reasons. The first one is that the APS units are already installed in Agios Efstratios Island eliminating the initial capital cost for these units. The second one is the higher renewable energy capacity projected for the second system which raises substantially the capital cost. On the other hand, among the positive facts for the second system is the fewer total fossil fuel consumption and the closer to zero total salvage value.

Fig. 13 depicts the details of the NPC by cost type for each optimal APS-hybrid system. The different colors represent the distribution of each cost type as a function of the system's components (PV modules, wind turbines, APS, batteries and converters). In both systems, the purchasing cost of the wind turbines is the dominant capital cost. The storage system is known to substantially affect upwards the total NPC of the renewable hybrid systems. In both systems, battery storage is the second most expensive component but the relatively low required storage capacity in both scenarios does not cause extraordinary battery costs for the systems. The replacement costs in the first system are slightly higher than the second system because one of the two 90 kW APS units has to be replaced before the project's end period.

5.3.2. PV/wind/battery system

In the third simulated scenario, we removed all APS units from the calculations aiming at discovering whether a nearly 100% renewable system is feasible, not only from a technical point of

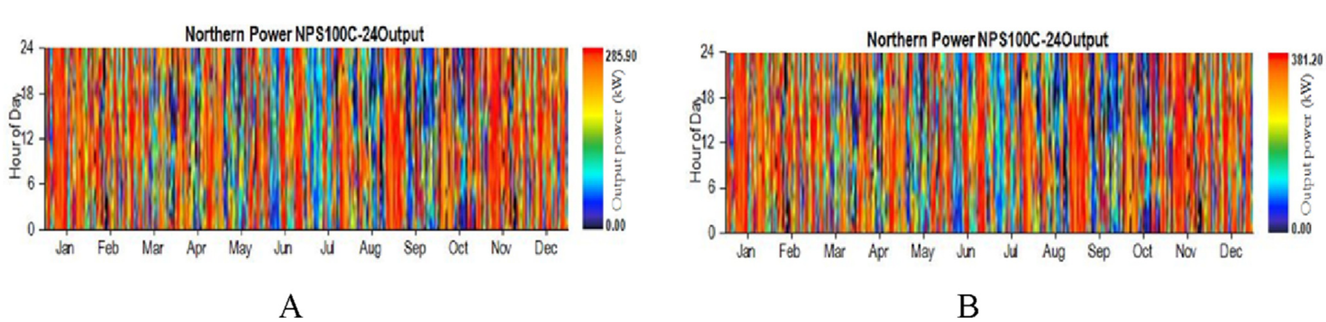

Fig. 12. The NPS100C-24 wind turbine monthly power output for a) three APS-hybrid system b) one APS-hybrid system.

Table 10
Annual emission gases by the two APS-hybrid systems (kg/yr).

Pollutant	Carbon dioxide	Carbon monoxide	Unburned hydrocarbons	Particulate matter	Sulfur dioxide	Nitrogen oxides	Total
Scenario 1	231,545	543.51	60.20	40.97	465.41	4849	237,504
Scenario 2	183,552	414.51	45.91	31.25	369.19	3698	188,111

Table 11
Economic characteristics of the two APS-hybrid simulated systems.

System	NPC (€)	L.C.O.E. (€/kWh)	Capital (€)	O&M (€)	Replacement (€)	Salvage (€)	Operating cost (€/yr)	Fuel (€)
Scenario 1	1,834,996	0.1658	767,500	239,475	80,860	−20,826	122,192	767,987
Scenario 2	2,249,666	0.2047	1,266,500	311,786	66,343	−3665	112,538	608,701

view but more important from an economic point of view.

The minimal amount of electricity demand that is continually created by customers is served by the base load power, the power that is always available by the power system to satisfy this demand. A number of common characteristics of power plants that operate to serve base load are the generation of electricity nearly constant power, a high capacity factor demand, output stability and reliable operation. In grid isolated systems like the one in Agios Efstratios, the APS units typically provide this sort of power. However, a standalone renewable energy system having nearly 100% renewable penetration could face a lack of capacity to supply electricity for the base load. The absence of a constant power to serve the base load in combination with the unreliable and intermittent nature of renewable energy has a huge effect on the configuration of the energy system. Table 12 shows the optimal physical configuration of the system based on NPC cost along with the most significant electrical and technical characteristics of the system. The increase in both renewable infrastructure capacity and battery storage equipment is enormous compared to the previous APS-hybrid studied systems which are clearly illustrated in Table 12. More specifically the required rated capacity of renewables grew to 1265 kW (wind and PV) and the necessary battery storage capacity increased to 2800 kWh indicating more than 700% increase compared to the previously discussed energy systems. The main reason for this substantial augmentation is that, most of the time, intermittent resources generate at less than their maximum potential capacity necessitating the need for higher installed capacities. In addition, the fact that wind speed and solar irradiation can be difficult to predict more than one or two days in advance with forecast errors of 20–50% not being uncommon [61], raises another problem for solely renewable dependent energy systems: the prediction of the exact time and quantity of power delivery. This problem combined with the fact that there is no source in the system to provide constant power resulted in the vast increase of battery storage.

Fig. 14 illustrates the monthly average production of the PV/energy/battery system while Fig. 15 shows the battery state of charge during the year. The system has a renewable fraction of 95% and an excess electricity of 73.5%. Fossil fuel is consumed only by the generic boiler to serve the thermal load. The high dependence of the PV/wind/battery system on the wind brings up to the surface the need of renewables integration with backup power and supplemental generation in order to smooth out fluctuations in generation capacity. In the case of Agios Efstratios, the currently installed APS units could provide this supplemental power but this is not always the case in renewable energy projects. For instance, Germany had to build a huge reserve margin (close almost to 50%) to back up its wind [62].

Technical difficulties are not the only barriers that a nearly 100% renewable system could face. Economic barriers especially in terms of infrastructure cost are equally important. The implementation of new renewable resources will necessitate high initial investments to build infrastructure. These investments surge the cost of providing renewable electricity, specifically during the first years. Table 13 presents the main economic aspects of the optimal PV/wind/battery system.

The total NPC cost of the system soared to nearly 6.5 million euros requiring a huge initial capital. Battery equipment is the most expensive component for the system confirming the fact that the size of the battery bank has a key impact on optimizing the power system, not only on the basis of life cycle cost but also on the cost of

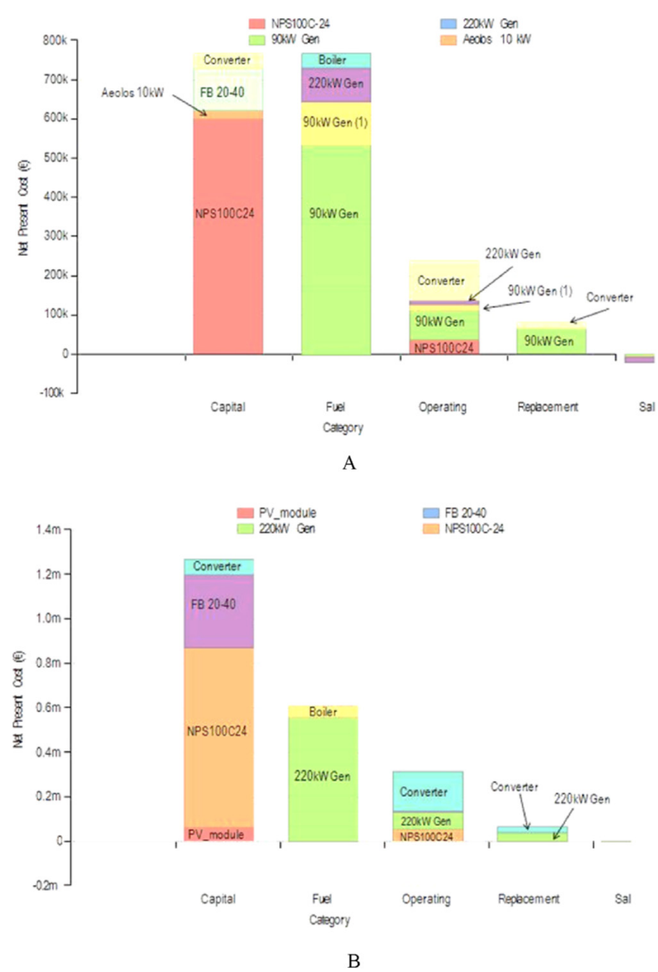

Fig. 13. NPC details as a function of the system's components for a) one APS-hybrid system b) three APS-hybrid system.

Table 12
Optimal physical configuration and technical/electrical characteristics of the optimal system based on the third scenario.

System components	Size	Electricity production		Mean output (kW)	Hours of operation (hrs/yr)
		kWh/yr	%		
NPS100C − 24	7 units (665 kW)	3,787,687	79.31	432.38	8585
PV	600 kW	988,280	20.69	112.82	4386
Total	1265 kW	4,775,967	100	–	–
Battery Cellcube 20–70	40 units (2800 kWh)	Energy in 120,601 kWh/yr	Energy out 77,242 kWh/yr	Annual throughput 96,552 kWh/hr	Autonomy 20.06 h
Converter Leonics BDI 3P	330 kW	Energy in 134,120 kWh/yr	Energy out 127,414 kWh/yr	Inverter 15.31 Rectifier 8.46	Inverter 1603 Rectifier 655

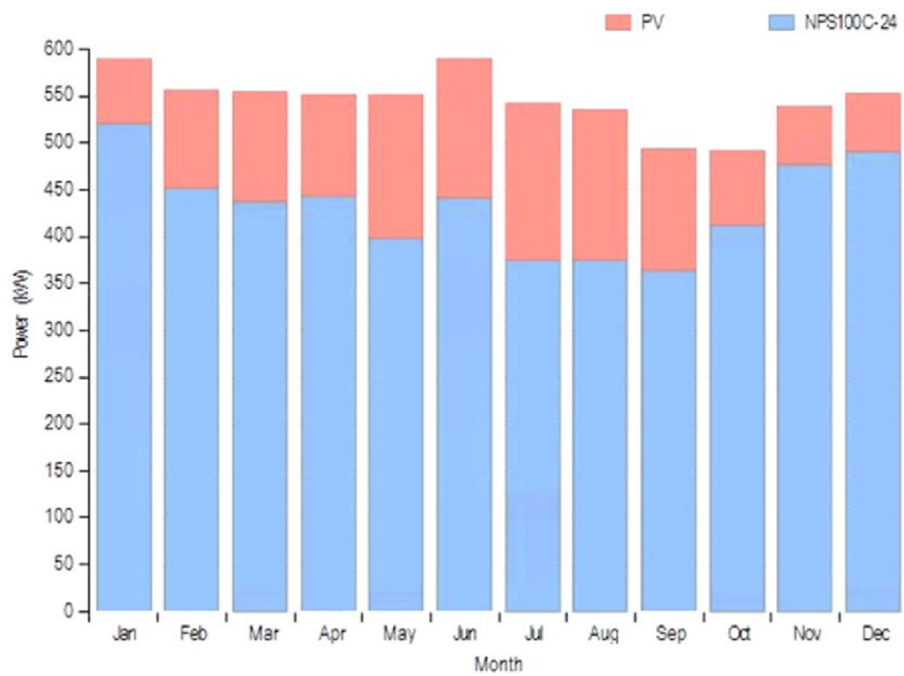

Fig. 14. Monthly average electric production for the PV/wind/battery system.

kWh of produced electricity during the system's lifetime. The levelized cost of energy in the PV/wind/battery system increased more than 300% compared to the previously discussed APS-hybrid systems reaching 0.61 €/kWh. On the other hand the operating costs per year for the PV/wind/battery system are much less compared to the APS-hybrid systems confirming the fact that although renewables generally require higher initial investments than fossil fuel plants, they require lower operating costs. Besides, standalone diesel generator systems have in general high operation and maintenance costs and are highly dependent on fossil fuel price. In addition, the required fossil fuel is substantially lower in comparison with the APS systems reducing overall system's greenhouse emissions.

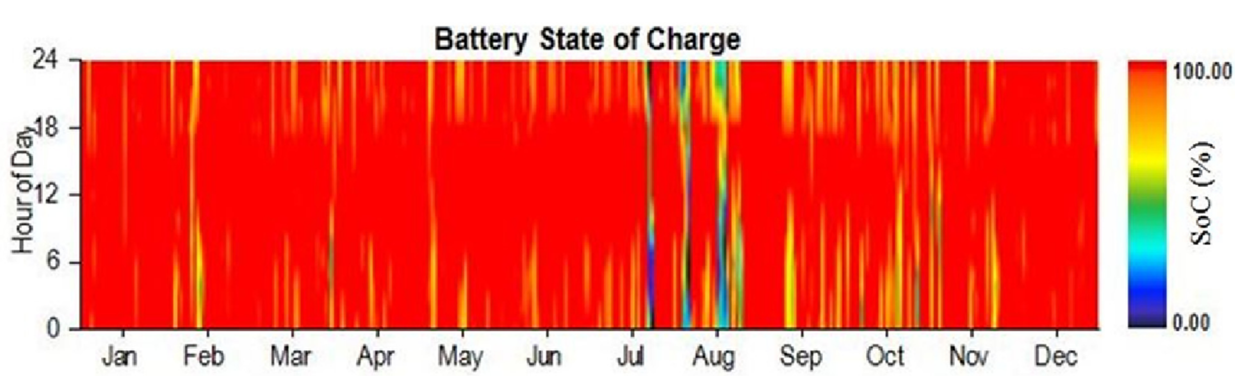

Fig. 15. State of charge of battery storage during a year for the PV/wind/battery system.

Table 13
Economic characteristics of the PV/wind/battery optimal system.

System	NPC (€)	L.C.O.E. (€/kWh)	Capital (€)	O&M (€)	Replacement (€)	Operating cost (€/yr)	Fuel (€)
PV	–	–	1,800,000	26,209	–	–	–
NPS100C-24	–	–	1,400,000	91,731	–	–	–
Boiler	–	–	–	–	–	–	63,867
Battery Cellcube	–	–	2,520,000	20,967	–	–	–
Converter Leon.		–	165,000	432,445	65,826	–	–
Total	6,586,044	0.6107	5,885,000	571,351	65,826	80,245	63,867

6. Conclusion

In this paper, we conducted a feasibility study for the electrification of Agios Efstratios Island, located in the northern Aegean Sea. An analysis of the methods used to assess the renewables resources potential of the island (wind and solar) explaining the approaches followed to complement the insufficient and missing weather data was performed. The load profile of the island is subject to seasonal variation throughout a year mainly because of the tourism industry during summer. As a result, the relatively low regular demand for energy of the island from September to May diverts to a high demand for energy during summer and huge peak loads especially during July and August. Solar irradiation varies also seasonally in the island. The average solar irradiation is highest during summer months which forces solar generators to produce the greatest amount of energy during the same time consumers' demand is highest. The fact that the maximization of solar energy production coincides with peak loads in the island gives photovoltaics a great value as a reliable source of power during extreme peak loads. The island's wind speed has a less seasonal profile. Wind potential is high during all the year making wind energy a favorable energy option.

It was attempted through this work to explore the possibility of utilizing a hybrid renewable energy system for Agios Efstratios Island which would be less dependent on fossil fuel power generation and, in the same time, would rely more on the existing renewable energy technologies. To this end, we performed several techno-economic analyses using the HOMER software for a projection period of 20 years by reducing gradually in each scenario the number of operating APS units in the island. The selection of optimum power generation systems was made on the basis of optimized NPC and LCOE concepts ensuring that systems can meet load demand at all time and that they are technically feasible.

Analysis revealed that the first economically optimal system (Scenario 1) consisted of a total 400 kW APS system (3 units), a 295 kW wind energy system, a 120 kWh storage system and a 75 kW power converter. This system had the lowest NPC and LCOE (1,834,996€ and 0.1658€/kWh, respectively) but also the highest greenhouse emissions footprint (231,545 kg/yr of CO_2). Analysis suggested the second economically optimal system (Scenario 2) consisted of a 220 kW APS unit, a 380 kW wind energy system, a 25 kW PV module, a 360 kWh of storage system and a 135 kW power converter with a NPC of 2,249,666€ and LCOE slightly higher at 0.2047€/kWh.

Simulation results showed that the island's existing diesel generators system could be fully replaced by a nearly 100% renewable energy system (Scenario 3). Although such a system could be technically feasible, it required an enormous capacity of solar and wind energy equipment to be installed as well as a huge battery storage system which surged the total NPC of the project (≈6.5 million €) and the LCOE (0.61 €/kWh). The consideration of PHES/CAES systems as additional energy storage options would possibly mitigate the massive required capacity of the battery storage system and thus constitute an excellent option for future implementation. In addition, such a high level of renewable penetration could result in technical difficulties for the system to maintain stable voltage and frequency in the grid. Finally, we discussed a number of other "not technical" barriers large-scale integration of renewables may face such as social and political issues as well as practical inertia of the traditional electricity generation system.

Acknowledgements

The authors would like to thank PPC S.A. for providing the load demand data for the autonomous power units and appreciate the provision of irradiance and wind speed data series from the CRES. The research was partially funded by EC under the FP7 RE-SIZED 621408 (Research Excellence for Solutions and Implementation of Net-Zero Energy City Districts) project.

References

[1] Vrettos EI, Papathanassiou SA. Operating policy and optimal sizing of a high penetration RES-BESS system for small isolated grids. IEEE Trans Energy Convers 2011;26(3):744–56.
[2] Papathanassiou SA, Boulaxis NG. Power limitations and energy yield evaluation for wind farms operating in island systems. Renew Energy 2006;31(4):457–79.
[3] Bernal-Agustín JL, Dufo-López R. Simulation and optimization of stand-alone hybrid renewable energy systems. Renew Sustain Energy Rev 2009;13(8):2111–8.
[4] Bagen, Billinton R. Evaluation of different operating strategies in small stand-alone power systems. IEEE Trans Energy Convers 2005;20(3):654–60.
[5] Khalilpour R, Vassallo A. Leaving the grid: an ambition or a real choice? Energy Policy 2015;82:207–21.
[6] Cavazzini G, Santolin A, Pavesi G, Ardizzon G. Accurate estimation model for small and micro hydropower plants costs in hybrid energy systems modelling. Energy 2016;103:746–57.
[7] Chauhan A, Saini RP. Techno-economic optimization based approach for energy management of a stand-alone integrated renewable energy system for remote areas of India. Energy 2016;94:138–56.
[8] Díaz G, Planas E, Andreu J, Kortabarria I. Joint cost of energy under an optimal economic policy of hybrid power systems subject to uncertainty. Energy 2015;88:837–48.
[9] Dekker J, Nthontho M, Chowdhury S, Chowdhury SP. Economic analysis of PV/diesel hybrid power systems in different climatic zones of South Africa. Int J Electr Power Energy Syst 2012;40(1):104–12.
[10] Shaahid SM, Elhadidy MA. Opportunities for utilization of stand-alone hybrid (photovoltaic + diesel + battery) power systems in hot climates. Renew Energy 2003;28(11):1741–53.
[11] Bajpai P, Dash V. Hybrid renewable energy systems for power generation in stand-alone applications: a review. Renew Sustain Energy Rev 2012;16(5):2926–39.
[12] Gonçalves FV, Costa LH, Ramos HM. Best economical hybrid energy solution: model development and case study of a WDS in Portugal. Energy Policy 2011;39(6):3361–9.
[13] Fathima AH, Palanisamy K. Optimization in microgrids with hybrid energy systems – a review. Renew Sustain Energy Rev 2015;45:431–46.
[14] Bin Shams M, Haji S, Salman A, Abdali H, Alsaffar A. Time series analysis of Bahrain's first hybrid renewable energy system. Energy 2016;103:1–15.
[15] Maleki A, Pourfayaz F, Rosen MA. A novel framework for optimal design of hybrid renewable energy-based autonomous energy systems: a case study for Namin, Iran. Energy 2016;98:168–80.
[16] Cozzolino R, Tribioli L, Bella G. Power management of a hybrid renewable system for artificial islands: a case study. Energy 2016;106:774–89.
[17] Zhou W, Lou C, Li Z, Lu L, Yang H. Current status of research on optimum

sizing of stand-alone hybrid solar–wind power generation systems. Appl Energy 2010;87(2):380–9.
[18] Radhakrishnan BM, Srinivasan D. A multi-agent based distributed energy management scheme for smart grid applications. Energy 2016;103:192–204.
[19] Wang C, Liu Y, Li X, Guo L, Qiao L, Lu H. Energy management system for stand-alone diesel-wind-biomass microgrid with energy storage system. Energy 2016;97:90–104.
[20] Rodrigues EMG, Godina R, Santos SF, Bizuayehu AW, Contreras J, Catalão JPS. Energy storage systems supporting increased penetration of renewables in islanded systems. Energy 2014;75:265–80.
[21] Rahman MM, Khan MM-U-H, Ullah MA, Zhang X, Kumar A. A hybrid renewable energy system for a North American off-grid community. Energy 2016;97:151–60.
[22] Koutroulis E, Kolokotsa D, Potirakis A, Kalaitzakis K. Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms. Sol Energy 2006;80(9):1072–88.
[23] Zhao B, Zhang X, Li P, Wang K, Xue M, Wang C. Optimal sizing, operating strategy and operational experience of a stand-alone microgrid on Dongfushan Island. Appl Energy 2014;113:1656–66.
[24] Katsaprakakis DA, Christakis DG, Zervos A, Papantonis D, Voutsinas S. Pumped storage systems introduction in isolated power production systems. Renew Energy 2008;33(3):467–90.
[25] Katsaprakakis DA, Christakis DG. Maximisation of RES penetration in Greek insular isolated power systems with the introduction of pumped storage systems. In: European wind energy conference and exhibition (EWEC); 2009.
[26] Ding H, Hu Z, Song Y. Stochastic optimization of the daily operation of wind farm and pumped-hydro-storage plant. Renew Energy 2012;48:571–8.
[27] Bayón L, Grau JM, Ruiz MM, Suárez PM. Mathematical modelling of the combined optimization of a pumped-storage hydro-plant and a wind park. Math Comput Model 2013;57(7–8):2024–8.
[28] Reuter WH, Fuss S, Szolgayová J, Obersteiner M. Investment in wind power and pumped storage in a real options model. Renew Sustain Energy Rev 2012;16(4):2242–8.
[29] Bueno C, Carta JA. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. Renew Sustain Energy Rev 2006;10(4):312–40.
[30] Dinglin L, Yingjie C, Kun Z, Ming Z. Economic evaluation of wind-powered pumped storage system. Syst Eng Procedia 2012;4:107–15.
[31] Wang SY, Yu JL. Optimal sizing of the CAES system in a power system with high wind power penetration. Int J Electr Power & Energy Syst 2012;37(1):117–25.
[32] Ibrahim H, Younès R, Basbous T, Ilinca A, Dimitrova M. Optimization of diesel engine performances for a hybrid wind–diesel system with compressed air energy storage. Energy 2011;36(5):3079–91.
[33] Bagdanavicius A, Jenkins N. Exergy and exergoeconomic analysis of a Compressed Air Energy Storage combined with a district energy system. Energy Convers Manag 2014;77:432–40.
[34] Safaei H, Keith DW. Compressed air energy storage with waste heat export: an Alberta case study. Energy Convers Manag 2014;78:114–24.
[35] Fazeli A, Khajepour A, Devaud C. A novel compression strategy for air hybrid engines. Appl Energy 2011;88(9):2955–66.
[36] Hafez O, Bhattacharya K. Optimal planning and design of a renewable energy based supply system for microgrids. Renew Energy 2012;45:7–15.
[37] Dalton GJ, Lockington DA, Baldock TE. Feasibility analysis of renewable energy supply options for a grid-connected large hotel. Renew Energy 2009;34(4):955–64.
[38] Lambert T, Gilman P, Lilienthal P. Micropower system modeling with Homer. In: Farret FA, Simões MG, editors. Integration of alternative sources of energy. Hoboken, NJ, USA: John Wiley & Sons, Inc; 2005. p. 379–418.
[39] European Central Bank, Harmonised long-term interest rates for convergence assessment purposes. Available: https://www.ecb.europa.eu/stats/money/long/html/index.en.html.
[40] Eurostat, HICP – inflation rate – Annual average rate of change (%). Available: http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=tec00118&plugin=1.
[41] Katsaprakakis DA, Christakis DG. "The exploitation of electricity production projects from renewable energy sources for the social and economic development of remote communities. The case of Greece: an example to avoid. Renew Sustain Energy Rev 2016;54:341–9.
[42] Kaldellis JK, Zafirakis D. Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency. Energy 2007;32(12):2295–305.
[43] Aegean Energy Agency. Strategic Energy Planning for energy conservation, promotion of RES and emissions' reduction in Aegean islands. 2009.
[44] Graham VA, Hollands K. A method to generate synthetic hourly solar radiation globally. Sol Energy 1990;44(6):333–41.
[45] Page JK. The estimation of monthly mean values of daily short wave irradiation on vertical and inclined surfaces from sunshine records for latitudes 60° N to 40° S. Department of Building Science, Faculty of Architectural Studies, University of Sheffield; 1976.
[46] Zabara K. Estimation of the global solar radiation in Greece. Sol Wind Technol 1986;3(4):267–72.
[47] Manwell JF, McGowan JG, Rogers AL. Wind energy explained: theory, design and application. second ed. Chichester, U.K: Wiley; 2009.
[48] Tzamalis G, Zoulias EI, Stamatakis E, Varkaraki E, Lois E, Zannikos F. Techno-economic analysis of an autonomous power system integrating hydrogen technology as energy storage medium. Renew Energy 2011;36(1):118–24.
[49] Haidar AM, John PN, Shawal M. Optimal configuration assessment of renewable energy in Malaysia. Renew Energy 2011;36(2):881–8.
[50] Li C, Ge X, Zheng Y, Xu C, Ren Y, Song C, et al. Techno-economic feasibility study of autonomous hybrid wind/PV/battery power system for a household in Urumqi, China. Energy 2013;55:263–72.
[51] Ragheb M, Ragheb AM. Wind turbines theory - the Betz equation and optimal rotor tip speed ratio. In: Carriveau R, editor. Fundamental and advanced topics in wind power. InTech; 2011.
[52] Poonpun P, Jewell WT. Analysis of the Cost per Kilowatt Hour to Store Electricity. IEEE Trans Energy Convers 2008;23(2):529–34.
[53] Austing J, Nunes Kirchner C, Komsiyska L, Wittstock G. Investigation of crossover processes in a unitized bidirectional vanadium/air redox flow battery. J Power Sources 2016;306:692–701.
[54] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: a critical review. Prog Nat Sci 2009;19(3):291–312.
[55] Leung P, Li X, Ponce de León C, Berlouis L, Low CTJ, Walsh FC. Progress in redox flow batteries, remaining challenges and their applications in energy storage. RSC Adv 2012;2(27):10125.
[56] Ma T, Yang H, Lu L. A feasibility study of a stand-alone hybrid solar–wind–battery system for a remote island. Appl Energy 2014;121:149–58.
[57] Lau KY, Yousof M, Arshad S, Anwari M, Yatim A. Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions. Energy 2010;35(8):3245–55.
[58] Katiraei F, Abbey C. Diesel plant sizing and performance analysis of a remote wind-diesel microgrid. In: IEEE power engineering society general meeting; 2007. p. 1–8.
[59] Rohani G, Nour M. Techno-economical analysis of stand-alone hybrid renewable power system for Ras Musherib in United Arab Emirates. Energy 2014;64:828–41.
[60] Beccali M, Brunone S, Cellura M, Franzitta V. Energy, economic and environmental analysis on RET-hydrogen systems in residential buildings. Renew Energy 2008;33(3):366–82.
[61] Piwko R, Osborn D, Gramlich R, Jordan G, Hawkins D, Porter K. Wind energy delivery issues [transmission planning and competitive electricity market operation. IEEE Power Energy Mag 2005;3(6):47–56.
[62] Sovacool BK. The intermittency of wind, solar, and renewable electricity generators: technical barrier or rhetorical excuse? Util Policy 2009;17(3–4):288–96.
[63] Feldman D, Barbose G, Margolis R, Bolinger M, Chung D, Fu R, et al. Photovoltaic system pricing trends: historical, recent, and near-term projections. 2015. Edition. Available: https://emp.lbl.gov/sites/all/files/pv_system_pricing_trends_presentation.pdf.
[64] Wiser R, Bolinger M. Wind technologies market report. 2014. Available: http://energy.gov/sites/prod/files/2015/08/f25/2014-Wind-Technologies-Market-Report-8.7.pdf.