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Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency

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Abstract

The high wind and solar potential along with the extremely high electricity production cost met in the majority of Greek Aegean islands comprising autonomous electrical networks, imply the urgency for new renewable energy sources (RES) investments. To by-pass the electrical grid stability constraints arising from an extensive RES utilization, the adaptation of an appropriate energy storage system (ESS) is essential. In the present analysis, the cost effect of introducing selected storage technologies in a large variety of autonomous electrical grids so as to ensure higher levels of RES penetration, in particular wind and solar, is examined in detail. A systematic parametrical analysis concerning the effect of the ESSs' main parameters on the economic behavior of the entire installation is also included. According to the results obtained, a properly sized RES-based electricity generation station in collaboration with the appropriate energy storage equipment is a promising solution for the energy demand problems of numerous autonomous electrical networks existing worldwide, at the same time suggesting a clean energy generation alternative and contributing to the diminution of the important environmental problems resulting from the operation of thermal power stations.

Keywords: Electricity generation; Energy storage; Autonomous electrical network; Renewable energy sources; Electricity production cost

1. Introduction

The ongoing electricity consumption increase to be satisfied along with the environmental protection to be considered, have long since imposed the need for the renewable energy sources (RES) application [1]. In this context, the compliance with the targets set by the EU [2,3] and adopted by each member state, also calls for further RES technologies' promotion. Besides, strong incentives supported by attractive pricing regarding the purchase cost of certain RES technologies' energy yield by the local grid—such as in the case of the recent law enactment in Greece [4]—suggest the revival of the investing interest. If also taking into account the high wind and solar potential met in the majority of Greek Aegean islands along with the extremely high electricity production cost of the existing thermal power stations [5], additional reasons for the RES substantial adoption are evident.

On the other hand, the variable or even stochastic wind energy production causing side-effects that affect the smooth operation of an electrical network [6,7]—especially in the case of isolated grids such as autonomous island networks—presents some inability to thoroughly conform to the local electricity demand. Similarly, the "de facto" restricted generation of a photovoltaic unit, depending on the solar irradiance during daytime, also underlines the necessity for the treatment of the current electricity production status. A number of studies addressing the importance of further RES exploitation in the particular featured island grids are encountered [8–14]. However, wind energy (and most RES) applications have been treated for a long time period as simple fossil fuel saving installations. This strategy not only underestimates the capabilities of RES-based hybrid power stations (e.g. to provide firm capacity) but also limits their contribution in the weak autonomous (island) networks to single digit figures. In fact, there are several examples where a

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Nomenclature

c_e	specific energy storage system's capacity cost (€/kWh)
c_f	specific equivalent energy cost of fuel used (€/kWh)
c_p	specific energy storage system's power cost (€/kW)
c_w	specific input energy cost (€/kWh)
d_o	energy autonomy of the energy storage system (h)
e	electricity price escalation rate
$\mathrm{DOD_L}$	maximum permitted depth of discharge of the energy storage system
e_f	mean annual escalation rate of fuel price
$\mathrm{EC_w}$	cost of input energy utilized to charge the energy storage devices (€)
E_{dir}	energy demand covered directly by the existing power stations (kWh)
E_{ss}	energy storage capacity of the energy storage system (kWh)
E_{tot}	annual energy demand of the local electricity network (kWh)
$\mathrm{FC_{ss}}$	fixed M&O cost of the energy storage system (€)
g_k	mean annual change of cost for major parts to be replaced
g_{ss}	annual fixed M&O cost inflation rate
i	capital cost of the local market
IC_n	future value of the initial investment cost (€)
$\mathrm{IC_{ss}}$	initial investment cost of the energy storage system (€)
k_o	major parts to be replaced during the system's service period
l_k	times of replacement for major parts being replaced (integer number)
m	M&O cost coefficient
n	years of operation for the proposed configuration (years)
n_k	lifetime of energy storage system's major components
n_{ss}	service period of the energy storage system (years)
N_p	annual peak load demand of the local electrical network (kW)
N_{ss}	nominal power of the energy storage system (kW)
r_k	replacement cost coefficient for the major parts to be replaced
$\mathrm{VC_{ss}}$	variable maintenance cost of the energy storage system (€)
w	mean annual escalation rate of the input energy price

Greek letters

γ	state subsidy percentage to the total investment cost
ε	energy demand ratio covered directly by the energy storage system
ζ	peak load demand ratio covered by the energy storage system
η_p	power efficiency of the energy storage system
η_{ss}	energy transformation efficiency (round-trip) of the energy storage system
ρ_k	mean annual change of technological improvement for the major system components

remarkable wind energy production cannot be absorbed by the local autonomous network due to the mismatch between the electricity production and the corresponding load demand. The outcome of this incapability is the significant financial loss of the wind parks owners, hindering the further exploitation of the local renewable potential.

In order to confront the variable or even stochastic behavior of the RES often not being able to meet the electricity grid's needs, the adaptation of an appropriate energy storage system (ESS) is thought to be essential, Fig. 1. The beneficial character describing the ESSs' implementation as ancillary units is further supported by the improvement of already existing power units' operational features and the avoidance of new ones' installation. On the other hand, storage technologies are faced with controversies mainly referring to the high initial cost rates, the additional transformation losses and the noteworthy environmental impacts, largely depending on the correlation between the type of technology used and the site selected [15].

Generally speaking, an ESS, when sized properly, can match a highly variable power production to a generally variable and hardly predictable system demand, remarkably limiting the energy production cost and improving the operational behavior of the local system thermal power units [16].

In the present analysis, the cost effect of introducing certain storage techniques for the greater penetration of renewable energy technologies (specifically wind and solar), in either a small or a large-scale autonomous electrical grid, is comprehensively examined. On top of this, a systematic parametrical analysis concerning the impact of the main ESS parameters on the economic behavior of the entire installation is also included.

Closing, one should not disregard the alternative solution recently revived and regarding either the islands' connection to the mainland's electricity network [17] or the option of internal interconnection among certain Aegean islands. In this way, a gradual retirement of the local autonomous power stations joined by high rates of RES

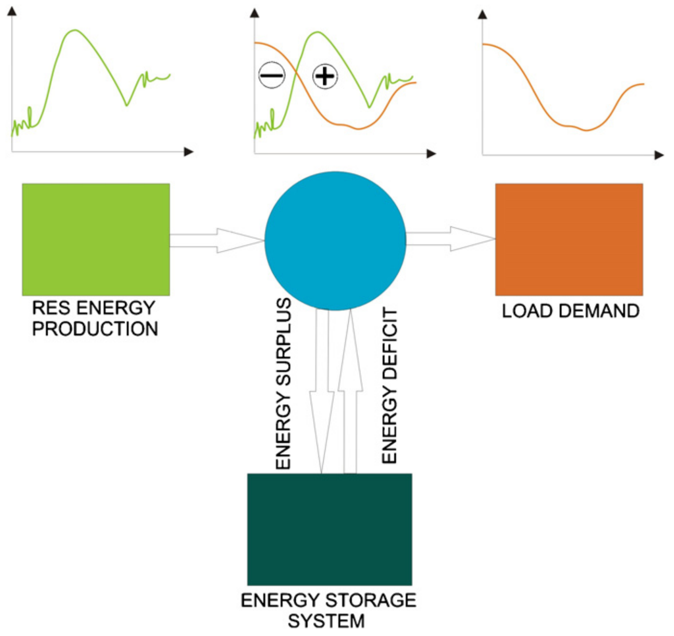

Fig. 1. Typical energy storage system configuration.

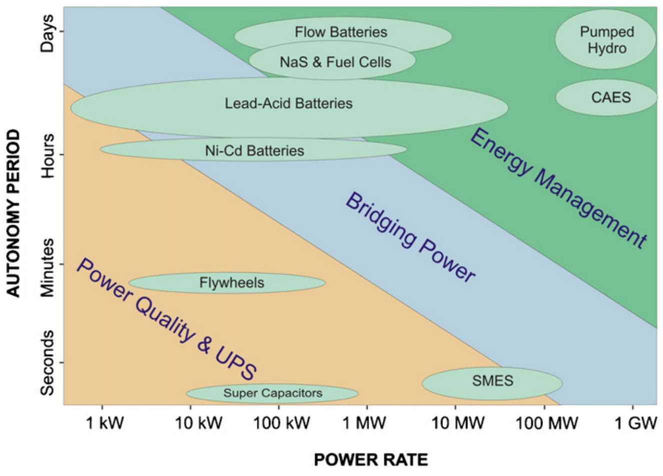

Fig. 2. Energy storage systems applications' range (based on material by ESA), presenting the autonomy period and the power covered by each specific energy storage system.

absorption by the national electricity network and the integrated group-island grids may be ensured.

On the other hand, such an electricity production strategy has to face the significant technological problems related to the undersea electricity transportation, the rather high first installation cost (approximately 3 million euros per km of transportation grid) and the strong opposition of local societies claiming important impacts on the marine fauna. Additionally, the "sacrifice" of particular islands—either being close to the mainland (e.g. Skyros island) or being favored by remarkable RES potential (e.g. geothermal fields in Milos)—in order for large-scale RES projects to be installed, jeopardizes the tourist character of the islands in the name of bulk power production units.

On the contrary, the distributed generation provided by RES–ESS configurations ensures greater levels of energy autonomy based on rational project-scale requirements, thus allowing for the implementation of compatible to the local environment energy production configurations.

2. Energy storage systems basic parameters

A widely accepted demarcation (see Fig. 2) divides the storage systems in those described by high-power provision and being able to confront the power quality issues (flywheels, super-capacitors, superconducting magnetic energy storage, etc.), and in those presenting high-energy capacity rates and being able to deal with the energy management applications, i.e. pumped hydro storage (PHS), compressed air energy storage (CAES), hydrogen storage coupled with fuel cells (HS-FC), most of the batteries and flow batteries. The ESSs under study have been selected with respect to the scope of managing the load loss probability deriving from the extensive exploitation of RES. Since the power quality provision is not examined, the systems serving the specific purpose will not be currently evaluated.

In the present analysis, the evaluation model developed is applied to autonomous electrical networks (e.g. remote islands) described by the given values of annual energy demand "E_{tot}" and maximum (peak) load demand of the system "N_{p}". Since we assume the installation of an ancillary storage unit to support the electricity grid status incorporating RES-based applications, the contribution of the former must be determined. Hence, during the present analysis we assume that the total energy demand is covered either directly by the existing power stations "E_{dir}" or via the storage system. In order to describe the contribution of the storage system to the total energy consumption we define the parameter "ε" as

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

where "ε" takes values between 0 (no storage system usage) and 1 (all the energy consumption is covered through the storage system). Between these two extreme values, a contribution range determined by the existing power units' principle features (including photovoltaics and wind turbines) dictates the potential use of the system on an annual basis.

In the following, one should define the energy storage capacity "E_{ss}" and the nominal power "N_{ss}" of the entire energy storage subsystem. Concerning the energy capacity required, the typical hours of energy autonomy "d_{o}", the maximum depth of discharge "$\mathrm{DOD}_{\mathrm{L}}$" and the energy transformation (round-trip) efficiency of the ESS "η_{ss}" should also be taken into account. Hence, one may write:

$$E_{\mathrm{ss}} = d_{\mathrm{o}}\left(\frac{\varepsilon E_{\mathrm{tot}}}{8760}\right)\frac{1}{\eta_{\mathrm{ss}}}\frac{1}{\mathrm{DOD}_{\mathrm{L}}}. \tag{2}$$

With regard to the nominal power of the storage unit, it is the power efficiency "η_p" that must be considered as well, i.e.

$$N_\mathrm{ss} = \zeta \frac{N_\mathrm{p}}{\eta_\mathrm{p}}, \tag{3}$$

where "ζ" is the peak power percentage of the local network that the energy storage branch should cover.

Having specified the storage capacity and the nominal power of a typical ESS, an effort to express the initial cost "$\mathrm{IC_{ss}}$" as a function of the two previous parameters entails the introduction of two new coefficients. The first "c_e" (€/kWh) related to the storage capacity and type of the system, and the second "c_p" (€/kW) referring to the nominal power and type of the storage system. Thus one may use the following relation:

$$\mathrm{IC_{ss}} = c_\mathrm{e} E_\mathrm{ss} + c_\mathrm{p} N_\mathrm{ss} = c_\mathrm{e} d_\mathrm{o} \left(\frac{\varepsilon E_\mathrm{total}}{8760} \right) \frac{1}{\eta_\mathrm{ss}} \frac{1}{\mathrm{DOD_L}} + c_\mathrm{p} \zeta \frac{N_\mathrm{p}}{\eta_\mathrm{p}}. \tag{4}$$

In order to obtain a first idea of the numerical values of the above-mentioned parameters (i.e. $\mathrm{DOD_L}$, η_ss, η_p, c_e, c_p), one may use the data of Table 1, based on the available information in the international literature [18–21]. In the same Table 1, the service period "n_ss" and the corresponding annual M&O factor "m" are also included. As it becomes obvious from Table 1, a wide range of values have been obtained for most ESSs under investigation, since their exact values are usually site dependent. In the present analysis mean values have been adopted, while in a forthcoming study the entire values' range may be analyzed.

3. Energy production cost evaluation model

The future value (after $-n$ years of operation) of the total investment cost of an energy storage installation [22] is a combination of the initial installation cost and the corresponding maintenance and operation cost, both quantities expressed in current values. Taking into consideration the analysis of Section 2, the future value of the initial investment cost can be expressed as

$$\mathrm{IC}_n = \mathrm{IC_{ss}}(1-\gamma)(1+i)^n, \tag{5}$$

where "γ" is the subsidization percentage by the Greek State and "i" is the capital cost of the local market.

In addition to the initial investment cost one should also take into consideration the input energy cost "$\mathrm{EC_w}$", i.e. the cost of energy supplied to the storage system in order to be able to provide the amount of energy expected ($\varepsilon E_\mathrm{total}$). Since the amount of energy needed to charge the storage system is expressed as ($\varepsilon E_\mathrm{total}/\eta_\mathrm{ss}$), the corresponding input energy cost for a time period of "n" years can be expressed as

$$\mathrm{EC_w} = \varepsilon \frac{E_\mathrm{total}}{\eta_\mathrm{ss}} c_\mathrm{w} \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j (1+i)^n, \tag{6}$$

where "c_w" is the specific input energy cost value and "w" is the mean annual escalation rate of the input energy price. In most cases the typical values of "c_w" range from 0 €/kWh (i.e. in the case when the provider of the energy input is also the owner of the storage configuration and uses the excess electricity production of an existing power station) to 0.2 €/kWh.

Accordingly, the M&O cost can be split into the fixed maintenance cost "$\mathrm{FC_{ss}}$" and the variable one "$\mathrm{VC_{ss}}$". Expressing the annual fixed M&O cost as a fraction "m" (see Table 1) of the initial capital invested and assuming an annual increase of the cost equal to "g_ss", the future value of "$\mathrm{FC_{ss}}$" is given as

$$\mathrm{FC_{ss}} = \mathrm{IC_{ss}} m \sum_{j=1}^{j=n} \left(\frac{(1+g_\mathrm{ss})}{(1+i)} \right)^j (1+i)^n. \tag{7a}$$

The distinctive nature of a CAES principle operation imposes the need for a fuel factor to be included [23]. In fact, a typical CAES requires a considerable fuel input in the combustion chamber of the installation [24]. This required amount of fuel is the main subject of controversy over the unconditional acceptance of such systems. In an effort to disengage the CAES from the fossil fuel (e.g. natural gas) dependency, one proposal supports the use of biofuel [25]. In any case, Eq. (7a) is rewritten in order to include the fuel input contribution as following:

$$\mathrm{FC_{ss}} = \mathrm{IC_{ss}} m \sum_{j=1}^{j=n} \left(\frac{(1+g_\mathrm{ss})}{(1+i)} \right)^j (1+i)^n + c_\mathrm{f}(\varepsilon E_\mathrm{total}) \sum_{j=1}^{j=n} \left(\frac{(1+e_\mathrm{f})}{(1+i)} \right)^j (1+i)^n. \tag{7b}$$

Table 1
Major characteristics of the energy storage systems examined [18–21]

Storage system	Service period n_ss (years)	DOD (%)	Power efficiency, η_p (%)	Energy efficiency, η_ss (%)	Specific energy cost, c_e (€/kWh)	Specific power cost, c_p (€/kW)	M&O, m (%)
PHS	30–50	95	85	65–75	10–20	500–1500	0.25–0.5
CAES	20–40	55–70	80–85	70–80	3–5	300–600	0.3–1
Regenesys	10–15	100	75–85	60–70	125–150	250–300	0.7–1.3
HS--FC	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

The "c_f" coefficient derives by combining the specific energy cost of the fuel used with the amount of fuel needed per kWh produced via the gas turbine incorporated. Besides, "e_f" expresses the mean annual escalation rate of fuel input price in case of CAES.

Concerning the variable maintenance and operation cost, it mainly depends on the replacement of "k_o" major parts of the installation which have a shorter lifetime "n_k" rather than the complete installation "n_{ss}". Using the symbol "r_k" for the replacement cost coefficient of each one of the "k_o" major parts of the installation, the "VC_{ss}" term can be expressed as

$$\mathrm{VC}_{ss} = \mathrm{IC}_{ss} \sum_{k=1}^{k=k_o} r_k \left\{ \sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{1+i} \right)^{l n_k} \right\} (1+i)^n \tag{8}$$

with "l_k" being the integer part of the following Eq. (9), i.e.

$$l_k = \left[\frac{n-1}{n_k} \right], \tag{9}$$

while "g_k" and "ρ_k" describe the mean annual change of the price and the corresponding level of technological improvements for the "kth" major component of the energy storage installation.

Recapitulating, the future cost ascribed to the storage system installation and operation after "n" years may be estimated using Eq. (10):

$$\begin{aligned} C_{ss} = \mathrm{IC}_{ss} \Bigg\{ & (1-\gamma) + m \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j \\ & + \sum_{k=1}^{k=k_o} r_k \left[\sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{(1+i)} \right)^{l n_k} \right] \Bigg\} (1+i)^n \\ & + (\varepsilon E_{\mathrm{total}}) \Bigg\{ \frac{c_w}{\eta_{ss}} \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j \\ & + c_f \sum_{j=1}^{j=n} \left(\frac{(1+e_f)}{(1+i)} \right)^j \Bigg\} (1+i)^n. \end{aligned} \tag{10}$$

For the estimation of the energy production cost (€/kWh, in present values) of the entire energy storage installation one should divide the total cost of the installation (Eq. (10)) with the corresponding total energy production, i.e.

$$c_{ss} = \frac{C_{ss}}{\varepsilon E_{\mathrm{total}} \sum_{j=1}^{j=n} [(1+e)/(1+i)]^j (1+i)^n}, \tag{11}$$

where the electricity price escalation rate "e" should also be included. Note that an energy storage investment is financially attractive if the energy production cost value of Eq. (11) is less than the energy production cost of the existing thermal power stations. One should also take into account the additional benefits related to the ESS operation, due to the increased reliability of the entire electrical network and the improved quality of the electricity offered.

4. Application results

The developed evaluation model aims to determine the cost-effectiveness of incorporating a storage unit in an existing electrical network. In the current analysis the evaluation model is applied to two electrical systems differing in terms of scale, however described by similar master characteristics. To be more precise, the case studies investigated refer to two Aegean Sea islands, i.e. Donoussa and Lesbos (Fig. 3) islands, comprising a very small- and a large-scale isolated electrical grid, respectively. In Table 2 one may find the main parameters of the local networks to consider.

Both islands' electrical networks present similar operational characteristics, like the intense demand fluctuations on an annual basis, the quite narrow power security margin and the extremely high production cost [5] (especially the small island of Donoussa), mainly owed to the corresponding fuel consumption rates and the existing outmoded APS maintenance needs. If also considering the favorable wind and solar potential met in the specific areas, an additional reason for the investigation of adopting ESSs in collaboration with appropriate renewable based power stations appears.

Finally, by taking into account the potential installation of several ESSs and by examining various scenarios of the latter contribution (impact of "ε" parameter), also involving the levels of autonomy (impact of "d_o" parameter) supported by the selected storage units, the electricity production cost in a given electrical grid on the basis of the existing storage system may be calculated. To get a broader view of the systems' cost effectiveness against alternative productive methods however, one should also consider the input energy (necessary for the systems' charging) cost value "c_w" on the total electricity production cost of the

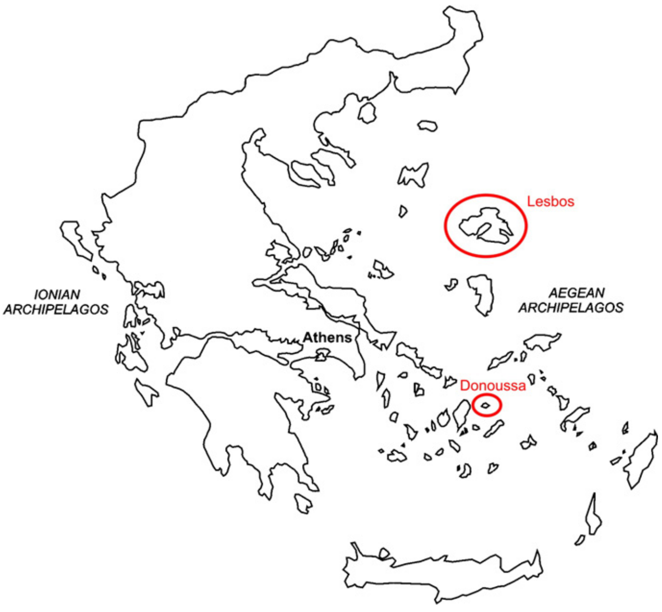

Fig. 3. Donoussa and Lesbos islands allocation.

Table 2
Main parameters of the Donoussa and Lesbos electricity systems

Island	Peak power demand (kW—2005)	Total annual energy consumption (MWh—2005)	RES-based power unit	Population (2001 census)	Area (km^2)
Donoussa	194	460	PV	166	14
Lesbos	60,000	246,000	Wind turbines	90,643	1630

entire installation. More precisely, in cases of high wind potential the input electricity cost is set equal to the corresponding wind park marginal production cost (0.05 €/kWh) [26], while for locations of excellent solar potential one may use the photovoltaic power stations marginal production cost (0.1 €/kWh) [27,28]. In any case, the impact of different input energy costs on the calculation results is examined using an appropriate parametrical analysis.

4.1. Lesbos island

Lesbos island is one of the largest Greek islands (area 1630 km^2, population 90,600), located in the northeastern part of the Aegean Sea. According to the available data, the electricity consumption of the island exceeds 250 GWh (2005), while the corresponding peak power demand approaches 60 MW. At the same time, the marginal electricity generation cost of the local thermal power station is almost 0.12 €/kWh, presenting a mean annual increase of the order of 5% [5]. On the other hand, the island possesses very high wind potential, i.e. in several places throughout the island the long-term average wind speed approaches 8.5 m/s, and significant solar potential, i.e. annual specific solar energy available equal to 1550 kWh/m^2. However, in an attempt of the local network manager to protect the local weak electrical system from unwanted instabilities and also maintain the necessary power quality, the contribution of wind energy and photovoltaics is limited, theoretically [6] up to 30% and practically [29] up to 15% on annual basis. This is not the case for the wind energy penetration in the strong interconnected electrical networks (e.g. Denmark), where the contribution of wind energy may approach 20% on an annual basis.

In this context, the only way to increase the RES penetration in the Lesbos island electrical system is to incorporate an appropriate ESS that shall guarantee the system stability and cover the energy demand in a scheduled way. Taking into consideration the quality of the local wind potential and the relative size of the island, the storage system contribution range currently recommended, even suggesting an annual participation of 20%, finally extends to an 80% proportion, i.e. $20\% \leqslant \varepsilon \leqslant 80\%$. According to the official data, the specific participation value means that the electricity provided to the consumption via the ESS annually ranges from 50 up to 200 GWh. Note that the above-mentioned energy amount can be produced by using wind parks (CF = 25%, $\eta_{ss} = 0.7$) of a rated power starting from 30 up to 120 MW. Currently, the already operating wind parks of the island are almost 10 MW, contributing almost 10% to the annual electricity consumption [30].

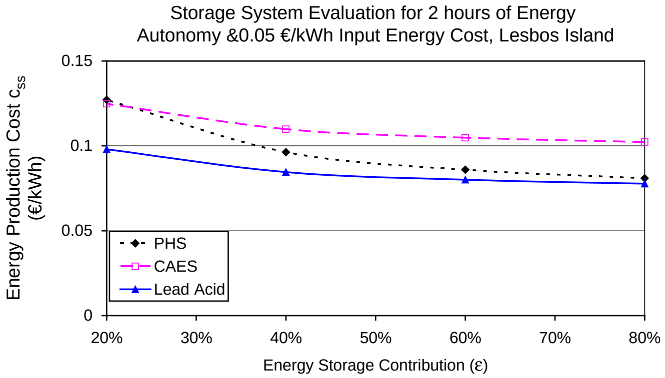

Fig. 4. Electricity production cost of selected energy storage systems, low system energy autonomy.

The systems selected to study comprise bulk ESSs and apart from the typical technologies of PHS and CAES, lead-acid batteries may also prove capable of supplying the necessary services in the electrical network of Lesbos. Due to the system's size and the storage system contribution percentage selected, the system energy autonomy range examined varies between 2 and 24 h, i.e. the energy storage capacity required varies between 16 MWh ($\varepsilon = 0.2$, $d_o = 2$ h) and 780 MWh ($\varepsilon = 0.8$, $d_o = 24$ h), while the peak power of the ESS should be equal to 70.5 MW ($\eta_p = 85\%$, $\zeta = 1.0$).

The first case analyzed concerns the electricity production cost of the energy systems under evaluation for low autonomy ($d_o = 2$), while the corresponding input energy cost is assumed equal to 0.05 €/kWh, a realistic value for typical wind parks of Lesbos [26]. According to the results obtained, even at low ESS contribution ($\varepsilon = 20\%$), the energy production cost is less than 0.1 €/kWh for the lead-acid batteries configuration (Fig. 4). In fact, for low autonomy cases ($d_o = 2$ h) the lead-acid batteries seem to be the most beneficial of the solutions examined, while "ε" varies between 20% and 80%. What should be noted though is the low-energy density of the lead-acid batteries, thus leading to the employment of a large area [31] and therefore not entailing a possible application benefit over the unconditionally bulk PHS and CAES.

As the autonomy values increase over 6 h, the PHS systems gradually become more attractive (Fig. 5), especially where "ε" approaches 40%. As in the previous scenario, the total energy production cost of the energy storage subsystem is lower than the current marginal production cost of the existing thermal power stations (i.e. 0.12 €/kWh). Only, for the very low ESS contribution ($\varepsilon = 20\%$) the lead-acid batteries show a lower cost than the PHS.

For greater autonomy encountered, the PHS systems show the most favorable rates in almost the entire energy production participation spectrum, as displayed in Figs. 6 and 7. In fact, PHS and CAES show no remarkable variation in relation to the autonomy increase (Figs. 6 and 7). On the other hand, the lead-acid batteries cost is strongly affected by the necessary duration "d_o" of energy provision called to satisfy. According to the results obtained, the CAES may only be considered in cases of low annual contribution ($\varepsilon = 0.2$) and significant autonomy (over 6 h) (see also Fig. 8). Taking into consideration the fuel impact, since CAES does not show a great deviation when compared with PHS rates, a fuel price decrease may lead to the former supremacy.

Subsequently, it is interesting to mention that a remarkable energy production decrease is encountered as the energy system annual contribution "ε" increases (Fig. 9). This decrease is stronger for PHS compared to CAES and lead-acid batteries.

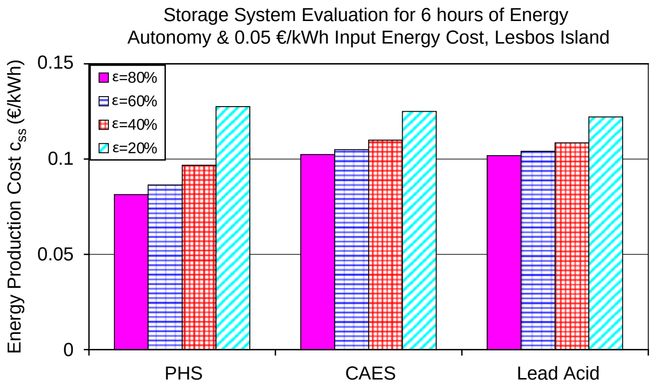

Fig. 5. Comparing the electricity production cost of selected energy storage systems, medium–low system energy autonomy.

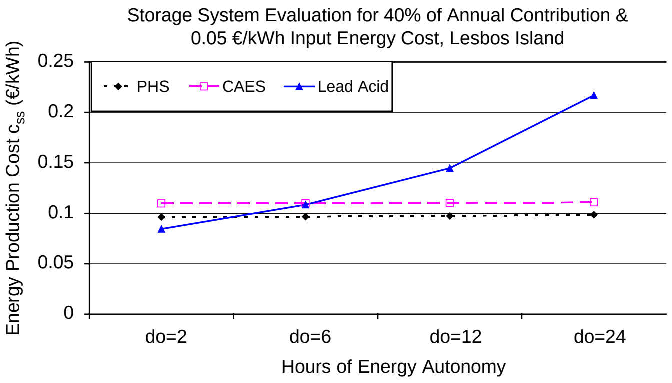

Fig. 6. Electricity production cost of selected energy storage systems for 40% annual energy contribution.

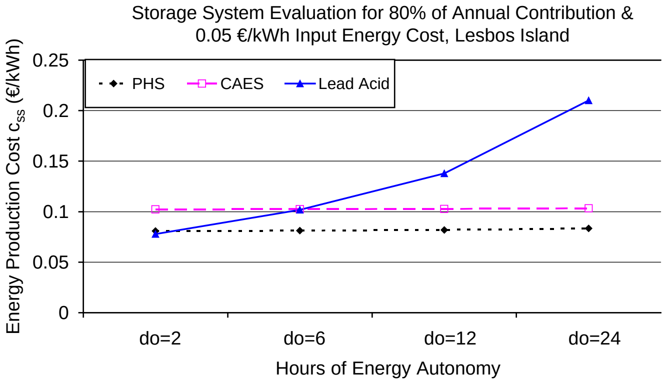

Fig. 7. Electricity production cost of selected energy storage systems for 80% annual energy contribution.

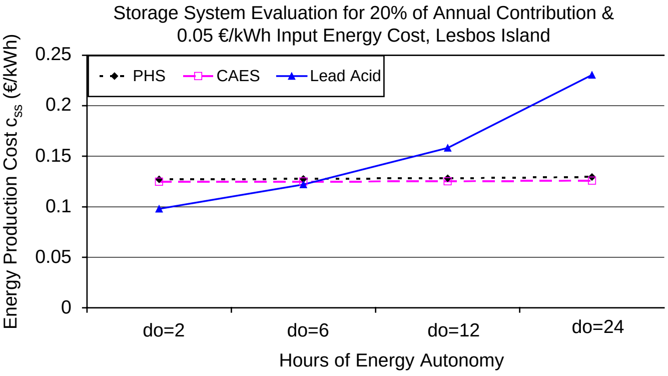

Fig. 8. Electricity production cost of selected energy storage systems for 20% annual energy contribution.

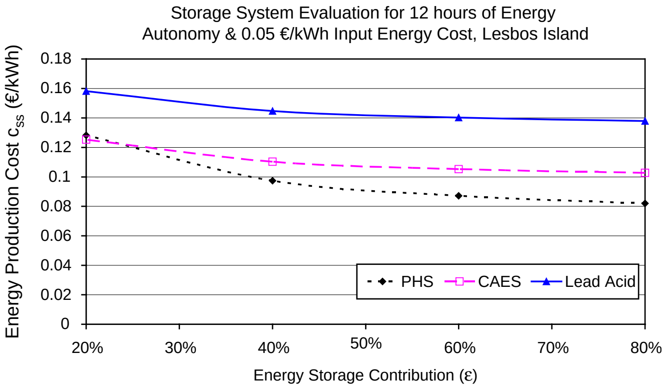

Fig. 9. The impact of the energy storage contribution on the electricity generation cost for medium system energy autonomy.

One of the main parameters influencing the energy cost of the ESS is the input energy cost value "c_w". Note that in cases of an existing pricing for the energy input, the cost of energy needed to charge each of the storage systems comprises the most important factor (see Fig. 10). According to the results demonstrated, the energy

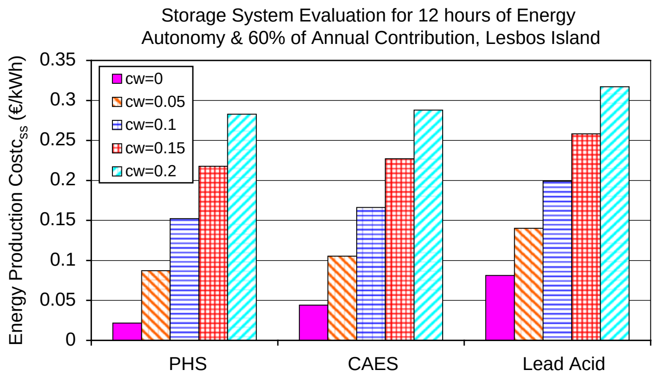

Fig. 10. The impact of the input energy price on the electricity generation cost of selected energy storage systems, Lesbos Island.

production cost for $c_w = 0$ (using the rejected excess energy production of an existing wind power installation is very low (i.e. 0.022 €/kWh for PHS, 0.044 €/kWh for CAES and 0.081 €/kWh for lead-acid batteries)). However, a significant energy production cost is encountered as "c_w" increases.

Finally, as far as the CAES is concerned, when the input energy cost is zero, the fuel contribution in the overall specific cost configuration is thought to be catalytic. More precisely, in the present analysis, the share of specific cost attributed to the necessary fuel consumption exceeds 50% at all times and may even reach 80% of the total electricity generation cost.

4.2. Donoussa island

The second case analyzed concerns the island of Donoussa which is located near the Naxos island (see also Fig. 3). To be more precise, the case study investigated refers to a tiny isolated electrical micro-grid, i.e. total annual electricity consumption of approximately 460 MWh and peak load demand of almost 194 kW. On the basis of the official data [5] available the corresponding electricity production cost approaches 460 €/MWh. In fact, Donoussa is a very small island (population 166 habitants—approximately 45 families—area of 14 km^2) where the main economic activities of the local society are fishing and tourism. The island has very good solar potential, since the annual mean solar energy approaches 1700 kWh/m^2, at horizontal plane, hence one may examine the possibility to meet the electricity demand of the local community on the basis of a photovoltaic power station in collaboration with an appropriate ESS [27].

Taking into account the quality of the available solar potential, the proposed photovoltaic-based system is expected (according to the hours of sunlight available and the corresponding load demand profile) to cover directly between 20% and 50% of the local electricity consumption. Therefore, the rest of load demand is left to be covered by existing internal combustion engines and the PV panels via the energy storage installation. In fact, the photovoltaic system if properly sized may—apart from the direct grid's partial needs—be able to cover the charging of the existing storage system. In this case, the energy storage subsystem can be employed in order to cover the rest of the consumption during the low (or zero) solar irradiance periods. Thus, the resulting contribution range of the corresponding ESS, as far as Donoussa is concerned, varies between 50% and 80%, i.e. $0.5 \leqslant \varepsilon \leqslant 0.8$.

With regard to the systems examined, the peak power met in the local network along with the expectation of a significant energy production provision, have both led to the exclusion of certain systems. The systems proposed for evaluation in such a small-sized electrical grid are certain types of conventional batteries (lead-acid and Na–S), hydrogen storage incorporating fuel cells (HS-FV), and the comparatively novel flow battery technology (Regenesys). Larger systems such as PHS and CAES are not examined since their viability depends strongly on the scale of the demands confronted [23,32]. The autonomy range undertaken suggests a minimum of 2 h and a maximum of 24 h to consider.

According to the results obtained regarding the Donoussa island, the following could be noted:

a. The most cost-effective solution appearing in cases of low-energy autonomy examined (Figs. 11 and 12), i.e. up to 20 h, is the Na–S batteries. If we also keep in mind the high rates of energy density describing the current technology, the Na–S batteries may actually comprise a favorable solution for the load management of the island. With regard to a higher autonomy scale (24 h) however, the Regenesys flow batteries do present a slight advantage (Fig. 13).
b. Taking into consideration the Na–S batteries' limited operation, owed to their moderate depth of discharge, and provided that a higher autonomy is the dominant criterion, Regenesys flow batteries should be preferred. It must be underlined though that these technologies are more suitable for larger applications and are currently

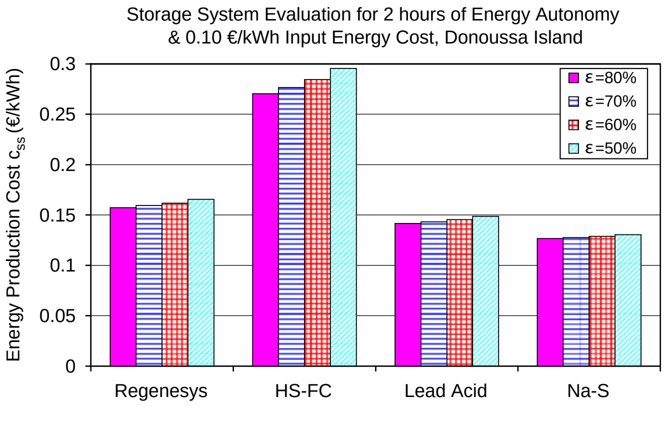

Fig. 11. Comparing the electricity production cost of selected energy storage systems, low system energy autonomy.

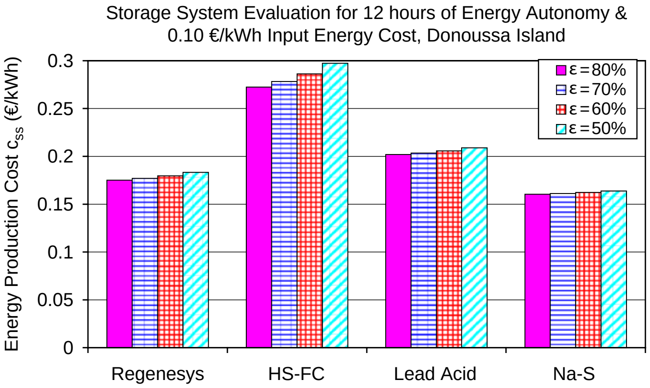

Fig. 12. Comparing the electricity production cost of selected energy storage systems, medium system energy autonomy.

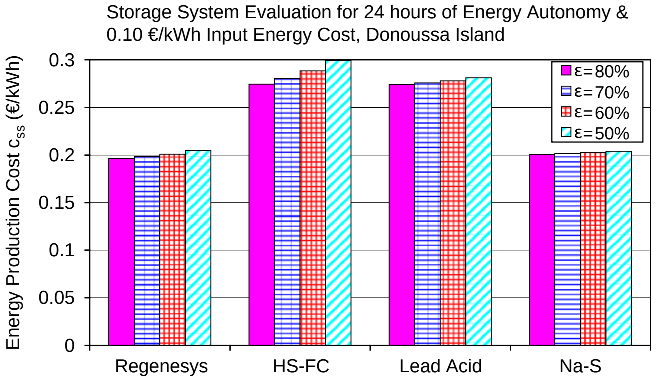

Fig. 13. Comparing the electricity production cost of selected energy storage systems, high system energy autonomy.

included so as to demonstrate their advantage over greater levels of autonomy.

c. In respect of the hydrogen storage (HS-FC), the non-promising results appearing for a few hours of autonomy tend to mitigate for a higher duration of discharge. In fact, if one extends the autonomy up to 24 h and for certain contribution percentages, the hydrogen storage coupled fuel cells may present one of the most attractive solutions to be considered [33].

d. Concerning the rest of the technologies investigated, it is clear that they have a similar behavior. What can be mentioned is the comparatively lower rate of cost increase presented by the lead-acid batteries. In an overall evaluation however, the specific systems should not be thought as promising solutions.

To somehow decode the behavior of each ESS against the parameters of energy contribution "ε" and autonomy "d_o", a parametrical analysis concerning the calculated relative cost values has been carried out (see Figs. 14 and 15). As noted, the hydrogen storage cost is not affected by the energy autonomy increase, while the rest of the systems show a remarkable cost increase (Fig. 14). Lead-acid batteries present the greatest cost increase while Regenesys are described by the corresponding mildest.

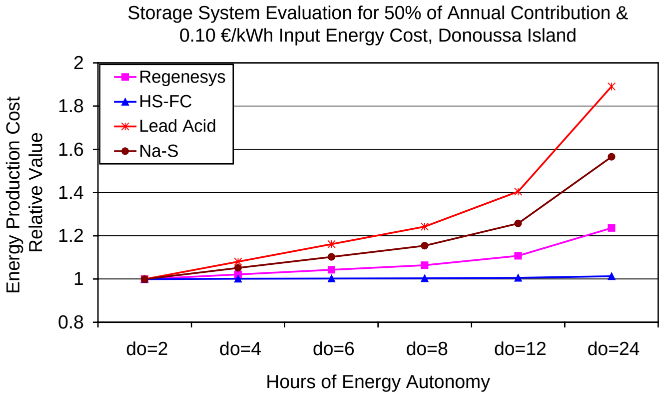

Fig. 14. The impact of energy autonomy hours on the relative electricity production cost for selected energy storage systems.

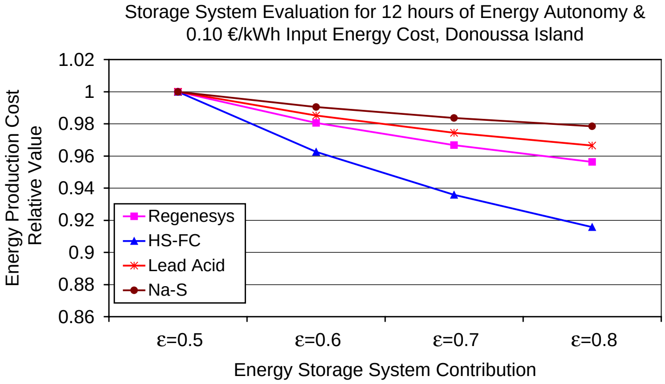

Fig. 15. The impact of energy storage contribution on the relative electricity production cost for selected energy storage systems.

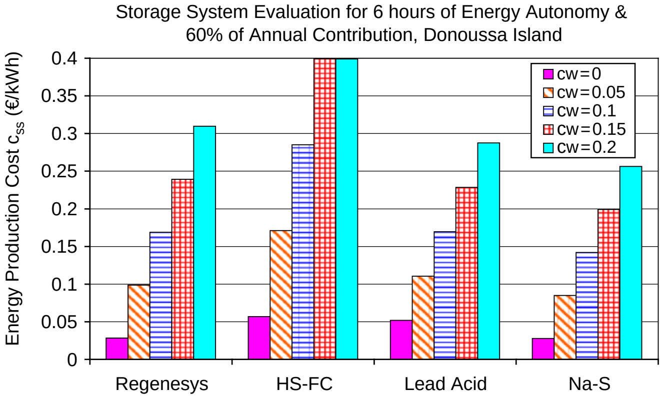

Fig. 16. The impact of the input energy price on the electricity generation cost of selected energy storage systems, Donoussa Island.

Regarding the energy contribution parameter "ε" effect, the opposite behavior may be encountered (Fig. 15). The systems presenting the most important variation of the relative cost value in the autonomy range are less influenced by the energy contribution factor. On the other hand, when the storage system is asked to cover a greater annual production share, hydrogen based and Regenesys systems demonstrate the most significant relative cost reduction.

Nevertheless, the determining factor of the cost variation is the input energy price achieved (see Fig. 16). Besides, for the two extreme scenarios of $\varepsilon = 50\%$, $d_\mathrm{o} = 24\,\mathrm{h}$, $c_\mathrm{w} = 0.05$ and $\varepsilon = 80\%$, $d_\mathrm{o} = 2\,\mathrm{h}$, $c_\mathrm{w} = 0.2$, the input cost parameter contribution to the final cost value ranges between 45% and 95% correspondingly, always depending on the system type.

5. Conclusions

In the present study, an integrated electricity production cost analysis for autonomous electrical networks based on RES and energy storage configurations is presented. The proposed analysis takes into consideration the initial cost of the energy storage equipment (based on the storage capacity and the corresponding nominal power), the input electricity and fuel costs, as well as the fixed and variable M&O cost of the entire installation.

Subsequently, the developed methodology is applied to two representative cases: one large and one very small isolated electrical micro-grid case, based on wind and solar potential exploitation respectively. Special attention is paid in order to demonstrate the effect of the selected ESSs' utilization on the electricity production cost value. Using the proposed model one may define the most appropriate configuration for each case investigated.

Keeping that in mind, the technologies of PHS, CAES and HS-FC do not seem to be limited by the selected autonomy level, while presenting attractive results of electricity production cost for higher levels of annual contribution. On the other hand, the rest of the technologies examined (i.e. conventional and flow batteries), although presenting a relative cost advantage in low autonomy cases, are strongly affected by the autonomy factor. Thus, by increasing the autonomy, an analogous increase of the systems' production cost is to be expected.

What seems to be the catalyst for the storage systems' viability is the input energy pricing, clearly determining the cost ascribed to the systems' implementation and—at the same time—underlining the need for achieving a satisfying price for the systems' charging. Excluding the scenario that the ESS uses the excess electricity production (not absorbed by the local network due to low demand and grid stability constraints), the input energy cost represents a considerable percentage (in practical cases up to 70%) of the total electricity production cost.

Recapitulating, according to the results obtained, a properly sized RES-based electricity generation station in collaboration with the appropriate energy storage equipment is a promising solution for the energy demand problems of numerous existing autonomous electrical networks, providing clean energy and contributing to the diminution of the important environmental problems resulting from the electricity generation sector.

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