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Integrated electrification solution for autonomous electrical networks on the basis of RES and energy storage configurations

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ABSTRACT

Most medium and small islands of the Aegean Archipelagos face serious infrastructure problems, strongly related with the limited electrical energy available at extremely high cost. On the other hand, the area is characterized by very high wind speeds and abundant solar energy, thus the exploitation of the available renewable energy sources (RES) may significantly contribute to the fulfillment of the local societies energy demand at minimum environmental and macroeconomic cost. However, the stochastic availability of wind energy and the variable availability of solar energy, the daily and seasonal electricity demand fluctuations, as well as the limited local electrical network capacity result in serious restrictions concerning the maximum renewable power penetration. In this context, the present paper investigates the possibility of creating a combined electricity generation facility based on the exploitation of wind or/and solar potential of an area as well as on the utilization of an appropriate energy storage configuration in order to replace the existing thermal power stations with rational investment requirements. For this purpose, the major parameters of the proposed integrated configuration are firstly calculated and its financial viability is accordingly analyzed. One of the main targets of the proposed solution is to maximize the RES exploitation of the area at a minimum electricity generation cost, while special emphasis is given in order to select the most cost-efficient energy storage device available. According to the results obtained the proposed solution is not only financially attractive but also improves the quality of the electricity offered to the local communities, substituting the expensive and heavily polluting existing thermal power stations.

1. Introduction

The Aegean Archipelagos is a remote Hellenic area at the east of mainland, including several hundreds of scattered islands of various sizes, Fig. 1. For administrative purposes these islands are divided in five groups, i.e. the islands belonging to Lesvos, Chios, Samos, Cyclades and Dodecanese prefectures. One of the major problems of the area is the insufficient infrastructure, which is strongly related to the limited electrical energy available and the extremely high electricity generation cost of most islands, see for example Fig. 2. In fact, the electricity demand in the Aegean Archipelagos islands has up to now been covered [1] by the existing (30) autonomous power stations (APS), based on internal combustion engines and gas turbines, which belong to the former Greek Public Power Corporation (PPC). The existing APS total installed capacity is approximately equal to 800 MW, while the corresponding electricity generation during 2005 is almost 2200 GWh [2]. Unfortunately there is a significant variation (Fig. 3) of the electricity consumption throughout the year since in most islands the electricity demand during summer season (June–August) represents more than 40% of the total annual consumption, while the corresponding peak load demand is usually two or even three times greater than the mean annual electricity demand [3]. On the other side, the electricity production cost varies between 0.12€/kWh for the big islands and 0.6€/kWh for the small remote Greek islands (Fig. 2), presenting a mean annual increase rate of 5%, during the last 15 years. Note that the corresponding electricity price for domestic users in all Greece is slightly above 80€/MWh, hence the operation of the Aegean Archipelago APS leads to severe financial loss, for the Greek PPC, approaching the 200,000,000€/year. Finally, in almost all these islands there is an extremely urgent need for additional power on annual basis, since the existing APS can hardly meet the corresponding peak load demand [3]. On top of this, the vast majority of the existing thermal power units is very old and should be replaced in the next few years.

At this point it is worthwhile mentioning that the area is characterized by very high wind speeds and abundant solar energy, Fig. 4. Thus the exploitation of the available renewable energy sources (RES) potential may significantly contribute to the fulfillment of the local societies energy demand at minimum environmental

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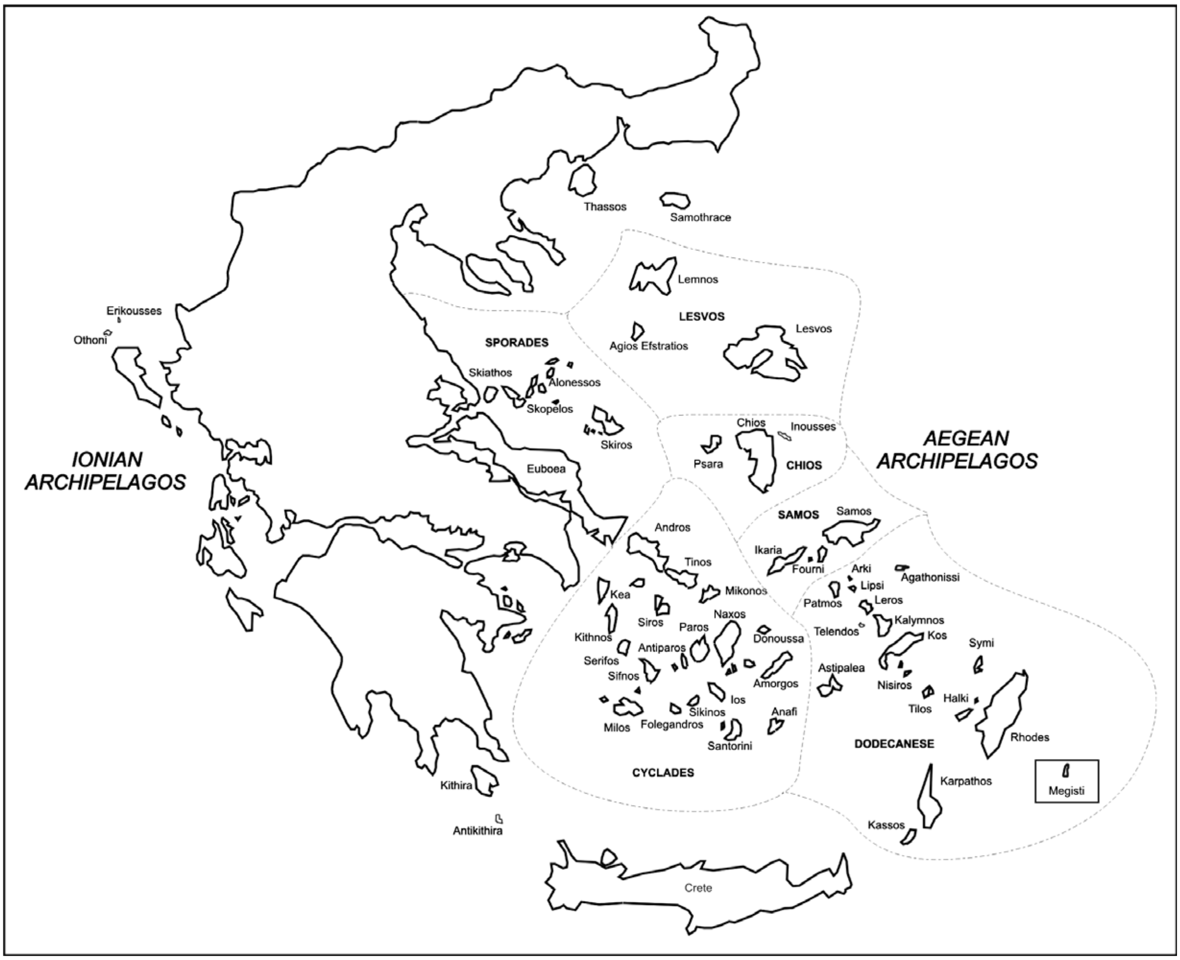

Fig. 1. Aegean Archipelagos complex of islands.

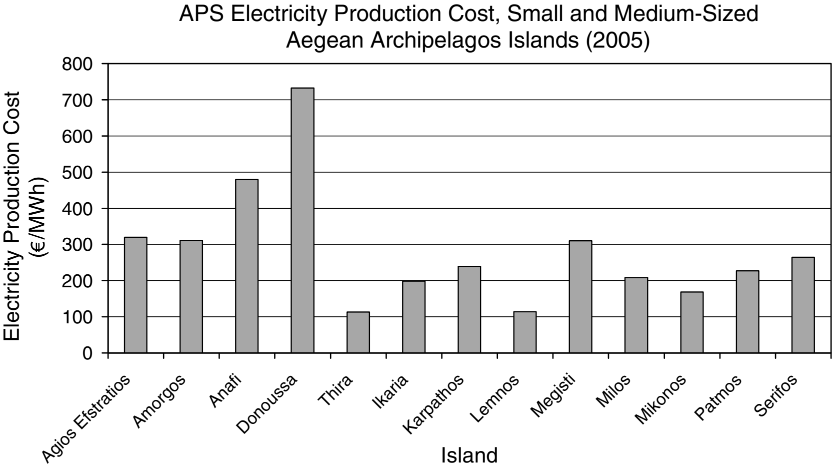

Fig. 2. Electricity production cost of selected Greek APS (PPC, 2005).

and macroeconomic cost [4]. However, the stochastic availability of wind energy and the variable availability of solar energy, the daily and seasonal electricity demand fluctuations, as well as the limited local electrical network capacity result in serious restrictions concerning the maximum renewable power penetration, in order to maintain the local grid stability [5]. For example, until recently, the local electricity utility (PPC) posed a 30% wind power penetration barrier to guarantee the local grid stability. However, even this strict limit has theoretical value, since economic viability criteria [6] deteriorate the maximum wind energy contribution to single digit numbers (i.e. $\leqslant 10\%$).

According to previous research [7–10] the prospect of creating a combined RES based energy production station with an appropriate energy storage system (ESS) is the only available – for those

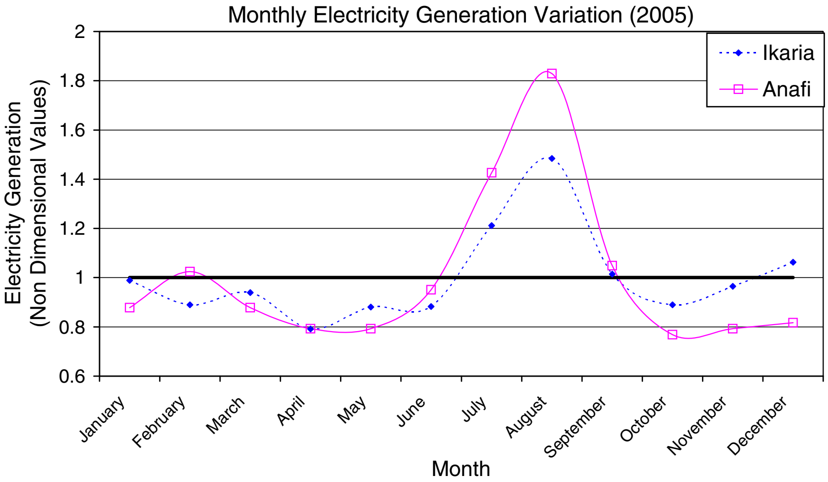

Fig. 3. Electricity generation annual variation for typical island cases.

regions – solution, provided that the central target is to maximize the renewable energy sources penetration in small and medium-sized islands, under the precondition of rational electricity production cost. Although the first installation cost of a combined RES–ESS power station is relatively higher than the corresponding cost of an equivalent thermal power station, the excellent RES potential and the extremely high production cost of local APS provide the proposed solution with an undoubted competition advantage even in terms of economic efficiency. On top of this, an energy storage system, when sized appropriately [11,12], not only can match a highly variable RES based energy production to a generally variable and hardly predictable system demand, but also improves the system reliability and contributes to the energy production cost reduction. Additionally, by reducing the operation hours of the existing thermal power units their service life is prolonged, therefore the need for extra investments concerning the installation of new internal combustion engines is postponed.

In this context, the present paper investigates the possibility of creating a combined electricity generation facility that is based on the exploitation of wind or/and solar potential of an area as well as on the utilization of an appropriate energy storage configuration in order to replace the existing thermal power stations with rational investment requirements. More precisely, one should first calculate the major parameters of the proposed integrated solution and accordingly analyze the financial viability of the resulting solution. As already mentioned one of the main targets of the proposed solution is to maximize the RES exploitation of the area at a minimum electricity generation cost, while special emphasis is given to improve the local network reliability. Besides, the most cost-efficient energy storage configuration is selected [12] on the basis of the developed minimum cost methodology, after analyzing various available ESS. Finally, the complete methodology is applied to representative island (autonomous electrical network) cases with very enlightening results.

2. Proposed solution

The proposed by the authors [7,9] integrated solution comprises a RES-based power station (usually a wind park or a photovoltaic generator) able to meet the electricity demand as well as an appropriate energy storage facility that guarantees the local community energy autonomy for a desired time period. Besides, the existing thermal power station may be also used either as a back up solution or to cover unexpected high load demand. More precisely the proposed configuration (Fig. 5) includes:

(a) One or more power stations based on the exploitation of the available wind or solar potential. The most attractive solutions are either wind parks for medium and large-sized islands or photovoltaic generators for small or very small islands. The rated power of the proposed installation is “N_{RES}”.
(b) A number of energy storage devices (e.g. lead-acid or Na–S batteries, a group of water reservoirs, etc.) combined with their corresponding energy production equipment (e.g. inverters, small hydro-turbines, etc.). The energy storage capacity of the installation is equal to “E_{ss}” and the input and output rated power values are “N_{in}” and “N_{ss}”, respectively. The selected ESS should be able to cover the local network electricity requirements for “d_o” typical hours without the contribution of any other electricity generation device.
(c) The existing thermal power units of the already operating APS, with rated power equal to “N_o”, may contribute on meeting the local system electricity consumption under specific circumstances by “δE”. The main target of the proposed solution is to minimize the contribution of the local APS to the local system electricity consumption ($\delta E \to 0$), as well as to use by priority the most cost-effective thermal power units.

During the long-term operation of the proposed system several operational situations may appear, i.e.:

(i) If the energy production of the RES-based power stations is greater than the local community consumption, the energy surplus is stored at the existing ESS. In case that the ESS is full, the excess energy is forwarded to low priority loads.
(ii) If the RES-based production is lower than the corresponding electricity demand and the ESS is not empty, the electricity deficit is covered via the ESS.
(iii) If the RES-based production is lower than the electricity demand and the ESS is practically empty, the electricity deficit is covered by the existing thermal power units, using diesel or heavy oil.
(iv) Finally, for practical reasons, the utilization of all available power units may be required in order to face unexpected energy production/demand problems or situations related to “Force Majeure” events.

In the following sections one should initially define the major dimensions of the proposed integrated electricity production

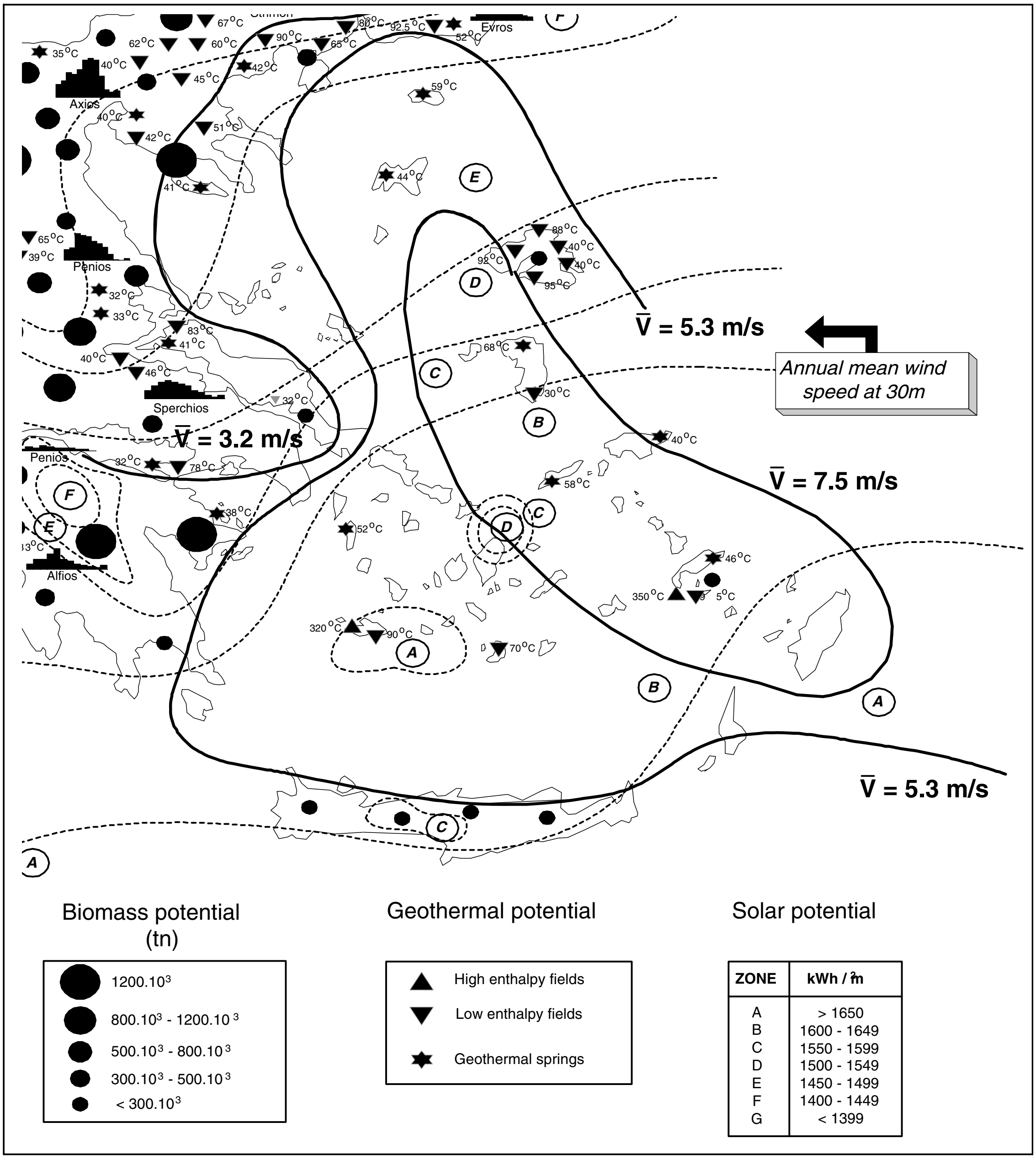

Fig. 4. RES potential in the Aegean Archipelagos region.

system and accordingly evaluate the financial behavior of the entire solution in comparison with the up to now existing systems based almost exclusively on a number of internal combustion engines.

3. Sizing a RES–ESS based system

The present analysis concerns an autonomous (island) electrical network with annual energy consumption equal to "E_{tot}", while the corresponding peak load demand is "N_{p}". The main target of the proposed solution is to meet the local demand using electrical power stations mainly based on renewable energy sources (RES) and appropriate energy storage systems (ESS), with rational production cost. Up to now the electrification solution [1] was based on the existing outmoded thermal power stations, which operate using diesel or heavy (mazut) oil with mean electricity production cost equal to "c^{*}" (Fig. 2) and provoking serious environmental and macroeconomic impacts [3,4]. For increased reliability purposes the most efficient thermal power units may be used as back up engines with annual energy contribution equal to "δE", where "$\delta E \ll E_{\mathrm{tot}}$".

In this context, one may assume that the total energy demand is covered either directly by the existing power stations "E_{dir}" (mainly wind parks, photovoltaic generators and complementary by thermal power stations) or via the energy storage system "E_{stor}". In order to describe the contribution of the storage system to the total energy consumption we define the parameter "ε" as:

$$\varepsilon = \frac{E_{\mathrm{stor}}}{E_{\mathrm{tot}}} = 1 - \frac{E_{\mathrm{dir}}}{E_{\mathrm{tot}}} \tag{1}$$

since:

$$E_{\mathrm{tot}} = E_{\mathrm{dir}} + E_{\mathrm{stor}} \tag{2}$$

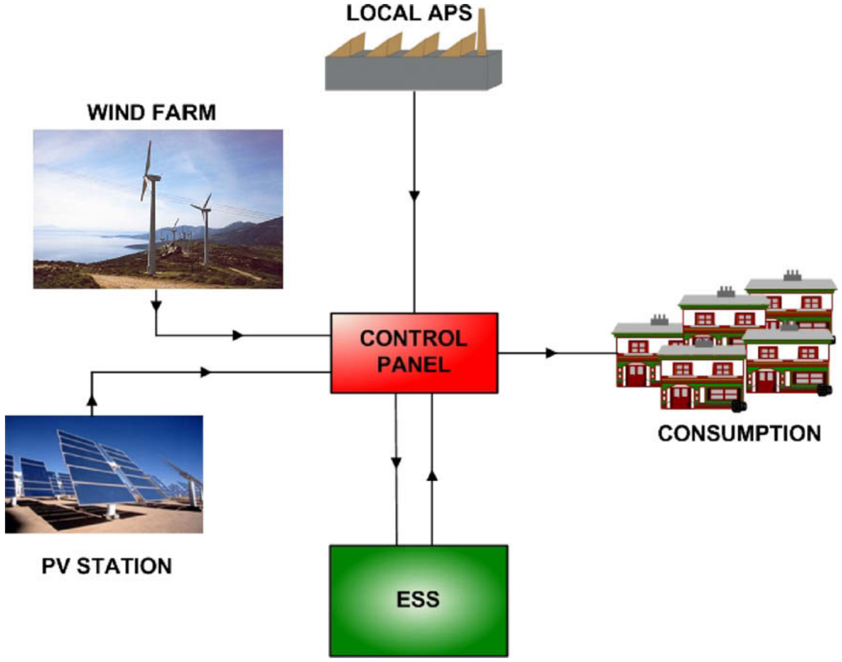

Fig. 5. Proposed electricity generation configuration for autonomous electrical grids.

As it is obvious, theoretically "ε" takes values between zero (no storage system usage) and one (all the energy consumption is covered through the storage system), i.e. $0 \leqslant \varepsilon \leqslant 1.0$. In practice, between these two extreme values, a contribution range determined by the existing power units' principle features (including photovoltaics and wind turbines) in relation with the corresponding load demand time-variation dictates the potential use of the ESS (i.e. the exact "ε" value) on an annual basis.

Taking into consideration that the RES based power stations should cover the major part of "E_{dir}" and provide also the necessary energy to the ESS (total energy efficiency η_{ss}), the corresponding annual energy production "E_{RES}" is estimated as:

$$E_{\mathrm{RES}} = (E_{\mathrm{dir}} - \delta E) + \frac{E_{\mathrm{stor}}}{\eta_{\mathrm{ss}}} = (1-\varepsilon)\cdot E_{\mathrm{tot}} - \delta E + \frac{\varepsilon \cdot E_{\mathrm{tot}}}{\eta_{\mathrm{ss}}} \tag{3}$$

Defining the capacity factor of the local electrical network "$\mathrm{CF_p}$" and the RES-based power stations "$\mathrm{CF_{RES}}$" using Eqs. (4) and (5), i.e.:

$$\mathrm{CF}_p = \frac{E_{\mathrm{tot}}}{8760 \cdot N_{\mathrm{p}}} \tag{4}$$

and

$$\mathrm{CF_{RES}} = \frac{E_{\mathrm{RES}}}{8760 \cdot N_{\mathrm{RES}}} \tag{5}$$

one may calculate the necessary nominal power of the proposed RES-based power stations as:

$$\begin{gathered} N_{\mathrm{RES}} = \max\left\{(1+\mathrm{SF})\cdot N_{\mathrm{p}}; \frac{E_{\mathrm{RES}}}{8760 \cdot \mathrm{CF_{RES}}}\right\} \Rightarrow \\ N_{\mathrm{RES}} = N_{\mathrm{p}} \cdot \max\left\{(1+\mathrm{SF}); \frac{\mathrm{CF_p}}{\mathrm{CF_{RES}}} \cdot \left[(1-\varepsilon) - \frac{\delta E}{E_{\mathrm{tot}}} + \frac{\varepsilon}{\eta_{\mathrm{ss}}}\right]\right\} \end{gathered} \tag{6}$$

where "$\mathrm{SF} \geqslant 0$" is an appropriate safety factor in order to guarantee that the RES-based power station can meet the local consumption peak load demand. In order to ensure the system reliability one should take into account that at the same time one may use either the ESS power units (inverters, hydro-turbines etc.) or the existing (back up) thermal power units.

Subsequently, the ESS – to be utilized in order not only to increase the RES penetration in the local electrical market but also to improve the reliability of the local system and the quality of the electrical energy provided to the consumption – is characterized by the energy storage capacity "E_{ss}" and the nominal input "N_{in}" and output power "N_{ss}" of the entire energy storage subsystem. More precisely, the energy storage capacity of ESS may be estimated by the following relation:

$$E_{\mathrm{ss}} = d_{\mathrm{o}}\left(\frac{\varepsilon \cdot E_{\mathrm{tot}}}{8760}\right)\frac{1}{\eta_{\mathrm{ss}}}\cdot\frac{1}{\mathrm{DOD_L}} = \varepsilon\cdot(d_{\mathrm{o}}\cdot E_{\mathrm{h}})\frac{1}{\eta_{\mathrm{ss}}}\cdot\frac{1}{\mathrm{DOD_L}} \tag{7}$$

where one should take into account the desired hours of energy autonomy "d_{o}", the maximum depth of discharge "$\mathrm{DOD_L}$" and the energy transformation efficiency of the ESS "η_{ss}". Note that "E_{h}" is the average hourly load demand of the electrical network under investigation defined as:

$$E_{\mathrm{h}} = \frac{E_{\mathrm{tot}}}{8760} \tag{8}$$

In regard to the nominal output power "N_{ss}" of the storage unit, it is the power efficiency "η_{p}" that must be considered as well, i.e.:

$$N_{\mathrm{ss}} = \zeta\cdot\frac{N_{\mathrm{p}}}{\eta_{\mathrm{p}}} = \zeta\cdot\frac{E_{\mathrm{h}}}{\mathrm{CF_p}}\cdot\frac{1}{\eta_{\mathrm{p}}} \tag{9}$$

where "ζ" is the peak power percentage of the local network that the energy storage branch should be able to cover, see also Eq. (4).

Accordingly, the input nominal power "N_{in}" of the ESS depends on the available power excess of the existing electricity generation units and the corresponding probability distribution [13] as well as the desired charge time of the installation. For practical cases and assuming that the charge and the discharge time period of the ESS are comparable one may finally write:

$$N_{\mathrm{in}} = \lambda \cdot N_{\mathrm{ss}} \tag{10}$$

where "λ" depends on the ratio of charge and discharge periods as well as on the efficiency of the energy transformation procedures involved. Generally speaking "λ" takes values in the range of 1.0–3.0.

4. Financial evaluation of the proposed solution

4.1. Initial investment cost

The total investment cost (after - n years of operation) of the proposed solution [14–16] is a combination of the initial installation cost and the corresponding maintenance and operation (M&O) cost, both quantities expressed in present values. In this context the initial investment cost "IC_o" takes into account the initial cost of the RES-based power station and the ESS as well as the balance of the plant, expressed as a function "f" of the initial cost of the RES-based power station, i.e.:

$$IC_o = IC_{RES} + f \cdot IC_{RES} + IC_{ss} \tag{11}$$

According to the available information the purchase cost of the RES-based station can be expressed by the following relation:

$$IC_{RES} = Pr \cdot N_{RES} \tag{12}$$

where "Pr" is the specific price (€/kW) of the RES-based power stations, see for example [14–16].

Accordingly, the initial cost "IC_{ss}" of an ESS can be expressed as a function of two coefficients. The first "c_e" (€/kWh) is related to the storage capacity and type of the system, and the second "c_p" (€/kW) is referring to the nominal power and type of the storage system in view of Eq. (10). Hence one may use the following relation:

$$IC_{ss} = c_e \cdot E_{ss} + c_p \cdot N_{ss} = E_h \cdot \left[\frac{c_e \cdot d_o \cdot \varepsilon}{\eta_{ss} \cdot DOD_L} + \frac{c_p \cdot \zeta}{CF_p \cdot \eta_p} \right] \tag{13}$$

In order to obtain a first idea of the numerical values of the above mentioned parameters (i.e. DOD_L, η_{ss}, η_p, c_e, c_p) the data of Table I can be used, based on the available information in the international literature [17–20]. In the same Table I, the service period "n_{ss}" and the corresponding annual M&O factor "m_{ss}" for every ESS are also included. As it is obvious from Table I, a wide range of values has been found for most energy storage systems under investigation. In the present analysis the corresponding mean values have been adopted.

According to the existing legislation there is a considerable subsidization by the Greek State for RES-based applications on the basis of the current development law (e.g. 3299/04) or the corresponding National Operational Competitiveness Program. Actually, the subsidy percentage "γ" equals to 30–50% of the total investment cost. However, in the current analysis the subsidization impact is neglected, hence "γ" is taken equal to zero.

4.2. Total investment cost

In addition to the initial investment cost one should also take into consideration the maintenance and operation cost of the entire installation, including the RES-based power station and the ESS. The M&O cost can be split [14] into the fixed maintenance cost "FC" and the variable one "VC". Expressing the annual fixed M&O cost as a fraction "m_{RES}" and "m_{ss}" (see [14–16] and Table I) of the initial capital invested and assuming an annual increase of the cost equal to "g_{RES}" and "g_{ss}" respectively, the present value of "FC" is given as:

$$\begin{aligned} FC &= FC_{RES} + FC_{ss} \\ &= m_{RES} \cdot IC_{RES} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{RES})}{(1+i)} \right)^j \\ &\quad + m_{ss} \cdot IC_{ss} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j \end{aligned} \tag{14}$$

where "i" is the capital cost of the local market. The distinctive nature of a compressed air energy storage (CAES) principle operation imposes the need of the fuel factor to be also included [21]. However, in the proposed solution an attempt is made to minimize the fossil fuel consumption, thus the utilization of CAES is excluded from the present analysis [22].

Subsequently, the variable maintenance and operation cost mainly depends on the replacement of "k_o" and "k_s" major parts of the RES-based power station and the energy storage facility respectively, which have a shorter lifetime "n_k" or "n_j" compared to the complete installation "n^*". Using the symbol "r_k" or "r_j" for the replacement cost coefficient of each one of the "k_o" and "k_s" major parts of the entire installation, the "VC" term can be expressed as:

$$\begin{aligned} VC &= IC_{RES} \cdot \sum_{k=1}^{k=k_o} r_k \cdot \left\{ \sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{(1+i)} \right)^{l \cdot n_k} \right\} \\ &\quad + IC_{ss} \cdot \sum_{j=1}^{j=k_s} r_j \cdot \left\{ \sum_{l=0}^{l=l_j} \left(\frac{(1+g_j)(1-\rho_j)}{(1+i)} \right)^{l \cdot n_j} \right\} \end{aligned} \tag{15}$$

with "l_k" and "l_j" being the integer part of the following Eq. (16), i.e.

$$l_k = \left[\frac{n-1}{n_k} \right] \text{ and } l_j = \left[\frac{n-1}{n_j} \right] \tag{16}$$

while "g_k" or "g_j" and "ρ_k" or "ρ_j" describe the mean annual change of the price and the corresponding level of technological improvements for the "kth" major component of the RES-based power station or the "jth" major component of the energy storage installation, respectively.

Recapitulating, the total cost "C" ascribed to the proposed RES-based installation and operation after "n" years (in present values) may be estimated using Eq. (17).

$$C = IC_o \cdot (1-\gamma) + EC + FC + VC - \frac{Y_n}{(1+i)^n} + APS \Rightarrow \tag{17}$$

where "Y_n" is the residual value of the installation after n-years of operation in current values and "EC" describes the cost of the input energy "δE" absorbed from the existing thermal power station. For practical applications this term can be estimated using the following relation, i.e.:

Table I
Major characteristics of the energy storage systems examined [17–20]

Storage system	Service period n_{ss} (years)	DOD_L (%)	Power efficiency η_p (%)	Energy efficiency η_{ss}(%)	Specific energy cost c_e (€/kWh)	Specific power cost c_p (€/kW)	M& O m_{ss}(%)
P.H.S.	30–50	95	85	65–75	10–20	500–1500	0.25–0.5
Flywheels	15–20	75–80	90–95	80–86	250–350	150–400	1–1.5
Regenesys	10–15	100	75–85	60–70	125–150	250–300	0.7–1.3
F.C.	10–20	90	40–70	35–45	2–15	300–1000	0.5–1
Lead acid	5–8	60–70	85	75–80	210–270	140–200	0.5–1
Na–S	10–15	60–80	86–90	75–85	210–250	125–150	0.5–1

$$\mathrm{EC} = \delta E \cdot c_{\mathrm{w}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j \tag{18}$$

where "c_{w}" is the specific input energy cost value ($c_{\mathrm{w}} \approx c^*$) and "$w$" is the mean annual escalation rate of the input energy price. Finally, "APS" is the cost of keeping the existing thermal power station as a back up station.

Substituting Eqs. (11), (14), (15) and (18) into Eq. (17) concludes to:

$$C = [\mathrm{IC}_{\mathrm{RES}} \cdot (1+f) + \mathrm{IC}_{\mathrm{ss}}] \cdot (1-\gamma) + m_{\mathrm{RES}} \cdot \mathrm{IC}_{\mathrm{RES}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{\mathrm{RES}})}{(1+i)} \right)^j + m_{\mathrm{ss}} \cdot \mathrm{IC}_{\mathrm{ss}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{\mathrm{ss}})}{(1+i)} \right)^j + \delta E \cdot c_{\mathrm{w}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j + \mathrm{VC} - \frac{Y_n}{(1+i)^n} + \mathrm{APS} \tag{19}$$

4.3. Comparison of the available solutions

The proposed RES and ESS-based configuration should be compared with the existing solution, which is based on the utilization of the existing thermal power station in order to cover the electricity demand "E_{tot}" of the local society. In this scenario, the current electricity production cost is assumed equal to "c^*", while the annual electricity price escalation rate "e" should also be included. More precisely, the total electricity production cost "C^*" of the existing thermal power station for a n-year time period can be approximated by the following relation:

$$C^* = c^* \cdot E_{\mathrm{total}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+e)}{(1+i)} \right)^j - \frac{Y_n^{\mathrm{TPS}}}{(1+i)^n} \tag{20}$$

where "Y_n^{TPS}" is the residual value of the existing thermal power units after n-years of operation in current values.

The time evolution of the total gains (or cost savings) "R" between the proposed and the existing electricity generation solutions can be expressed as:

$$R = C^* - C \tag{21}$$

In case that $R > 0$ the RES-based solution is more cost efficient than the utilization of the existing APS, while the opposite is valid if $R < 0$. Note that in the above presented analysis the following factors have been implicitly neglected:

(a) The increased reliability and the improved quality of the electricity offered by the RES and ESS-based solution.
(b) The reduction of the environmental (air pollution, oil leakages, thermal waste etc.) and macroeconomic (exchange loss and political dependency due to oil imports etc.) impacts.
(c) The need for gradual replacement of the existing outmoded internal combustion engines in the course of time.

Finally, in order to clarify the impact of the ESS on the improvement of the financial efficiency of the proposed solution, one may also repeat the calculation without the utilization of an ESS. In this case $\varepsilon = 0$ and the contribution of the ESS to the total cost of the installation is zeroed. Note that due to the existing penetration limits of the RES-based electricity production in the local electrical network [5,6] the existing thermal power units should cover the major part (approximately $\delta E \geqslant 0.75 \cdot E_{\mathrm{tot}}$) of the local community electricity demand, see also [23].

5. Application results

The developed methodology is accordingly applied to two representative cases of Aegean Archipelago islands, i.e. the islands of Ikaria and Anafi, see Table II. The scope of the analysis described is twofold: first to investigate the viability of an integrated RES and ESS-based electricity generation solution in comparison with the existing solution based on fossil fuel utilization and secondly to find the most appropriate energy storage configuration that maximizes the gains of the proposed solution.

Table II
Main parameters of Anafi and Ikaria islands

Island	Peak power demand kW-2005)	Total annual energy consumption (MWh-2005)	RES-based power unit	Population (2001 census)	Area (km^2)
Anafi	420	984	PV	272	38.35
Ikaria	7550	24,119	Wind turbines	8354	255.26

5.1. Wind energy based solution for a medium-sized island

Ikaria is a medium-sized island (population 8354 habitants, area of 255 km^2) of the East Aegean sea, located approximately 240 km from Athens and belonging to the Samos prefecture, Fig. 1. Its major town is Agios Kirikos with 2688 habitants, and the main economic activities of the local society are agriculture, fishing, merchant marine and tourism. The annual energy production of the local APS was 24,200 MWh for 2005, see also Fig. 6. The peak load demand –approximately 7550 kW – appears also during summer, while the corresponding minimum value is 1100 kW. The island has an excellent wind potential, since in several locations the annual mean wind speed approaches 9 m/s, at 10 m height, see for example Fig. 7. What is more, there is a remarkable natural water reservoir at almost 700 m elevation, which can be used as a basis for the application of a pump-hydro storage (PHS) solution [7].

On the other side, the evolution of the local APS production cost presents an average annual increase of 7.3%, see Fig. 6, while an important part of it (≈45%) is due to the fuel cost. The autonomous power station of Ikaria consists of seven internal combustion engines along with their electrical generators, and their specific fuel consumption is almost 270 gr/kWh. The rated capacity of the APS is 11,360 kW, while in the island a small wind park of seven (7 × 55 kW) outdated WM-15S wind turbines [24], rated power 385 kW, as well as a private wind turbine of 600 kW exist. Finally, the annual cost of the existing APS is approximately 5M€ [1,3].

In order to face the gradually increasing electricity demand of the island one may install several wind turbines of total nominal power resulting from Eq. (6) in collaboration with an appropriate ESS. Taking into account the wind potential of the area and the corresponding load demand time distribution the corresponding ESS contribution varies [23] between 50% and 60%, i.e. $0.5 \leqslant \varepsilon \leqslant 0.6$. In the current analysis the parameter "ε" is taken equal to 55%.

Accordingly, the ESS selected in order to collaborate with the proposed wind power station include on top of the well known lead-acid batteries and the pump-hydro storage systems, the Na–S batteries, the flow batteries (Regenesys) and the fuel cells (FC) [12,25]. The major characteristics of the technologies examined are summarized in Table I, see also [17–20]. At this point it is important to note that one of the main parameters influencing the techno-economic behavior of the proposed solution is the desired energy autonomy of the local electrical network, expressed via the hours of energy autonomy "d_{o}" of the system. In this context "d_{o}" varies between 6 h and 48 h, while the contribution of the existing APS ($\delta E/E_{\mathrm{tot}}$) takes values between 50% and 0%, respectively.

According to the results obtained, the rated power of the wind park required to cover the desired energy autonomy of the local network depends not only on the ESS technology adopted but also

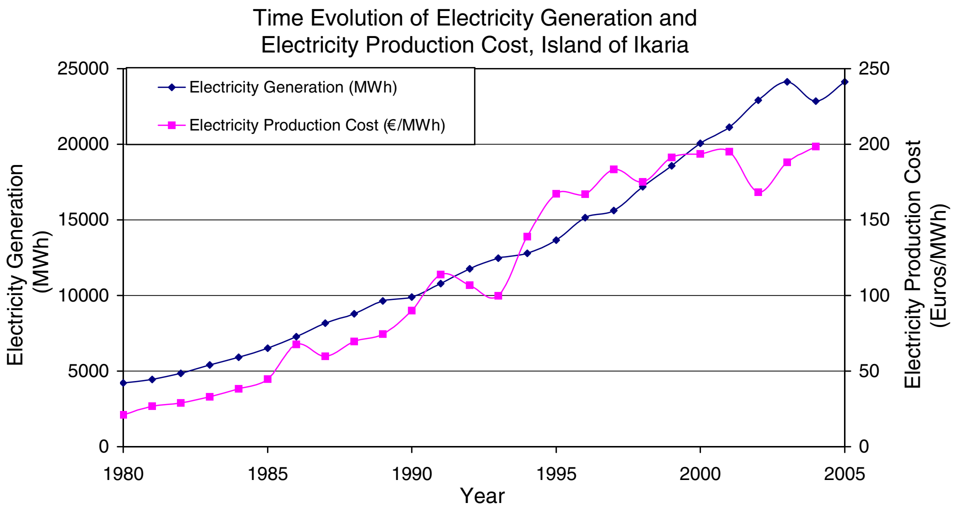

Fig. 6. Electricity consumption and electricity price time variation for Ikaria island.

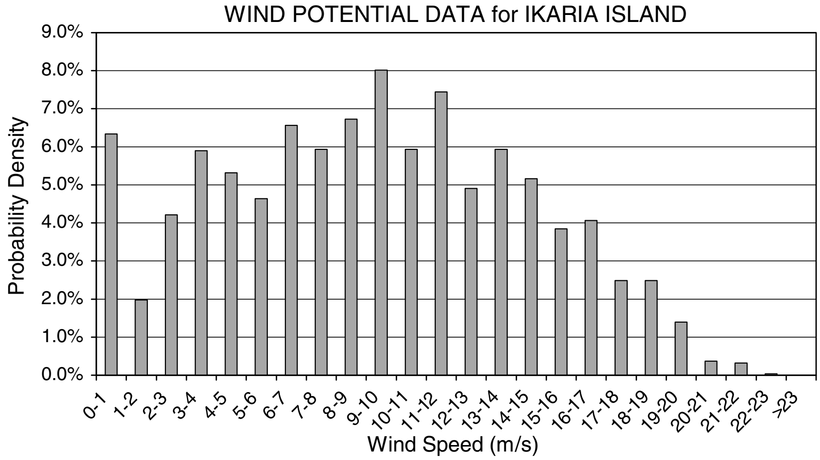

Fig. 7. Wind potential data for Ikaria island.

on the "d_o" value, see also Fig. 8. Actually, the wind park size increases (from 9 MW up to 12.5 MW) as the desired energy autonomy increases for all ESS analyzed, while for the fuel cells solution the corresponding range is between 13 MW and 18 MW due to their low energy transformation efficiency obtained up to now [25]. It is important to mention that for low "d_o" values the wind park rated power is defined (9 MW) by the peak load demand of the local network and the corresponding safety factor (SF = 0.2), see Eq. (6). For higher "d_o" values the "N_{RES}" value is dictated by the energy demand of the proposed installation and the APS contribution (δE), i.e. from the second term of the RHS of Eq. (6).

On the other side, the energy storage capacity "E_{ss}" of the ESS is directly analogous to "d_o" (Eq. (7)), while the corresponding rated power "N_{ss}" depends only on the peak load demand of the local network, see Eq. (9). In this context, one may examine the contribution of the various cost components (Eq. (19)) on the total operational cost of the proposed solution for a 20-year long service period. According to the data of Fig. 9 concerning the lead-acid and the PHS solutions for 24 h energy autonomy of the system two different cost patterns appear. The first category demonstrates (Fig. 9a) significant contribution of the ESS (initial cost and replacement or variable M&O cost), which represent almost the 60% of the total configuration cost. In the second alternative (Fig. 9b) the RES-based power station represents the main part of the total installation cost. In both cases the contribution of the input energy from the existing APS (representing only the 10% of the total annual consumption) is also remarkable (15–25%).

Accordingly, the total gains (or cost savings) of the proposed solution in relation to the operation of the existing APS are presented in Fig. 10 as a function of the desired hours of energy autonomy (R-d_o) for all the ESS tested. In the same figure one may also find the corresponding gains of a wind-only based solution, i.e. without the existence of an ESS. In this specific case the contribution of the wind-based power station in the annual electricity demand is rather low [23], i.e. approximately 20% ($\delta E/E_{tot} \approx 0.8$). As it is obvious from the results presented, all the RES and ESS based configurations tested are more cost-efficient than the APS based solution. On top of this, the utilization of an ESS improves the financial behavior of the RES-based power station, decreasing at the same time the utilization of imported oil.

After a closer inspection of Fig. 10 one may also state that the ESS analyzed present two different cost-saving distributions, at least in the autonomy range examined. More precisely, all the battery type ESS (lead-acid, Na–S and flow batteries) present one maximum cost saving value for a specific "d_o" value, after which the gains are decreasing. This is not the case for PHS and FC systems which present a continuously increasing gain distribution, at least in the autonomy range examined. In this context, flow batteries

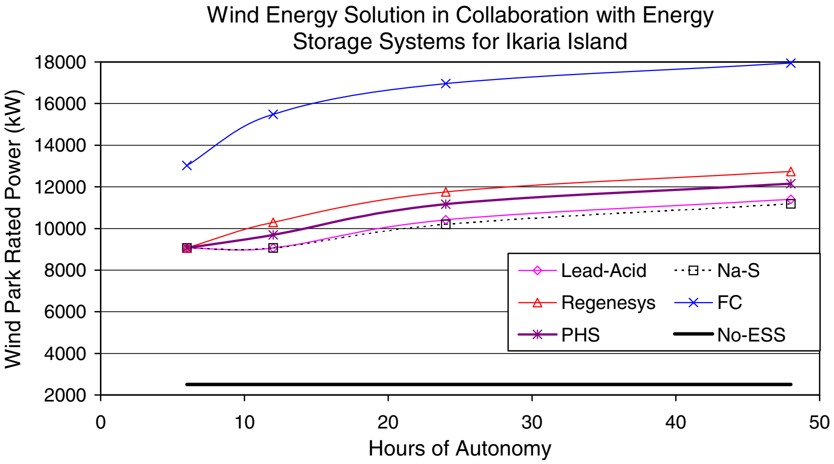

Fig. 8. RES-based power station rated power vs. energy autonomy hours of the ESS, Ikaria island.

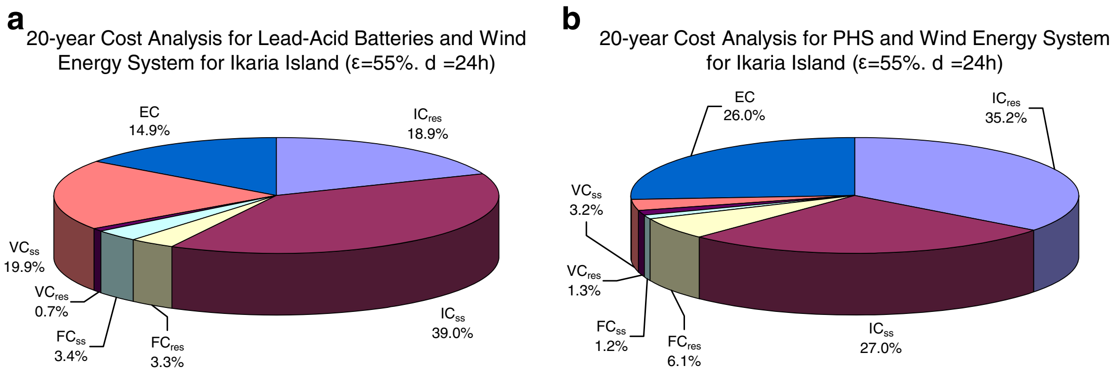

Fig. 9. (a) Total cost analysis of the combined RES-lead acid batteries based solution for Ikaria island. (b) Total cost analysis of the combined RES–PHS based solution for Ikaria island.

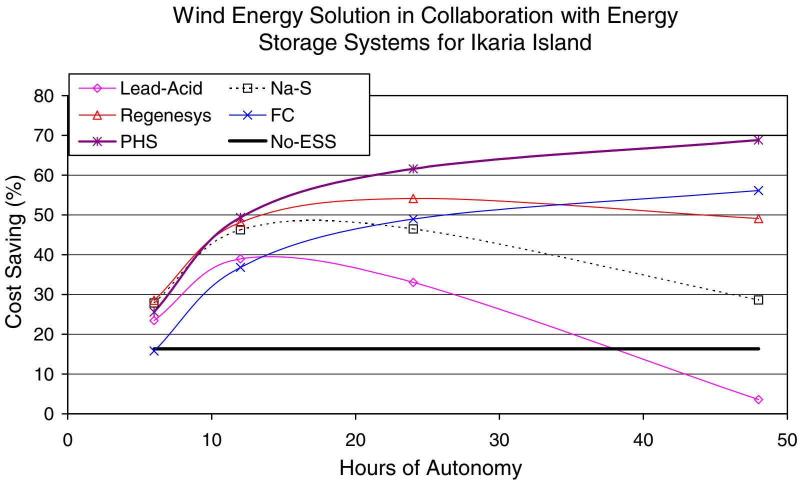

Fig. 10. Cost saving distribution of the wind-ESS based power station in comparison with the existing APS for Ikaria island.

and Na–S batteries present (Fig. 11) comparable gains for low “d_o” values, while for “d_o” values of 12 h-24 h the PHS and flow batteries solutions are the most cost-efficient ones. Finally, in case of high energy autonomy PHS and fuel cells present a significant cost saving advantage.

Recapitulating for the Ikaria island case, the exploitation of the excellent wind potential of the area remarkably reduces the electricity generation cost of the local network. However, the only possibility to significantly increase the contribution of the RES in the local system energy balance is by introducing an appropriate ESS. In this case, considerable energy production cost saving is encountered (50–70% cost decrease) which depends on the selected energy autonomy degree of the system (without the utilization of the local APS). According to the results obtained the pump-hydro

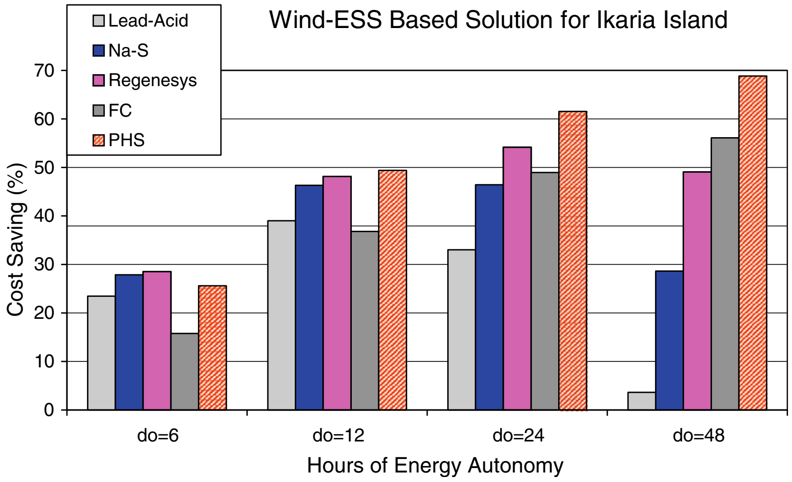

Fig. 11. The impact of the energy autonomy on the cost saving distribution of the wind-ESS based power station in comparison with the existing APS for Ikaria island.

storage is the most cost effective energy storage technology, especially for "d_o" values higher than 6 h ($d_o > 6$ h), while the flow batteries and the fuel cells may constitute an interesting alternative solution for low and high "d_o" values, respectively.

5.2. Photovoltaic based solution for a small island

Anafi is a very small island (population 272 habitants – approximately 70 families – area of 39 km^2) at the southeast edge of Cyclades complex. There is a complete lack of fresh water in the island, thus it has no remarkable flora and fauna. The local terrain is quite relief, including rocky hills and absence of flat fields. The main economic activities of the local society are fishing, and tourism. The annual energy production of the local APS was almost 1000 MWh for 2005, see also Fig. 12. The peak load demand – approximately 420 kW – appears during mid-August, while the corresponding minimum value is 50 kW (during winter). The island has very good solar potential, since the annual mean solar energy approaches 1700 kWh/m^2, at horizontal plane, Fig. 13.

The small APS of the island includes five small internal combustion engines of total rated capacity of 670 kW, while their mean specific fuel consumption is 242 gr/kWh. The high solar potential of the island and the extremely high electricity generation cost of the local APS, see also Fig. 12, exceeding the 480€/MWh, are two significant parameters that encourage the installation of a photovoltaic (PV) generator in the island. Besides the proposed PV-based solution requires minimum maintenance effort.

For this purpose, one may install a new PV generator of nominal power resulting from Eq. (6), which in collaboration with an appropriate ESS can meet the electricity demand of the local community. Taking into account the solar potential of the area (available during daytime) and the corresponding load demand time distribution the resulting ESS contribution varies [23] between 70% and 80%, i.e. $0.7 \leqslant \varepsilon \leqslant 0.8$. In the current analysis the parameter "ε" is taken equal to 75%.

Accordingly, the ESS examined in order to collaborate with the proposed photovoltaic generator include on top of the well known lead-acid and Na–S batteries, the relatively new flow batteries (Regenesys) and the fuel cells (FC). Due to the very small size of the network one may also examine the installation of a flywheel based system, while the utilization of a PHS is not recommended taking into consideration the size and the topography of the island as well as the total absence of local water reserves. However, the possibility of combined electricity and clean water production on the basis of the solar energy exploitation is an interesting idea to be examined [9].

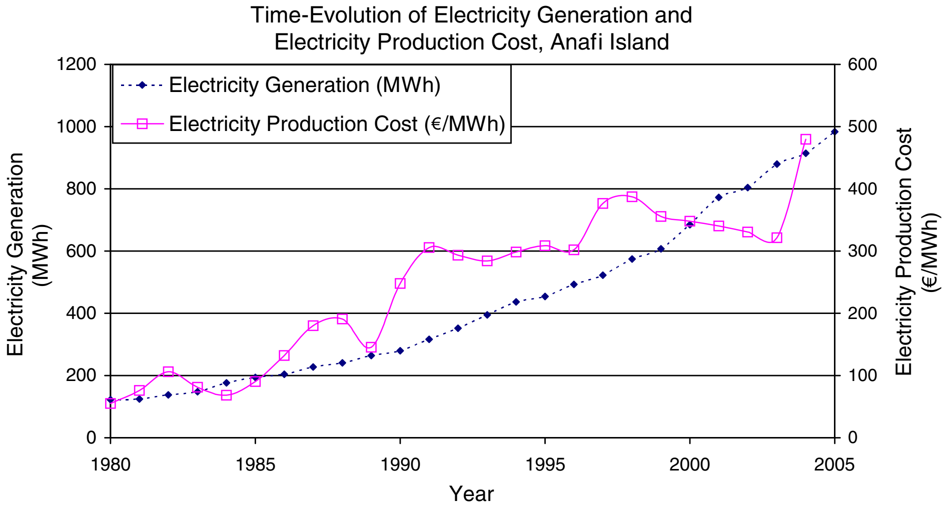

Fig. 12. Electricity consumption and electricity price time variation for Anafi island.

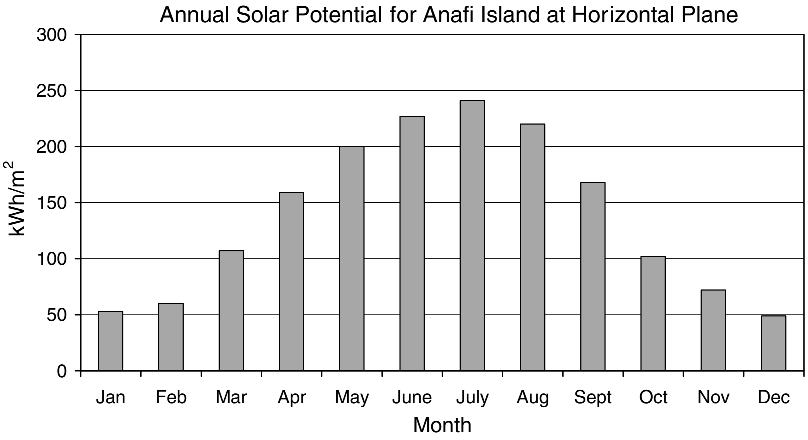

Fig. 13. Solar potential of Anafi island.

As in the previous case, the major characteristics of the technologies examined are summarized in Table I, see also [17–20]. Also note that the desired energy autonomy of the local electrical network, expressed via the hours of energy autonomy "d_o" of the system, is still the major parameter influencing the techno-economic behavior of the proposed solution. In this context "d_o" varies between 6 h and 48 h, while the contribution of the existing APS ($\delta E/E_{tot}$) takes values between 50% and 0%, respectively.

As in the wind park case of Ikaria, the PV rated power required to guarantee the desired energy autonomy of the local network depends not only on the ESS technology adopted but also on the "d_o", see also Fig. 14. More specifically, the PV generator size increases (from 500 kW up to 800 kW) as the desired energy autonomy increases for most ESS analyzed. This is not the case for the fuel cell solution, since the corresponding rated power exceeds the 1.1 MW. Note that the flow batteries system requires also quite high PV rated power. At this point, it is important to mention that for low "d_o" values the PV station rated power (500 kW) is defined by the peak load demand of the local network and the corresponding safety factor (SF = 0.2), see Eq. (6). For higher "d_o" values the "N_{RES}" value is imposed by the energy demand of the proposed installation and the APS contribution (δE), i.e. the second term of the RHS of Eq. (6).

Interesting conclusions may be achieved by examining the contribution of the various cost components (Eq. (19)) on the total operational cost of the proposed PV-based solution for a 30-year long service period. According to the information of Fig. 15 concerning the lead-acid and the Na–S batteries solutions for 24 h energy autonomy of the system, one should mention the dominant impact of the PV station initial cost, representing almost the 60% of the total 30-year long operational cost of the installation. This fact reduces the impact of the best ESS choice encountered for the wind-based case, see also Fig. 9. However, there is an implicit impact of the ESS type selected via the required rated power of the PV generator, Fig. 14. Finally, in both cases presented in Fig. 15a and b, the contribution of the input energy cost from the existing APS (representing only the 10% of the total annual consumption) is also remarkable (≈15%).

In Fig. 16 the variation of the proposed solution total gains in comparison with the operation of the existing APS as a function of the desired hours of energy autonomy (R–d_o) for all the ESS analyzed can be examined. In the same figure one may see the corresponding gains of a PV-only based solution, i.e. without the existence of an ESS. In this case, the contribution of the RES-based power station in the annual electricity demand is approximately 20% (i.e. $\delta E/E_{tot} \approx 0.8$). As it is obvious from the results presented, several RES and ESS based configurations tested are more cost efficient than the APS based solution. This is not the case for the fuel cells based option taking into consideration the small size of the installation. On top of this, the utilization of an ESS improves in

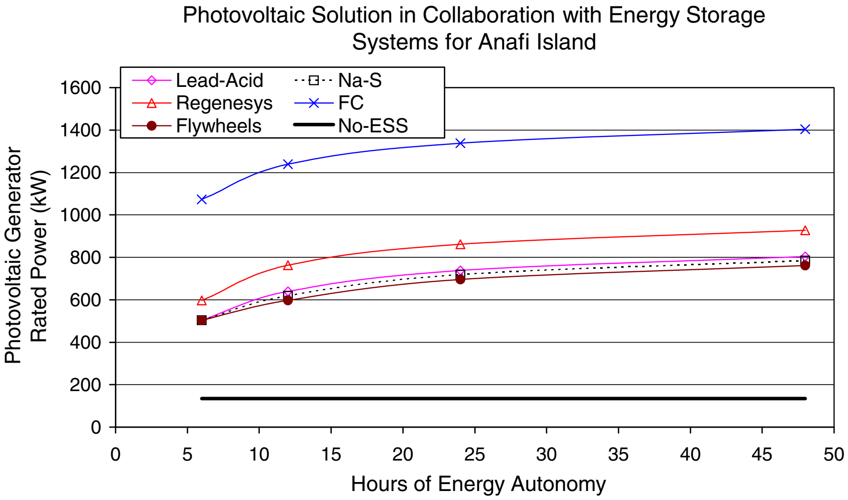

Fig. 14. RES-based power station rated power vs. energy autonomy hours of the ESS, Anafi island.

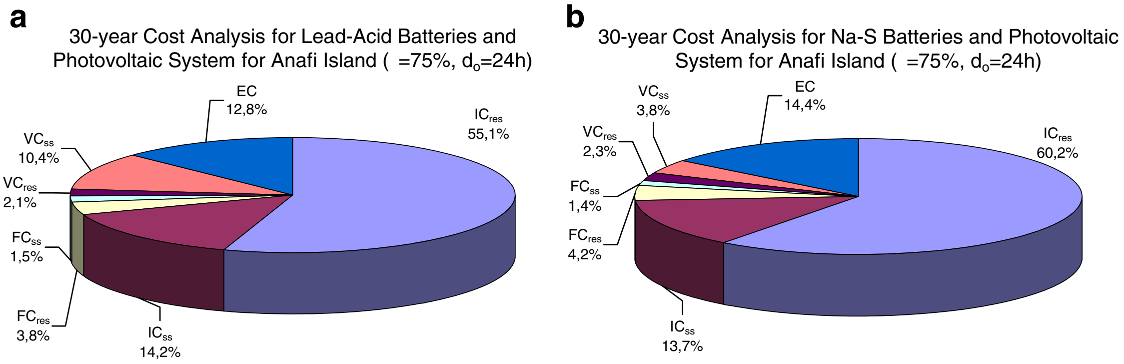

Fig. 15. (a) Total cost analysis of the combined RES-lead acid batteries based solution for Anafi island. (b) Total cost analysis of the combined RES-Na–S batteries based solution for Anafi island.

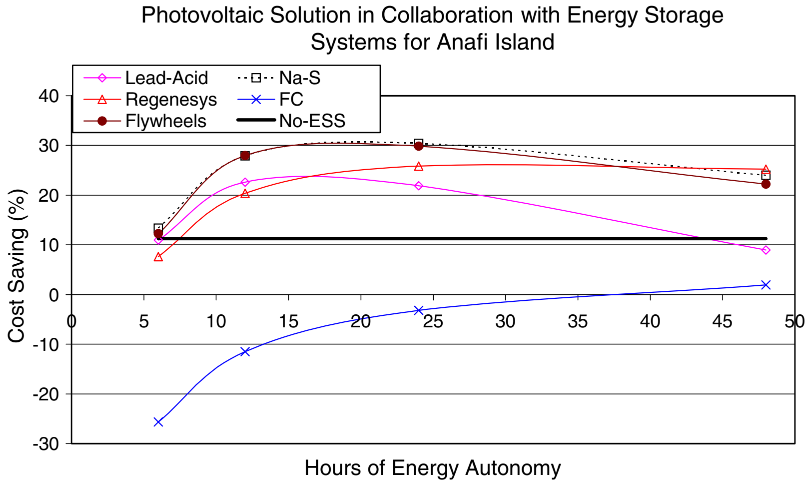

Fig. 16. Cost saving distribution of the PV-ESS based power station in comparison with the existing APS for Anafi island.

most cases the financial behavior of the RES-based power station, especially for 12 h and 24 h of energy autonomy.

After a closer inspection of Fig. 16, one may note that for all the cost-efficient ESS examined (excluding the fuel cells) the estimated gains present initially an increase approaching a maximum value between $d_o = 12$ h and $d_o = 24$ h, which is followed by a remarkable reduction as "d_o" approaches the 48 h. In this context Na–S batteries and flywheels present (Fig. 17) the best financial behavior for up to 24 h of energy autonomy, while for higher "d_o" values the flow batteries solution is slightly better than the Na–S batteries one.

Summarizing the Anafi island case, the exploitation of the high solar potential of the area is expected to reduce the electricity generation cost of the local network. In fact, remarkable energy production cost saving is estimated (≈30% cost decrease), which depends on the selected energy autonomy degree of the system, in relation to the local APS operation. According to the calculation results, the Na–S battery solution is the most cost effective energy

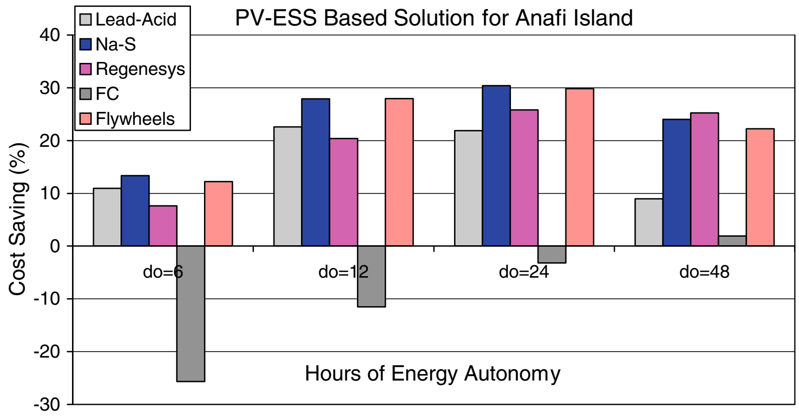

Fig. 17. The impact of the energy autonomy on the cost saving distribution of the PV-ESS based power station in comparison with the existing APS for Anafi island.

storage technology applied, especially for "d_o" values less than 24 h ($d_o < 24$ h), while the flywheels and the flow batteries may constitute an interesting alternative solution for low and very high "d_o" values, respectively.

Comparing now the two island cases examined one may state the following:

- The wind-based solution needs relatively lower energy storage support (at least for high wind potential areas) in comparison with the solar-based electricity generation configuration.
- In terms of total cost analysis, the PV-based configuration is dominated by the cost of the PV generator, while for the wind energy based solution both ESS and wind parks share the corresponding total cost of the installation.
- Finally, the financial gains of the wind-based solution is quite higher than the corresponding ones of the PV-based installation, although the electricity production cost [3] of the existing APS is much higher for the small island (PV solution) than for the medium-sized island (wind energy solution). This is mainly due to the higher specific price of PV generators in comparison with the commercial wind turbines as well as due to their lower capacity factor in relation to wind parks [26].

6. Conclusions

An integrated methodology, investigating the possibility of creating a combined electricity generation system based on the exploitation of wind and solar potential of the numerous islands of the Aegean Archipelagos as well as on the utilization of an appropriate energy storage configuration, is developed. The proposed electrification solution can replace the existing thermal power stations based on imported oil with considerable production cost reduction. In this context, the main parameters of the combined RES–ESS based installation are calculated first and accordingly used in order to prove the economic viability of the proposed solution.

During the analysis special attention is paid to select the most cost-effective energy storage strategy in order to maximize the RES penetration (minimizing at the same time the oil consumption) and to minimize the electricity generation cost. The developed methodology is subsequently applied on two representative autonomous island cases, based on the exploitation of the available wind and solar potential respectively. The calculation results are very encouraging, since in both cases the proposed configuration leads to quite lower electricity production cost than the existing thermal power stations. On top of this, the utilization of an appropriate ESS improves the financial behavior of the RES-based power station leading also to much higher wind or solar energy penetration levels in the local energy market.

According to extensive calculations, the pump-hydro storage for medium-sized islands and the Na–S batteries for small sized islands are the most cost effective energy storage techniques. Besides, flow batteries (i.e. Regenesys technology) are also a techno-economic interesting alternative for both cases analyzed, while the fuel cells based systems cannot compete with the existing energy storage systems, excluding the high energy autonomy cases. Finally, lead-acid batteries and flywheel systems may be an interesting energy storage option for small systems and limited energy autonomy scenarios.

Recapitulating, it is important to mention that the proposed integrated electrification solution based on the exploitation of the available RES potential in collaboration with an appropriate energy storage configuration is a financially attractive solution for the existing autonomous island networks of the Aegean Archipelagos. In fact, the proposed power stations are able to substitute the expensive and heavy polluting existing thermal power stations, improving the reliability of the local electrical networks and the quality of the energy offered to the local communities.

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