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Comparing electricity storage technologies for small insular grids

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HIGHLIGHTS

- Pumped Storage, lead-acid and lithium-ion batteries are compared for small islands.
- Pumped Storage can support long autonomy operation period and secure energy supply.
- All systems can offer economically feasible solutions for small islands.
- A 90% drop in the lithium-ion batteries price can trigger investors' interest.
- Pumped Storage can be feasible for small islands under favorable land morphology.

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ABSTRACT

The objective of this article is to investigate the technically and economically optimum electricity storage technologies for small, insular, autonomous electrical grids, integrated with Renewable Energy Sources (RES) power plants. Three autonomous Greek islands are investigated as case studies: Symi, Astypalaia and Kastelorizo, with annual peak demand at 4.0 MW, 2.2 MW and 0.9 MW respectively. All three islands exhibit excellent wind and solar potential, with ideal sites for the installation of seawater Pumped Hydro Storage (PHS). Two different approaches are investigated, regarding the electricity storage plants: PHS systems (for the two largest islands) and electrochemical storage, alternatively realized with lead acid or lithium-ion batteries. Wind parks and photovoltaic stations are considered as the potential RES units. Relevant operation algorithms are introduced. The dimensioning of the examined plants is optimized with a common target: the achievement of RES annual penetration percentage higher than 70%, ensuring the investments' economic feasibility, with electricity selling prices lower than the existing specific production cost. Given the favorable land morphology for PHS installations, it is shown that wind-PHS still remains a competitive alternative for Symi and Astypalaia, despite their relatively small size, while for Kastelorizo, a wind-photovoltaic-batteries features as the optimum option. 100% annual RES penetration can be achieved only with the PHS support. With electrochemical storage systems, the RES annual penetration can be between 80 and 90%. The economic feasibility is ensured with electricity selling prices between 200 and 350 €/kWh. The investments' payback periods are estimated between 6 and 10 years.

1. Introduction

During the last two years there is a centrally organized effort by the European Commission to promote the Renewable Energy Sources (RES) penetration in European non-interconnected islands [1]. Non-interconnected islands always constitute a very sensitive field of electricity production and generation, particularly with RES power plants.

Specifically, in most cases, small islands do not have conventional energy resources available in their territory (oil, gas, coal), on which the guaranteed power production from thermal generators could be based. So, the electricity production is most commonly based on imported fossil fuels, affecting negatively the energy supply security of the insular system and contributing to the increase of the electricity production specific cost. This is further deteriorated due to the requirements for spinning reserve maintenance, to overcome the vulnerability of weak insular systems against any potential grid contingencies, precisely due to the lack of any electrical interconnections with mainland grids. On the other hand, the sensitive and of high environmental value insular ecosystems normally introduces several constraints on the technologies employed in the electricity production sector. Finally, in most cases, the high availability of RES potential, mainly wind and solar, in combination with the above insular features, favors the installation of electricity production technologies from RES.

However, the abundant RES potential often met in insular,

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autonomous electrical systems can be exploited up to a maximum level, defined by the system's dynamic security and stability requirements [2,3]. Increasing and secure introduction of wind and photovoltaic (PV) parks in autonomous insular grids requires their integration with electricity storage technologies, configuring, thus, the so-called "hybrid power plants" [4].

The study of hybrid power plants' alternative configurations and layouts constitutes one of the most popular topics in the relevant literature. Since the potentially available alternatives on the base production units, namely the RES technologies, are rather limited, the executed research is mainly focused on the hybrid power plants' operation algorithms and the employed electricity storage technologies.

Different operation algorithms are determined by the scope of the introduced hybrid power plant, which can be:

- the coverage of a remote electricity load profile, e.g. in a remote residential building, a lighthouse, a desalination plant, a stock farming unit etc [5–7];
- the maximization of the RES units penetration in an autonomous insular grid, satisfying some very specific, pre-defined dimensioning energetic or economic criteria; this approach is often met in the relevant scientific literature [8–14];
- the operation of the hybrid power plant for peak shaving or load shifting purposes [15–18].

On the other hand, the executed research also regularly examines different involved electricity storage technologies. The most frequently investigated electricity storage systems are the:

- Pumped Hydro Storage (PHS) systems
- Compressed Air Energy Storage (CAES) systems
- electrochemical storage technologies (batteries).

The selection of the optimum one from the above storage technologies is imposed by the peculiarities and the conditions met in each investigated insular territory and the corresponding electrical system. For example, PHS is doubtlessly the most technically mature and economically competitive electricity storage technology, with hundreds of plants already installed and under operation worldwide, offering a huge technical awareness and practical experience. Particularly for insular autonomous electrical systems, PHS has been proved to be the optimum choice for medium and large size systems, with power demand higher than 5 MW [19–24]. This is due to the essential required infrastructure and the corresponding high set-up costs, which require a certain electricity consumption, normally available in medium and large electrical systems, in order to ensure the project's feasibility. In such cases, the set-up specific cost of the PHS system can be as low as 30 €/kWh of storage capacity [9], a figure that cannot be even approached by any other electricity storage technology. PHS also constitutes the unique storage technology which can offer energy storage capacities at the range of GWh or even TWh [25]. However, the above favorite features can be available on the condition of available sites with appropriate land morphology, which should comprise already existing couples of water natural reservoirs or flattened plateaus easily configured as artificial lakes, at adequate height difference between them and mild orography slopes.

In cases of absence of favorable land morphology or of electrical systems of small size (annual peak demand lower than 1 MW), Compressed Air Energy Storage systems of small size (micro CAES) [26–28] or electrochemical storage [11–31] feature as the most feasible options. Generally CAES systems exhibit the major drawback of the thermal power disposal during the air compression stage, which implies the necessity for the heating of the compressed air, most commonly by using fossil fuels, before expansion. This, on the one hand imposes significantly reduced storage cycle efficiency (at the range of 50%), while, on the other hand, requires the availability and the consumption of an exhaustible, conventional energy resource. The latter may not constitute a crucial issue in cases of domestic available fossil fuels in the insular territory. However, this is not the generally met case. Finally, the option of adiabatic CAES currently still remains under research, exhibiting significantly increased set-up costs and major technical difficulties [32,33].

Electrochemical storage offers a variety of alternative technologies, with the most economically competitive being the lead-acid batteries, while the most promising one is by far the lithium-ion batteries. In general, all electrochemical storage technologies exhibit quite high average storage cycle efficiency (at the range of 80–90%), however, they are characterized with relatively short life periods and high procurement cost, which becomes even higher for the whole life period of a hybrid power plant, due to the batteries' required replacements. For example, during the 20-year life period of a hybrid power plant, lead-acid batteries with 7-year life period should be replaced twice.

For insular, non-interconnected electrical systems with annual peak demand between 1 and 5 MW there is a grey zone, regarding the selection of the optimum storage technology, which depends strongly on particular features and characteristics met in the insular system (seasonal fluctuation of the power demand, available RES potential, availability of appropriate land morphology for PHS installation, availability of cheap fuel required for the operation of a micro-CAES system). For example, in cases with favorable land morphology, PHS systems can be feasible even in such small systems, despite their relatively high set-up cost, and vice-versa. Hence, a definite choice of the optimum storage technology for insular systems of this particular size is not possible, since this issue is highly "case-specific".

This article focuses on the investigation of the optimum storage technologies particularly on autonomous insular systems with annual peak demand from 1 to 5 MW, availability of high wind potential and solar radiation, availability of favorable land morphology for PHS installation and current electricity production specific cost higher than 0.25 €/kWh, mainly configured by the cost of imported fossil fuels consumed in local, autonomous thermal power plants. Such islands are most frequently met in the Aegean and the Mediterranean Sea, and not only. For these islands, the article's objective is to indicate the optimum storage technology, integrated with a RES power plant (wind park and/or photovoltaic stations), aiming, through the appropriate dimensioning, at secure RES annual penetration percentage higher than 70% versus the annual consumption, ensuring, also, the economic feasibility of the required investments with electricity selling prices lower than the existing electricity production specific cost from the local autonomous thermal power plants.

The above set objective constitutes the article's contribution to the existing state of the art on the topic of hybrid power plants' configuration for small size insular systems. Currently there is not any former work focusing on the comparative evaluation of the main alternative available storage technologies for hybrid power plants with nominal power lower than 5 MW, based on the above set criteria, namely the achievement of high and secure RES penetration, ensuring the project's economic feasibility with competitive electricity selling prices. This comparison emerges for insular territories with appropriate land morphology for PHS installation, which favor the introduction of this storage technology, even for small insular systems. The work presented in this article covers precisely this gap of the existing literature, highlighting decision parameters and potential results on the available options for the optimum electricity storage technology.

The above tasks are realized with two case studies for the Greek non-interconnected islands of Symi and Astypalaia, with annual peak demand at 4.0 MW and 2.2 MW respectively. In these two islands, alternative hybrid power plants' layouts with PHS or electrochemical storage technologies are investigated. Furthermore, for integration and comparison reasons, a third case study is also implemented for the easternmost Greek island of Kastelorizo, with annual peak demand at 0.9 MW. Due to the small size of this third island, only electrochemical

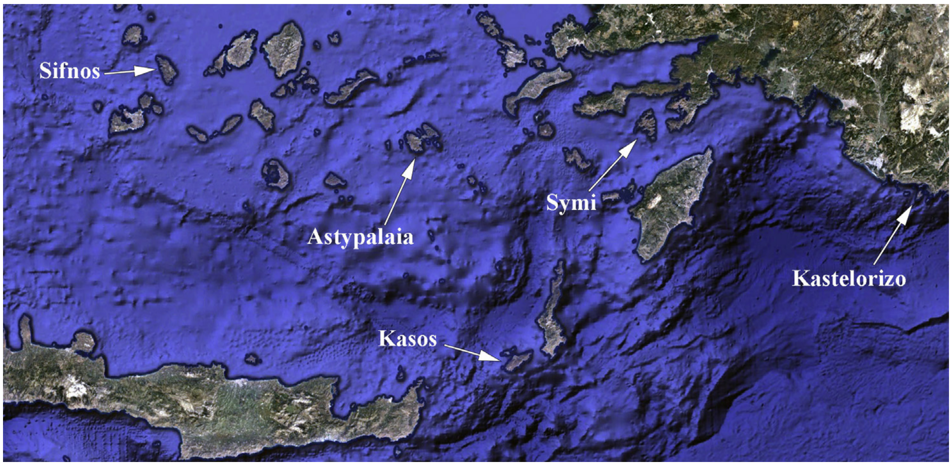

Fig. 1. The locations of the investigated islands in the Eastern Aegean Sea, Greece.

storage technologies are considered as potential storage components. Given the lack of any domestic fossil fuel in the under consideration islands, the CAES technology was not examined.

The above three islands have been announced as potential pilot islands for hybrid power plants' installations by the Greek Operator for autonomous insular systems. Consequently, this article also intends to constitute a first techno-economic documentation, in order to facilitate the potentially interested parties, by indicating basic prerequisites and parameters for the technical and economic feasibility of alternative available hybrid power plants' configurations.

2. The investigated insular systems

2.1. Existing power demand

Symi, Astypalaia and Kastelorizo are three small islands, all of them located in the eastern Aegean Sea (Dodecanese Complex, Greece), with permanent populations of 2590, 1330 and 498 inhabitants respectively. Their positions on the map are depicted in Fig. 1. In the same Figure, the islands of Sifnos and Kasos are also depicted, at which the employed wind potential measurements in this study were recorded, as described in Section 2.2.

The insular economy in these three islands is almost exclusively based on tourism. It is estimated that more than 90% of the annual gross income in the islands comes from activities directly or indirectly related to tourism. The tourist period in the islands lasts from June to September, with the peak season being from July to August. During the peak tourist season, the total population in the islands can be five times higher than the permanent [34]. This intensive seasonal variation of the executing activities and the population sensibly leads to a corresponding fluctuation of the power demand, as clearly depicted in Fig. 2.

All three islands are non-interconnected electrical systems. The electricity demand of each island is covered by autonomous thermal power plants (one for each island), equipped exclusively with diesel generators, operating with imported diesel oil, with a final procurement price (including taxes, rates etc) usually above 0.90 €/l, depending heavily on the international oil prices. Apart from some distributed photovoltaic stations of small size, most commonly installed on residential buildings' roofs under net-metering mode (annual electricity production – consumption compensation), no centralized RES power plants are involved in the electricity production sector in any of these islands.

The dynamic security and the stability in the three examined weak insular systems is usually approached with the maintenance of spinning reserve. This fact, combined with the significantly high procurement price of the consumed fossil fuel, results to remarkable increase of the electricity production annual, average specific cost. This feature, as derived by official data published by the grids' operator (HEDNO) [35], is presented in Table 1, along with some fundamental features of the annual electricity demand in the investigated islands. It must be underlined that the electricity production specific cost presented in Table 1 comprise both the fixed and the varied production cost. The fixed production cost is related to all permanently existing costs, regardless the thermal power plants' operation, such as the scheduled maintenance of the generators, the staff salaries, the equipment amortization etc. The varied production cost is related exclusively to any costs arisen directly from the generators' operation, which are basically the fuel procurement cost and any additional unscheduled maintenance, due to faults and damages.

Beyond the high electricity production specific cost, critical drawbacks of the existing power production sector in the investigated islands are also:

- the fact that the electricity production is based on imported, exhaustible energy resources, which, practically eliminates any sense of energy independency and security supply in the islands
- the impacts on the aesthetics and the natural environment in the small, sensitive insular ecosystems.

The extremely high electricity production specific cost, as evidently revealed in Table 1, and the above parameters, create the essential prerequisites for the economic feasibility of the introduction of hybrid power plants in these islands. Yet, another crucial parameter, is the availability of adequate RES potential, capable to support abundant electricity production for the current and future energy needs in the islands. This is examined in the next section.

2.2. The available RES potential

All Aegean Sea islands exhibit high wind potential and, naturally, solar radiation. Wind potential measurements with annual, average wind velocity higher than 10 m/s are usually recorded, while a value of 8.5 m/s is considered certain in most cases [36–44,31,32]. On the other hand, the annual global irradiation is higher than 1900 kWh/m^2 in the Greek insular region [45,46]. For the scope of this article, due to the lack of wind potential measurements captured at the geographical territory of the investigated islands, annual time series of average hourly wind data (velocity magnitude and direction) were used from certified annual wind potential measurements executed by three wind masts, installed in the west coast of Turkey (9.5 n.m. east of Symi) and in the islands of Sifnos (88 n.m. west of Astypalaia) and Kasos (137 n.m. southwest of Kastelorizo). These data sets were employed for the wind

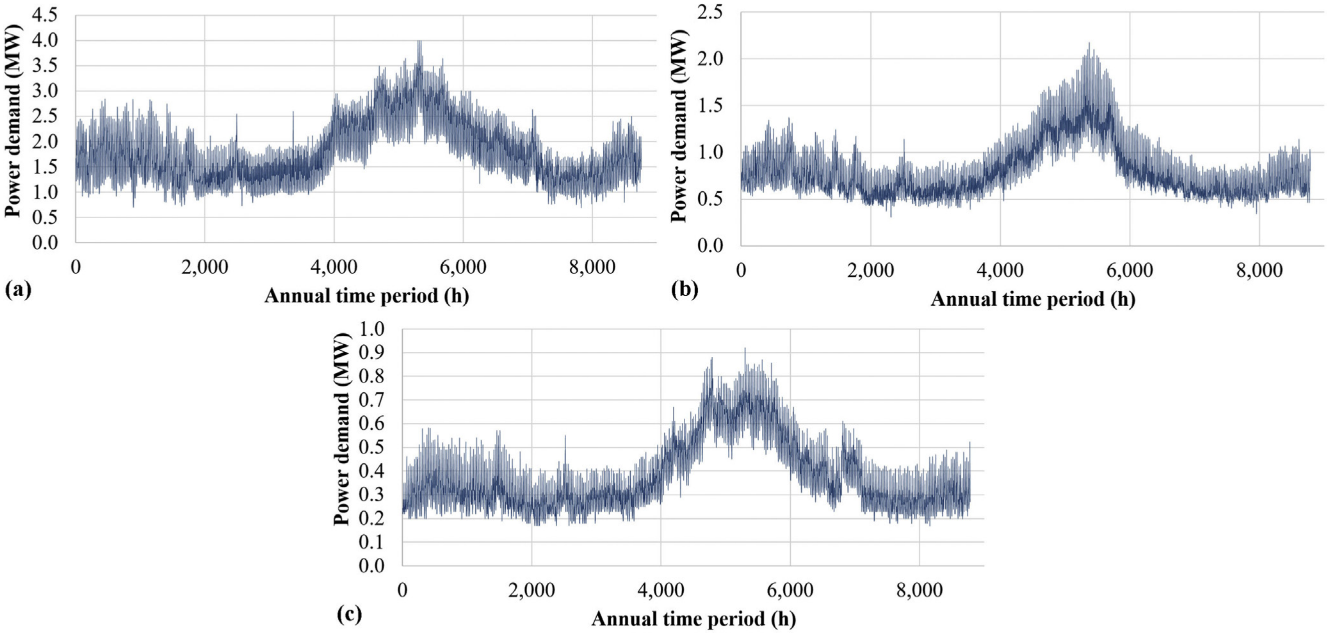

Fig. 2. Annual power demand time series in (a) Symi, (b) Astypalaia and (c) Kastelorizo in 2012.

Table 1
The fundamental features of the existing power demand in the investigated insular systems (2012).

Magnitude	Symi	Astypalaia	Kastelorizo
Annual electricity consumption (MWh)	15453.34	6999.73	3219.38
Annual peak demand (MW)	4.00	2.17	0.92
Annual average daily consumption (MWh)	42.34	19.18	8.82
Electricity production total specific cost (€/MWh)	386.36	424.15	492.94

potential evaluation for the islands of Symi, Astypalaia and Kastelorizo respectively. The use of these wind data sets can be considered secure, given the generally similar land morphology and climate conditions in the examined region.

In Fig. 3, the monthly average wind velocity fluctuation is depicted, based on the available annual wind measurements from the above mentioned locations. In the same figure, the annual fluctuation of the total incident solar irradiation on the horizontal plane is also plotted, based on measurements captured from the island of Samos, located also in the Eastern Aegean Sea, 85 n.m. north of Symi.

The high RES available potential is characteristically documented in Fig. 3, with monthly average wind velocities higher than 10 m/s. Nevertheless, what is even more important, is the high wind velocity observed during the summer months, especially in July and August, namely during the peak power demand period. For example, it is seen that the monthly average wind velocity is close to 11.5 m/s and 14 m/s in July and August respectively for the island of Kastelorizo and close to 12 m/s and 9.5 m/s for the island of Astypalaia in July and August respectively. This time coincidence between the peak power demand period and the high wind potential availability period is normally anticipated to considerably facilitate the achievement of high annual RES penetration percentages in these islands with the introduction of the hybrid power plants.

The same favorable time coincidence is also observed with incident solar radiation, which is normally maximized during summer. Incident solar radiation on horizontal plane often exceeds 1000 W/m^2, offering an alternative power source for days of low wind speeds, which, regularly, coincide with heat waves periods, which, in turn, lead to the maximization of the power consumption, due to the increasing use of indoor space conditioning systems.

The employed annual wind velocity and solar radiation time series are presented in Fig. 4. The wind velocity annual time series with hourly average values were retrieved by 10-min average certified wind

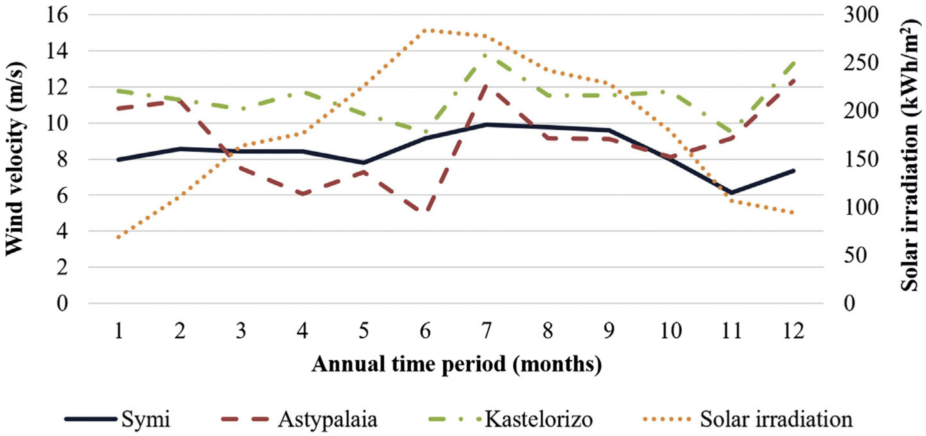

Fig. 3. Monthly average values of the employed wind and solar potential measurements for the investigated islands.

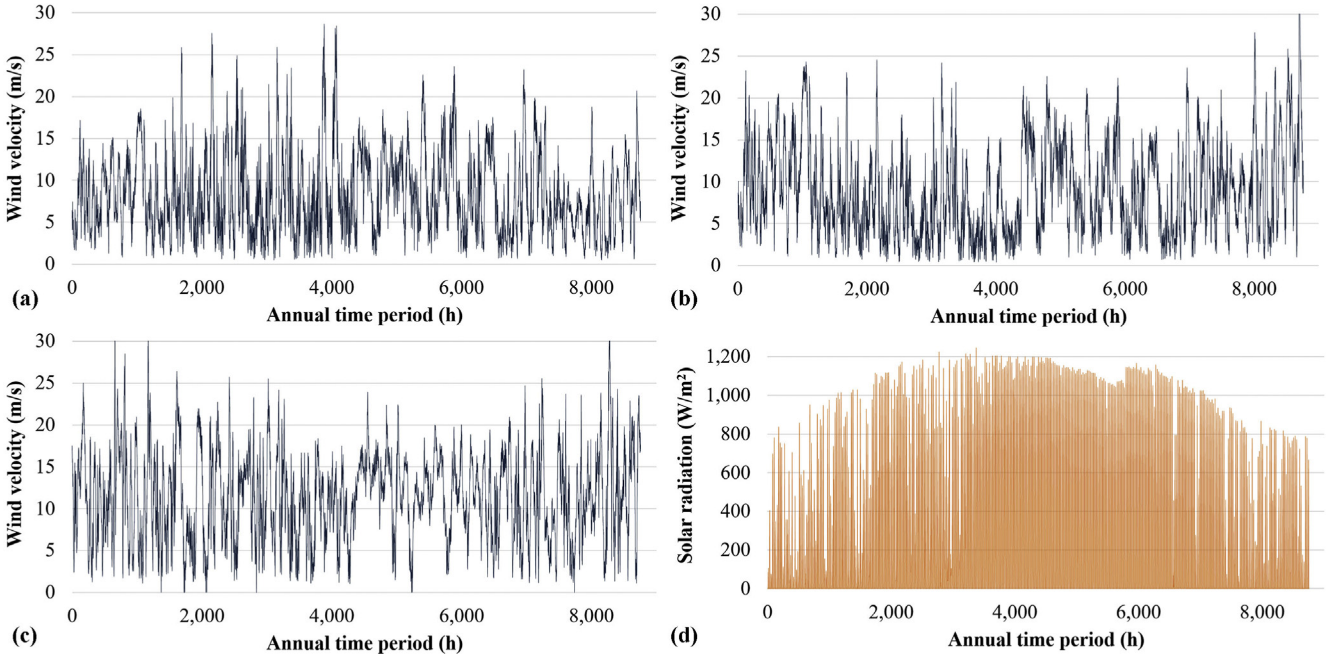

Fig. 4. Annual time series of the employed wind velocity measurements for the island of (a) Symi, (b) Astypalaia, (c) Kastelorizo and (d) annual solar radiation time series employed for all the investigated islands.

measurements, captured in Kasos from December 2010 to May 2012 (18 months measurement period) and in Sifnos from May 2016 to September 2017 (17 months measurement period). As mentioned above, these measurements were respectively used for the wind power production simulation in Kastelorizo and Astypalaia. Particularly for the wind potential measurements from Turkey, only monthly average wind velocity values were available for one year. The annual time series in this case was developed arithmetically, with linear interpolation with the wind potential measurements from Sifnos. It was utilized for the island of Symi.

To conclude with, the remarkably high wind potential and solar radiation and the existing problematic conditions regarding electricity production in the insular systems (high production cost, low energy supply security, environmental impacts), set the favorable background for the introduction of technically and economically feasible hybrid power plants in these insular systems.

3. The introduced hybrid power plants

Two alternative hybrid power plants' configurations are examined for the islands of Symi and Astypalaia. The main difference of the two alternative introduced layouts lays on the employed storage technology. In the first examined layout, a PHS system is introduced, while in the second one, lead-acid or lithium-ion batteries are alternatively examined, given that the lead-acid batteries still exhibit by far the lowest procurement cost, while the lithium-ion batteries feature as the most promising batteries' technology for the forthcoming years. Wind parks and/or photovoltaic stations are investigated as potential RES units.

In both systems, the RES units (wind park and photovoltaic station) are allowed to directly penetrate in the electrical grid up to a maximum percentage, due to security and stability reasons. In case of the PHS systems, the direct RES power penetration percentage is kept at 40% maximum, versus the current power demand, for dynamic security reasons. The remaining RES power production is provided for the PHS system (pumps) to be stored. The dimensioning of the system should ensure that there will always be enough water stored in the PHS reservoirs to enable continuous power production from the hydro turbines, to cover the remaining power demand (which will at least be equal to 60% of the initial power demand).

In case of electrochemical storage technologies, the RES direct penetration percentage can be as high as 100%, due to the immediate response of the electrochemical batteries, after a potential power production loss, through their bidirectional inverters. This high RES direct penetration percentage actually constitutes a necessity for the fulfilment of high annual RES penetration percentage, given the low storage capacity offered by the electrochemical storage technologies, which will be documented below.

The PHS systems should be constructed with double penstocks, while an adequate number of independent batteries strings, indicated by the dimensioning process, should be developed, in order to enable the concurrent charge and discharge process of the storage technology, maximizing the flexibility of the hybrid power plant.

The two PHS systems were accurately sited in digitized map terrain and all the required volumetric calculations were computationally executed. Ideal sites were found for both islands for the upper reservoirs' installation, with absolute altitudes at 440 m and 330 m for Symi and Astypalaia respectively, located close to the sea coast, with mild mountain slopes towards the coast, enabling the on-ground installation of the penstocks, avoiding, thus, the expensive tunnel constructions and underground installations. Finally, the mild available coastline morphology in both sites will also enable the construction of the hydro power plant and the pump station with the minimum possible land configuration, contributing to further set-up cost reduction. Based on the experience and the gathered data from similar works implemented by the authors, the total PHS specific set-up cost for these particular investigated islands should be estimated at the range of 3000 €/kW of installed hydro turbines' power [4,8,9,19,47]. Both PHS systems will operate with seawater, pumped directly from the sea, given the inadequate potable water quantities available in the insular territories from natural rainfalls. More technical details on the design and siting of seawater PHS systems are provided in [47]. A 3D representation of the PHS siting in the two investigating systems is provided in Fig. 5. Also, in Table 2, some essential technical features of the two PHS systems are also presented, as calculated by the computational volumetric calculations, executed on the digitized maps. Based on the

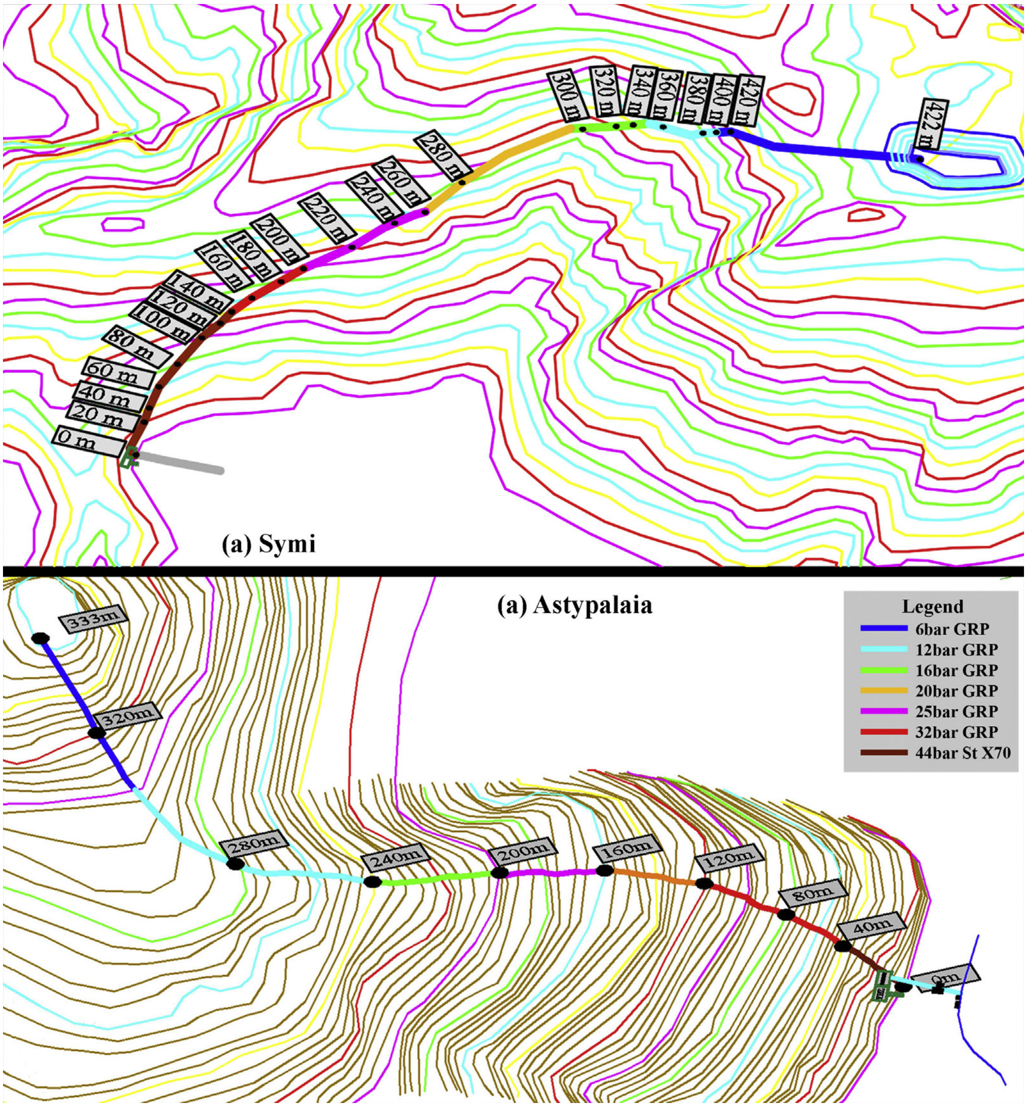

Fig. 5. 3D representation of the PHS systems siting on the digitized map for the island of (a) Symi and (b) Astypalaia.

Table 2
Characteristic features of the PHS systems.

Feature	Symi	Astypalaia
Total reservoir volume (m^3)	693,922	269,238
Reservoir effective volume (m^3)	663,216	255,648
Minimum remaining volume in reservoir (m^3)	30,706	13,590
Reservoir's free upper surface (m^2)	59,903	30,503
Inner reservoir's total surface (m^2)	62,285	31,676
Absolute altitude of reservoir's upper surface (m)	440	348
Absolute altitude of reservoir's bottom surface (m)	420	333
Maximum reservoir's depth (m)	20	15
Total achieved energy storage capacity (MWh)	715.5	367.8
Penstock length (m)	2555	1485

experience and the gathered data from similar works implemented by the authors, the total PHS specific set-up cost for these particular investigated islands should be estimated at the range of 3000 €/kW of installed hydro turbines' power [4,8,9,19,47].

In both cases, the wind turbines or the photovoltaic panels are sited either around the upper reservoir shore (Astypalaia), or in a neighboring mountain ridge (Symi), eliminating, thus, several infrastructure set-up costs (connection grids, new access roads etc).

Finally, for the island of Kastelorizo, only a wind, PV and electrochemical storage plant will be studied. This is because of the small size of this insular system, due to which the relatively high infrastructure set-up cost of the PHS systems (reservoirs, hydrodynamic machines facilities, penstocks), cannot be compensated in case the plant is exclusively utilized for energy storage.

4. Methodology

Following the analysis presented in the previous section, two different hybrid power plants' layouts are investigated for the two largest islands, the one of them with two alternative batteries technologies, namely:

- 1st investigated layout:
  - RES units: wind park – photovoltaic station
  - Storage unit: PHS system
- 2nd investigated layout:
  - RES units: wind park – photovoltaic station
  - Storage unit: electrochemical storage devices, either lead acid or lithium-ion batteries.

It is conceivable that for each one of the two largest islands, in total three alternative hybrid power plants' layouts are examined, one of them supported by a PHS system and the other two by electrochemical storage, alternatively lead acid or lithium-ion batteries.

Additionally, for the smallest island of Kastelorizo, the latter of the above layouts is also examined, again with the two alternative batteries technologies. In total $2 \times 3 + 2 = 8$ different hybrid power plants' configurations are examined and optimized for all the three insular systems under consideration.

The overall methodology is based on the computational simulation of the hybrid power plants' annual operation, with hourly calculation steps. To this end, the annual time series of average hourly values for the following involved magnitudes were introduced:

- The power demand: the data provided by the insular system's operator presented in Fig. 2 are employed.
- The potential power production from the involved RES technologies. This set of data is retrieved from the available annual wind velocity and solar radiation time series, presented in Fig. 3, the power curves of the introduced wind turbine models and the essential calculation methodology of the power production from photovoltaic stations [48,49]. For the island of Symi, due to its larger size, a 2.3 MW wind turbine was selected, while for the other two investigated islands, a 900 kW wind turbine was introduced.

The simulation is executed with software applications developed by the authors on the realization of the operation algorithms presented in the following subsections.

4.1. Operation algorithm of hybrid power plants with PHS systems

The operation algorithm of hybrid power plants supported by PHS systems and aiming at 100% annual R.E.S. penetration is analyzed in the following steps:

1. For each calculation time step, the total available power production from the RES units P_{RES} and the current power demand P_d are introduced. The maximum RES direct penetration percentage versus the power demand p_{max} is defined at 40%.
2. The RES direct penetration P_{RESp} is calculated from the following relationships:
   a. If $P_{RES} > p_{max} \cdot P_d$, then $P_{RESp} = p_{max} \cdot P_d$.
   b. If $P_{RES} \leq p_{max} \cdot P_d$, then $P_{RESp} = P_{RES}$.
3. Once the R.E.S. direct penetration has been defined, there will be:
   a. a potential R.E.S. power production surplus: $P_{RES} - P_{RESp}$
   b. a remaining power demand still uncovered: $P_d - P_{RESp}$.
4. The water volume V_p is then calculated, required to be pumped in the PHS upper reservoir, in order to store the power surplus $P_{RES} - P_{RESp}$, available for the duration t of the calculation step (H_p the available net pumping head, γ the water's specific weight, η_P the pump units average overall efficiency during the current calculation time step):

$$V_p = \frac{(P_{RES} - P_{RESp}) \cdot t \cdot \eta_p}{\gamma \cdot H_p} \tag{1}$$

5. Similarly, the water volume V_h is calculated, required to be removed from the PHS upper reservoir, so as the remaining power demand $P_d - P_{RESp}$ will be produced by the hydro turbines for the duration t of the calculation step (H_T the available water falling net head):

$$V_h = \frac{(P_d - P_{RESp}) \cdot t}{\gamma \cdot H_T \cdot \eta_h} \tag{2}$$

6. The remaining water volume stored in the PHS upper reservoir after the end of the current calculation time step j will be:

$V_{st}(j) = V_{st}(j-1) + V_p - V_h$.

7. The remaining water volume $V_{st}(j)$ in the PHS upper reservoir is checked whether it exceeds or not the reservoir's maximum storage capacity V_{max}:
   a. If $V_{st}(j) > V_{max}$, then:
      $P_h = P_d - P_{RESp}$
      $P_{th} = 0$
      $P_{st} = 0$
      $P_{rej} = P_{RES} - P_{RESp}$
      $V_{st}(j) = V_{st}(j-1) - V_h$.

where P_h the power produced by the hydro turbines, P_{th} the power produced by the thermal generators, P_{st} the power absorbed by the pump units and P_{rej} the R.E.S. units rejected power.

b. If $V_{st}(j) \leq V_{max}$, then we proceed to the following step.

8. The remaining water volume $V_{st}(j)$ in the PHS upper reservoir is checked whether it is lower or not than the minimum water volume V_{min} which always remains stored in the reservoir, mainly due to constructive reasons (e.g. due to the position of the water's intake):
   a. If $V_{st}(j) < V_{min}$, then:
      $P_h = 0$
      $P_{th} = P_d - P_{RESp}$
      $P_{st} = P_{RES} - P_{RESp}$
      $P_{rej} = 0$
      $V_{st}(j) = V_{st}(j-1) + V_p$.
   b. If $V_{min} \leq V_{st}(j) \leq V_{max}$ then:
      $P_h = P_d - P_{RESp}$
      $P_{st} = P_{RES} - P_{RESp}$
      $P_{th} = 0$
      $P_{rej} = 0$
      $V_{st}(j) = V_{st}(j-1) + V_p - V_h$.

The above described operation algorithm in graphically presented in Fig. 6.

4.2. Operation algorithm of hybrid power plants with electrochemical batteries

The operation of hybrid power plants supported by electrochemical batteries follows the algorithm presented below. For every calculation time step j the following tasks are executed:

1. It is reminded that the RES direct penetration percentage is set at 100%. This implies that the RES direct penetration is determined as:
   - If $P_{RES} \leq P_d$, then: $P_{RESp} = P_{RES}$.
   - If $P_{RES} > P_d$, then: $P_{RESp} = P_d$.
2. The charge level $b_i(j-1)$ is checked for all the electrochemical battery strings, as configured from the previous time step j-1. The subscript i designates the number of each battery string (i = 1, 2, 3, …). The following sub-cases are distinguished:
   - $P_{RES} \leq P_d$:

If there is enough energy stored in the batteries, namely if:

$$\sum_i b_i(j-1) \cdot C_{bati} - t \cdot (P_d - P_{RESp}) \geq \sum_i (1 - d_{dis}) \cdot C_{bati}$$

then the power production deficit is covered by the storage unit: $P_{bat} = P_d - P_{RESp}$. The power production from the back-up units (diesel generators) is null.

The new charge level for each battery string is: $b_i(j) = b_i(j-1) - P_{bati} \cdot t / (\eta_{disi} \cdot C_{bati})$

where P_{bati} and η_{disi} the discharge rate and efficiency respectively of the batteries string i during the discharge process. Obviously it is:

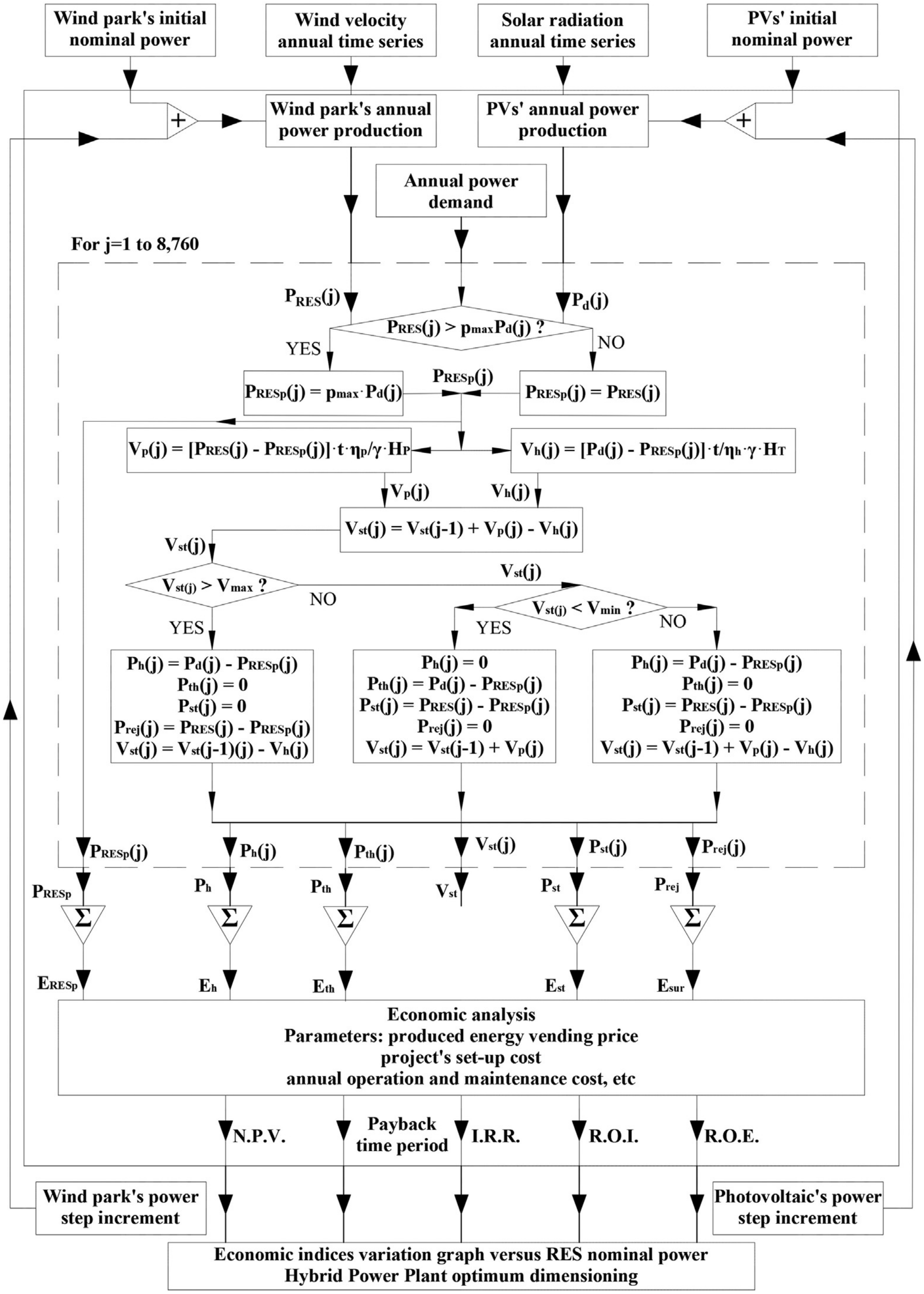

Fig. 6. Operation algorithm of a hybrid power plant with a PHS system as storage unit.

$$P_{bat} = \sum_{i=1}^{n} P_{bati}$$

where n is the total battery strings number.

If there is not enough energy stored, namely if:

$$\sum_{i} b_i(j-1)\cdot C_{bati} - t\cdot(P_d - P_{RESp}) < \Sigma(1-d_{dis})\cdot C_{bati}$$

the storage units power production will be restricted by their maximum discharging level. In this occasion it will be:

$$P_{bat} = \sum_{i} \{[b_i(j-1) - (1-d_{dis})/\eta_{disi}]\cdot C_{bati}\}/t$$

where C_{bati} the total storage capacity of the batteries string i, d_{dis} the batteries maximum discharge percentage (e.g. 60%) and t the calculation time step duration.

The new charge level for all the battery strings will be equal to their minimum required charge level: $b_i(j) = 1 - d_{dis}$.

The power production from the thermal generators P_{th} after the batteries contribution is:

$$P_{th} = P_d - P_{RESp} - P_{bat}.$$

The power storage P_{st} will be null.

- $P_{RES} > P_d$:

If there is enough storage space, namely if:

$$\sum_{i} [1 - bi(j - 1)]\cdot Cbati + t\cdot(PRES - PRESp) \leq Cbat$$

the RES power production surplus will be stored in the battery strings: $P_{st} = P_{RES} - P_{RESp}$. The new charge level for the battery strings will be:

$$b_i(j) = b_i(j - 1) + \eta_{chi}\cdot P_{sti}\cdot t/C_{bati}$$

where P_{sti} and η_{chi} the charge rate and efficiency for the battery string i. Obviously it is:

$$P_{st} = \sum_{i=1}^{n} P_{sti}$$

If there is not enough storage space to store the RES production surplus, namely if:

$$\sum_{i} [1 - bi(j - 1)]\cdot Cbati + t\cdot(PRES - PRESp) > Cbat$$

then the stored power of each battery string will be restricted by its storage capacity. The total storage power will be:

$$Pst = \sum_{i} [Cbati - bi(j - 1)\cdot Cbati\cdot \eta chi]/t$$

In that case, the charge level for the battery strings will be equal to their storage capacity.

The RES power production surplus will be:

$$P_{RESsur} = P_{RES} - P_{RESp} - P_{st}.$$

The above described operation algorithm in graphically presented in Fig. 7.

The computational simulation process was iteratively executed, so as alternative dimensioning scenarios were examined for each one of the examined layouts, varying the installed power of the involved RES power plants and the storage capacity of the storage plants. The target was to conclude to the optimum dimensioning of each examined system for each insular grid, aiming at annual RES penetration percentage at least higher than 70%, approaching ultimately 100%, optimizing, at the same time, the economic feasibility of the investments, documented on the basis of specific economic indices.

The economic evaluation of the examined systems is based on real procurement costs for the major components of the required equipment and the results from similar works executed by the authors for former studies [4,8,9,20], with regard to the civil engineering works and the annual operation and maintenance cost of the hybrid plants. Especially for the lithium-ion batteries, due to the forecasts on the expecting significant drop of their procurement cost in the next decade, an additional economic analysis was executed for the corresponding systems, adopting a procurement cost for the specific technology of 50 €/kWh of storage capacity (this feature today ranges at 500 €/kWh) [50,51,52]. The procurement cost for lead acid batteries is assumed at 150 €/kWh with a lifetime period of 7 years [51,52]. The lifetime period of the lithium-ion batteries was adopted equal to 10 years [51,52].

Finally, a crucial and fundamental prerequisite adopted in the economic evaluation of the examined systems is a particular limitation introduced on the electricity selling price, which should be lower than the existing electricity production total specific cost in the under consideration insular systems, presented in Table 1.

Summarizing the above, the dimensioning process aims at the optimization of the economic indices of the required investments, with the following two main restrictions:

- annual RES penetration percentages higher than 70%, aiming at 100% versus the annual consumption
- electricity selling prices lower than the currently existing production cost of the local thermal power plant.

The optimization process is executed with software applications developed by the authors on LabVIEW environment.

5. Results

A number of iterative executions of the computational simulation process was accomplished, varying, at each iteration, the wind park's and / or the photovoltaic station's nominal power and the energy storage capacity of the involved storage plant. The dimensions of the resulting systems that satisfy the pre-defined dimensioning criteria, set in the previous section, are presented in Table 3, which is focused particularly on the technical characteristics of the examined systems.

At the same time, these systems also satisfy the essential dimensioning economic criteria set in Section 4, namely the optimization of the required investments' economic indices with electricity selling prices lower than the existing electricity production specific cost. The corresponding economic parameters and results are summarized in Table 4.

The economic analysis was executed with the following assumptions:

- the funding scheme was composed of 50% equities and 50% loan investment from the European Investment Bank, with 1.50% loan rate and 15 years payback period
- the economic analysis was executed on the basis of a 20-year life period for all systems
- it is underlined that for the calculation of the storage plants' set-up specific costs, all the batteries' replacements required during the life period of the hybrid power plants were also considered
- the presented economic indices refer to the equities of the corresponding investment.

In Table 3, it is seen that with all the introduced alternative layouts, the requirement of annual RES penetration percentage higher than 70% is fulfilled. In fact, the lowest achieved annual RES penetration percentage is calculated at 78% for the case of Symi and for a hybrid power plant supported by lithium-ion batteries. This should be considered sensible, since Symi is the largest system among the examined ones, hence the achievement of such high RES penetration percentages with the support of electrochemical storage technologies, namely with technologies exhibiting relatively low storage capacities, is more difficult than in the other two smaller systems. The RES annual penetration percentage is calculated as the ratio of the total annual electricity production from the RES and the storage plants, over the total annual electricity demand.

Moreover, 100% annual RES penetration percentages can be only achieved with the support of PHS systems, hence only for the islands of Symi and Astypalaia. This should be also considered sensible, due to the high storage capacity offered by the PHS systems, capable to guarantee the hybrid power plant's adequacy to fulfil the electricity demand even during long periods of low RES potential availability. On the other hand, the maximization of the annual electricity production from the hybrid power plant with the PHS support, potentially at 100%, is also an essential prerequisite, imposed by the necessity to compensate the high set-up costs and to ensure the investments' economic feasibility.

The remarkably high storage capacity offered by the PHS systems is another important characteristic of the obtained results. The autonomy operation period of the hybrid power plants supported by the PHS systems is calculated at 17 and 19 days for Symi and Astypalaia respectively, contributing significantly to the energy supply security enforcement. On the other hand, the offered autonomy operation period by the hybrid power plants equipped with electrochemical storage technologies is less than 1 day in all the resulting optimum systems, revealing the remarkably low storage capacity of the electrochemical batteries, as imposed by the economic feasibility of these systems. The autonomy operation period is calculated as the period that the storage

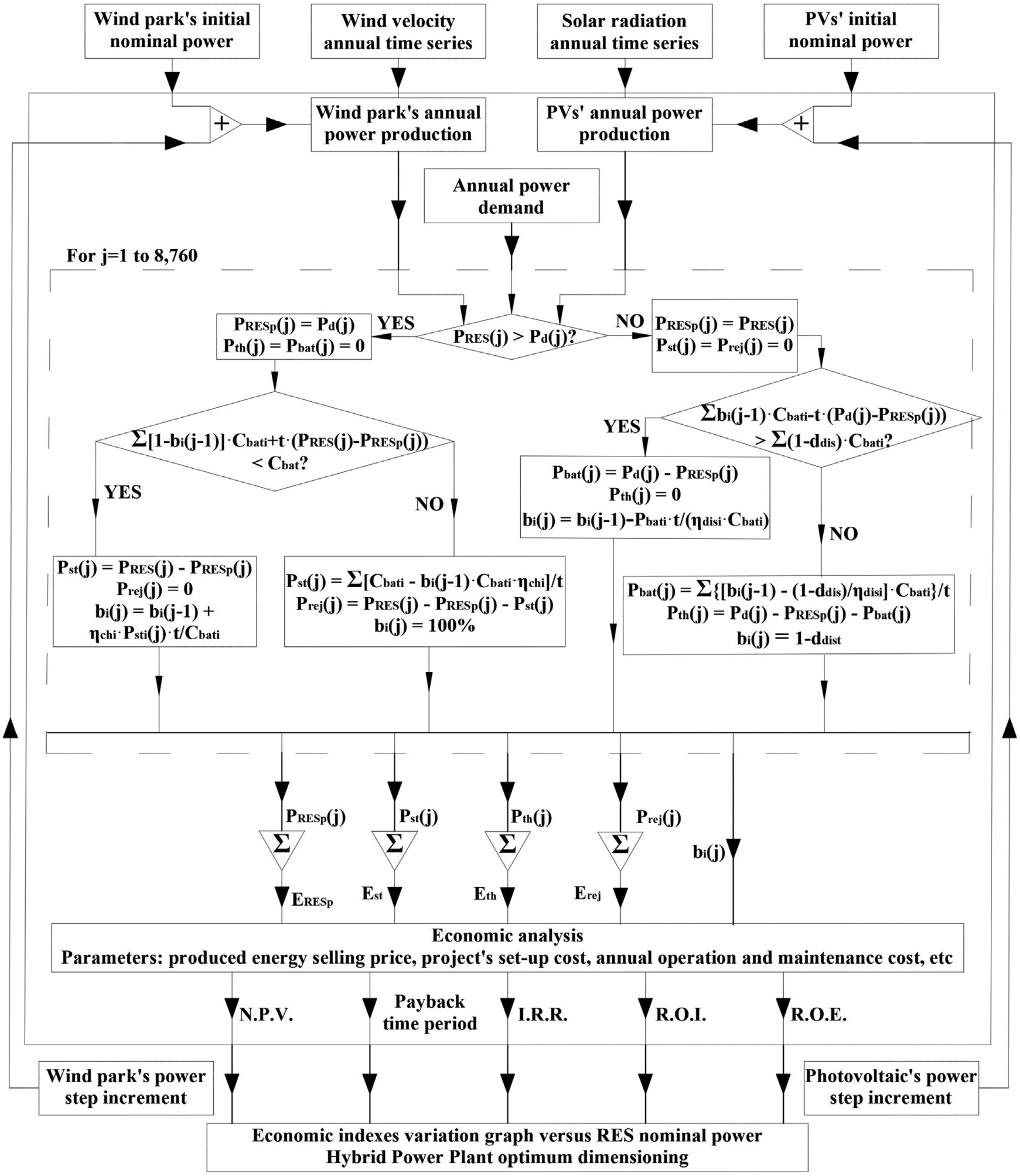

Fig. 7. Operation algorithm of a hybrid power plant with electrochemical batteries as storage units.

Table 3
Results summary of the dimensioning optimization calculations.

Island	Storage plant	Dimensioning				RES annual penetration	
		Wind park power (MW)	PV power (MW)	Storage nominal capacity (MWh)	Autonomy operation period (days)	RES annual penetration (%)	RES annual surplus (%)
Symi	PHS	6.9	2.5	715.457	16.88	100.0	26.35
	Lead acid	4.5	2.0	18.000	0.43	79.30	30.09
	Lithium-ion	4.5	2.0	12.150	0.29	78.03	31.88
Astypalaia	PHS	4.5	0.0	367.762	19.17	100.0	23.61
	Lead acid	3.6	1.0	14.440	0.75	88.78	51.96
	Lithium-ion	3.6	1.0	10.125	0.53	87.23	53.19
Kastelorizo	Lead acid	0.910	0.900	7.200	0.82	85.8	26.3
	Lithium-ion	0.910	0.900	6.075	0.69	89.1	38.8

Table 4
Results summary of the economic evaluation of the examined power plants.

Island	Storage plant	Set-up cost (M€)	Storage plant set-up specific cost (€/kWh)	Electricity total selling price (€/MWh)	Internal Rate of Return (%)	Payback period (years)
Symi	PHS	24.795	34.67	250	11.96	7.81
	Lead acid	18.255	428.08	200	11.31	7.93
	Lithium-ion – current procurement price	20.064	906.55	200	9.95	8.31
	Lithium-ion – procurement price at 50 €/kWh	10.151	90.65	150	17.53	5.37
Astypalaia	PHS	17.375	33.79	300	10.06	8.01
	Lead acid	13.222	433.68	300	12.14	7.50
	Lithium-ion – current procurement price 500 €/kWh	16.139	906.55	350	12.09	7.27
	Lithium-ion – procurement price at 50 €/kWh	7.878	90.65	200	13.51	6.65
Kastelorizo	Lead acid	5.894	409.41	300	10.33	8.51
	Lithium-ion – current procurement price 500 €/kWh	9.387	906.55	350	8.31	9.29
	Lithium-ion – procurement price at 50 €/kWh	4.410	90.65	250	15.42	6.03

plant can fully cover the power demand in the insular grid, starting from 100% charge level and without any intermediate energy storage during this period. It is calculated by considering the average daily electricity consumption in the island.

Finally, the high annual RES production surplus calculated for the systems supported with electrochemical storage devices is also worthy of mentioning, reaching values even higher than 50% for the case of Astypalaia. This is also another negative consequence of the relatively low storage capacity of these systems, with regard to the size of the overall hybrid power plant. The RES annual surplus percentage is calculated as the ratio of the annual electricity production from the RES plants which cannot either directly penetrate in the electrical grid, or be stored in the storage plant, over the total annual electricity production from the RES units.

In Figs. 8–10, annual power production synthesis graphs are presented for the examined hybrid power plants and the alternative layouts in the under consideration islands. From these graphs we may conclude to the several remarks, which in fact constitute direct consequences of the introduced parameters and limitations in the operation algorithm.

For example, for the islands of Symi and Astypalaia, the lack of any thermal power production during the whole annual period is clearly depicted in Figs. 8a and 9a. In these Figures it is also seen that the RES direct penetration is always restricted below 40% versus the current power demand. The potential 100% RES direct penetration percentage is also clearly shown in Figs. 8b, 9b and 10b, referring to the examined hybrid power plants supported by electrochemical storage technologies. In the same Figures, the considerably low power production from the storage technologies is depicted. This is due to the possible 100% direct RES penetration percentage and, obviously, due to the low storage capacity of the involved storage technologies.

In Fig. 8b, referring to the island of Symi (the largest among the examined insular systems), it is seen that thermal power production is met during the whole annual period, indicating the inadequacy of the electrochemical storage technologies to sufficiently support high RES penetration as the size of the electrical system increases. In Figs. 9b and 10b, referring to the islands of Astypalaia and Kastelorizo, it is seen that the thermal power production is limited mainly during the peak demand period (summer season) and slightly in winter, most probably due to the use of heat pumps for indoor space heating, proving the increasing technical adequacy of electrochemical storage technologies to support high RES penetration for small insular systems.

With regard to the economic results, by observing Table 4, we may state that with the concluded dimensioning, the required selling price of the produced electricity should be between 250 and 350 €/MWh for the currently existing storage technologies, while it is reduced between 150 and 250 €/MWh in case of a future drop of the lithium-ion batteries procurement cost. At the same time, the required investments exhibit quite satisfying economic indices, with payback period and Internal Rate or Return (I.R.R.) at the range of 6–10 years and 9–15% respectively. Consequently, one of the main criterion of the dimensioning process, namely the economic feasibility of the introduced projects with electricity selling prices lower than the currently existing electricity production specific costs in the examined insular systems, is fulfilled.

Additionally, PHS systems still remain highly competitive, despite the low size of the investigated islands, offering a series of advantages, such as high storage capacity, low set-up specific cost per unit of storage capacity, long autonomy time period, long life period and it is the only system that can guarantee 100% RES penetration. The impressively low specific set-up cost of the PHS systems per unit of energy storage capacity, configured at the range of 34–35 €/kWh, is also worthy of mentioning. This magnitude is calculated as the ratio of the total set-up and operation cost of the storage plants (including maintenance or equipment replacements during the adopted 20-year life period of the hybrid plants), over the offered energy storage capacity. The corresponding feature of the electrochemical storage systems today is calculated as high as 400 €/kWh for lead acid batteries and 900 €/kWh for

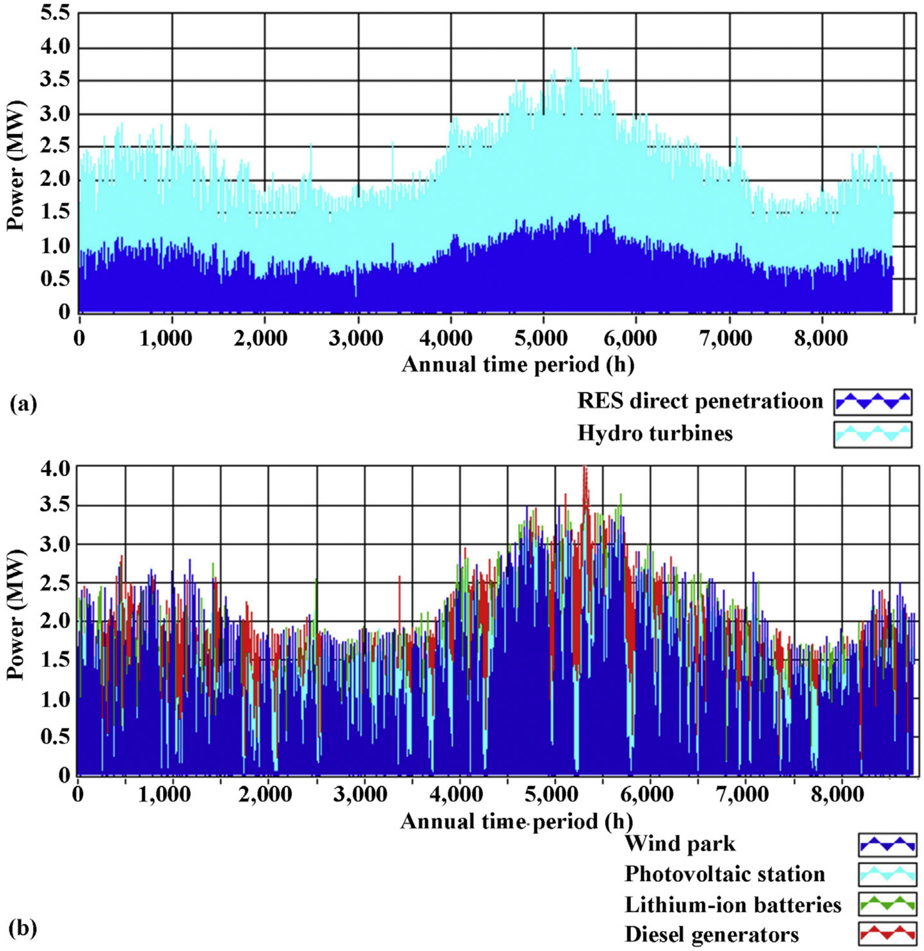

Fig. 8. Annual power production synthesis graphs in Symi with the support (a) of PHS and (b) lead-acid batteries.

lithium-ion batteries, for a life time period of 20 years. Even with the assumption of a procurement price drop of lithium-ion batteries at 50 €/kWh in 15 years, and assuming a life period of 10 years, the specific set-up cost is only reduced at 90 €/kWh for a 20-year life period hybrid plant, namely roughly three times higher than the achieved feature with the PHS systems.

On the other hand, the major drawback of the hybrid power plants with PHS systems is the high set-up cost, which can potentially constitute a major barrier towards the implementation of the project, despite the attractive economic indices and technical features of these projects.

Clearly from the investment point of view, the optimum economic indices are calculated for the hybrid power plants equipped with the lithium-ion batteries, yet on the condition of a procurement price at 50 €/kWh, which corresponds at 10% of the currently actual price. Although this scenario currently constitutes a theoretical approach, it clearly shows that a probable 90% drop of the lithium-ion batteries procurement price in the next 10–20 years, will most possibly lead to a significant increase of the investors’ interest in the development of hybrid power plants in insular autonomous systems.

Finally, it is noted that the economic analyses were executed for 20 years life periods. In case of longer life periods (e.g. 50 years), the economic feasibility would be much more favorable for the systems with PHS support, due to the more required replacements of the electrochemical batteries and the subsequent increase of the life cycle cost of the corresponding plants.

6. Qualitative approach & extensions

Apart from the above technical and economic aspects regarding the examined electricity storage technologies, the following qualitative parameters can also influence the selection of the storage technology.

- Added value – contribution to local development:

PHS systems are accompanied with the construction of a cluster of infrastructure works, such as roads, reservoirs, harbors (in case of seawater PHS) etc, which exhibit high added-value for the local social and economic community, both during the construction period, with the employment of local available machinery, engineers and machinery’s operators, and during the operation period, for the support of the projects’ operation and maintenance needs.

Additionally, the deployment of this infrastructure creates the basis for the development of further professional activities, such as tourism, and the combined used of the PHS system for both energy and water resources management, which in turn can be utilized for the creation of a series of new growth prospects. All these important perspectives are not offered by “plug and play” systems, such as electrochemical storage technologies, which are transferred on site and installed by their manufacturers, which also undertake all the highly specialized service and maintenance needs, with the involvement of local experts and technicians being minimized, if not eliminated.

- Licensing process – construction required time period:

On the other hand, precisely these PHS systems’ favorable features

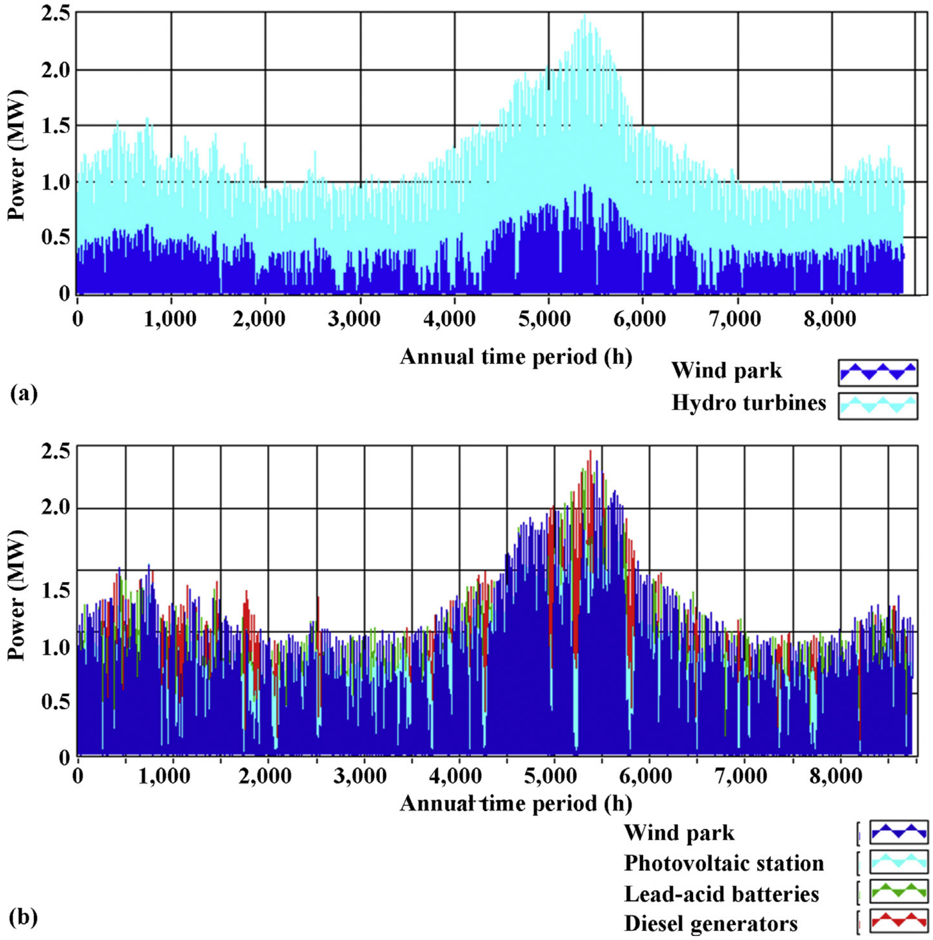

Fig. 9. Annual power production synthesis graphs in Astypalaia with the support (a) of PHS and (b) lithium-ion batteries.

that increase their added value and creates all these positive perspectives for the local communities, require, in most cases, large scale works, which imply often labor-demanding and time-consuming licensing processes. In extreme cases, there is also the risk for the cancellation of the project, for instance due to violation of environmental impacts, restrictions on land uses etc. These consequences can be considerably crucial, given the fact that the technical and economic feasibility of PHS systems are strongly depended on the installation site's appropriateness, especially in small insular territories, with relatively low annual electricity demand and corresponding limited margins for economic profits. A potential exclusion of the most favorable locations for PHS installation on an insular territory due to licensing reasons, may practically lead to the cancellation of the use of this storage technology in the hybrid power plant, simply due to the considerably increasing set-up cost in other, less favorable locations. It is conceivable that all these difficulties are not met in case of electrochemical storage systems, which are put in containers and can be installed anywhere. The licensing process is also much simpler in this case.

Finally, it is also obvious that the construction period is much longer in case of PHS systems, with works and tasks that can potentially cause more intensive nuisances and disturbances in the local communities.

- Energy security supply – energy independency:

The energy security supply – energy independence has to do with the ability of hybrid power plants to guarantee the electricity production in autonomous insular systems, following the power demand in a secure and stable approach. It may be distinguished to the contribution of the hybrid power plant to the dynamic security and stability of the electrical grid and to their capability to guarantee adequate energy availability for long time periods, regardless the availability of the stochastic RES potential.

With regard to dynamic security and stability of electrical insular systems, former studies have indicated the ability of both examined layouts, to contribute to the regulation of the electrical grid's fundamental frequency and RMS voltage at the predefined standards [9,53–58] and offer a fast and adequate reaction in case of system's faults and contingencies. In case of electrochemical batteries, these services are offered by the power electronics provided by the batteries' inverters. In case of PHS systems, the dynamic security is supported by both the potential electrical load curtailments, in case of an emergency, provided with the possible disconnection of the PHS pumps off the grid, and the power production regulation through the fast load response of the hydro turbines. The hybro turbines, as the production units of PHS systems, offer the additional advantage of robust spinning reserve availability, leading, in turn, to a series of potentially offered ancillary services (first, secondary, tertiary control, black-start capability, voltage control etc).

The capability of a hybrid power plant to guarantee adequate energy availability for long time periods, regardless the RES potential availability, is practically imposed by its storage capacity. The large energy storage capacity and the corresponding long autonomy operation period can guarantee secure energy supply in the autonomous electrical grid, even during periods of low RES potential availability, leading to real energy independence for the local communities. As analysed previously, this significant feature is offered only by the PHS systems, which, actually, constitute the only energy storage technology that can store large quantities of energy.

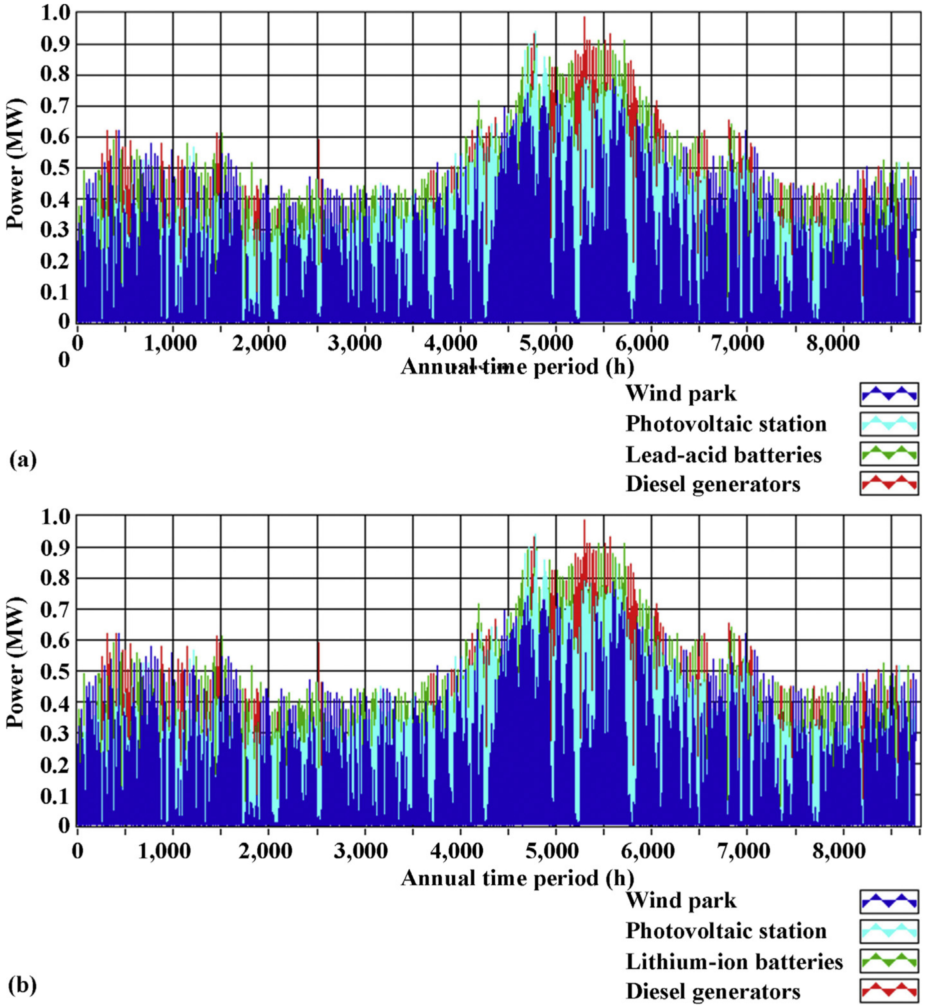

Fig. 10. Annual power production synthesis graphs in Kastelorizo with the support (a) of lead-acid batteries and (b) lithium-ion batteries.

Table 5
Annual CO_2 emission saving with the examined hybrid power plants.

Island	Storage plant	Initial diesel oil annual consumption (klt)	Annual RES penetration (%)	New diesel oil annual consumption (klt)	Diesel oil annual saving (klt)	Annual CO_2 saving (tn)
Symi	PHS	4138.199	100.00	0.000	4138.199	11315.04
	Lead-acid		79.30	961.542	3176.657	8685.90
	Lithium-ion		78.03	1019.875	3118.324	8526.40
Astupalaia	PHS	2099.769	100.00	0.000	2099.769	5741.38
	Lead-acid		88.78	234.456	1865.313	5100.31
	Lithium-ion		87.23	266.734	1833.035	5012.05
Kastelorizo	Lead-acid	1027.098	85.80	145.890	881.208	2409.48
	Lithium-ion		89.10	153.257	873.841	2389.33

- CO_2 emissions:

As shown in the precedent analysis, all the examined hybrid power plants, with the appropriate dimensioning, can guarantee high RES penetration in the under consideration insular systems. Given this fact, the avoided thermal energy production and the corresponding fossil fuel and CO_2 emissions saving remain, more or less, the same between the alternatively examined hybrid power plants for each investigated island. Hence, the CO_2 annual saving practically does not constitute a critical comparative parameter between the alternative, investigated technologies. Given that diesel oil is the only consumed fuel in the existing operation of the under consideration systems and assuming a CO_2 emission factor of 74.1 tn per TJ of consumed diesel oil [59], the CO_2 emission annual saving calculation is presented in Table 5. The annual diesel oil consumption calculation for the existing system's operation and with the introduction of the examined hybrid power plants is based on the annual simulation of the systems' operation, considering the existing thermal generators with all the involved technical specifications (efficiency curves, technical minima and maximum output capacities etc).

7. Conclusions

The article investigates the technical and economic prerequisites for the introduction of hybrid power plants in three Greek insular autonomous systems with annual peak power demand lower than 5 MW, aiming to indicate the optimum electricity storage technologies for this particular insular systems' size and for typical Mediterranean conditions. PHS systems and electrochemical batteries are examined as alternative storage technologies, aiming to ensure high RES penetration and economic feasibility with electricity selling prices lower than the existing production specific cost of the autonomous systems. A general remark is that the above targets can be achieved with all the alternative plants.

By comparing the different investigated technologies between them, we conclude that:

- With the electrochemical technologies annual RES penetration percentages from 78 to 89% are achieved.
- 100% annual RES penetration percentage is achieved only with the PHS systems. This is due to the high energy storage capacity offered by this storage technology.
- PHS systems offer very long time period of autonomy operation, a fact of crucial importance for autonomous grids. For the two investigated insular systems, autonomy operation periods of 17 and 19 days are offered.
- PHS systems exhibit the highest set-up cost, which, can potentially constitute a major barrier towards their implementation. However, the high set-up cost is compensated with time due to the fact that it is constructed only once and no replacements are required, as in case of batteries.
- PHS systems exhibit the lowest set-up specific cost per unit of storage capacity. For the investigated systems it was calculated at the range of 35 €/kWh, while the corresponding feature of electrochemical storage technologies was calculated at 400 €/kWh and 900 €/kWh for lead-acid and lithium-ion batteries respectively.
- The main attractive features of the power plants supported by batteries technologies are the low set-up costs and the simpler and faster licensing and construction process.
- Lithium-ion batteries can be a highly attractive option in case of 90% procurement cost drop in the next 10–20 years, provoking considerable interest from the investors' side for the implementation of hybrid power plants.
- Given a funding scheme of 50% equities and 50% bank loan (1.50% rate, 15 years payback period), payback periods between 6 and 10 years are achieved, calculated on the investments' equities, maintaining the electricity selling price lower than the currently existing electricity production cost.
- PHS systems exhibit important favorable features regarding their contribution on the energy security supply and energy independence in the insular systems, as well as their contribution to the economic and social growth of the insular communities. All these are practically consequences of the high offered storage capacity.
- The above stand on the condition of favorable land morphology for PHS installations. The lack of favorable land morphology may cancel all the above mentioned positive features and may exclude the PHS systems as a potential option for the realization of hybrid power plants.

Summarizing the above conclusions, PHS systems offer a series of important facilities for the insular non-interconnected systems, including high operation autonomy periods, improved energy supply security, a cluster of ancillary services, significant perspectives for local economic growth etc. Their economic feasibility can be ensured even for small size systems, on the condition of the availability of favorable land morphology. On the other hand, from an investment point of view, optimum dimensioning leads to similar economic indices for hybrid power plants equipped with either PHS systems or electrochemical storage technologies. A technological revolution is expected with the anticipated procurement cost drop of the lithium-ion batteries, which will enable investments on hybrid power plants with considerably improved economic indices.

Acknowledgment

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