Optimal Design and Economic Evaluation of a Battery Energy Storage System for the Maximization of the Energy Generated by Wind Farms in Isolated Electric Grids

by

E. Koutroulis, D. Kolokotsa, and G. Stavrakakis

REPRINTED FROM

WIND ENGINEERING

VOLUME 33, NO. 1, 2009

MULTI-SCIENCE PUBLISHING COMPANY
5 WATES WAY · BRENTWOOD · ESSEX CM15 9TB · UK
TEL: +44(0)1277 224632 · FAX: +44(0)1277 223453
E-MAIL: mscience@globalnet.co.uk · WEB SITE: www.multi-science.co.uk

Optimal Design and Economic Evaluation of a Battery Energy Storage System for the Maximization of the Energy Generated by Wind Farms in Isolated Electric Grids

E. Koutroulis,[1] D. Kolokotsa,[2] and G. Stavrakakis[1]
[1]Department of Electronic and Computer Engineering, Technical University of Crete
Tel: +30 28210 37233, Fax: +30 28210 37542, e-mail: efkout@electronics.tuc.gr
[2]Department of Natural Resources and Environment, Technological Educational Institute of Crete

ABSTRACT
In this paper, a methodology for the optimal sizing of a Battery Energy Storage System (BESS) targeting to supply a predefined and constant (guaranteed) amount of power to an isolated electric grid during the peak load-demand hours is presented. The BESS battery bank is charged using that part of the energy produced by wind parks interconnected with the power system, which is rejected by the electric network due to grid stability limitations. Thus, using the proposed BESS configuration results in increment of the wind energy penetration in the isolated power system and reduction of the air pollution caused by the thermal power stations. The economic viability of the optimally sized BESS configuration is investigated by calculating the investment discounted payback period and internal rate of return. The proposed method has been applied for the optimal design of a BESS supporting the isolated electric network of a remote island with significant wind potential. According to the economic analysis results, the installation of the proposed BESS is economically beneficial for both the BESS investor and the local electric network operator.

Keywords: Battery energy storage, Wind energy, Genetic algorithms, Isolated power grids.

1. INTRODUCTION
The energy storage systems are an essential part of the electricity infrastructure as they improve the electric energy power quality and the power system reliability through frequency control and voltage regulation methods [1]. Moreover, they can support load leveling, spinning reserve, peak shaving and demand reduction features and they are effectively coupled with distributed and autonomous systems [2]. The energy storage capability can be achieved using various means, such as batteries, pumped hydro storage [3] and fuel-cell arrays [4]. The Battery Energy Storage Systems (BESS) have been used in the past to store the energy surplus during the low load-demand time intervals and release this energy back to the system during the peak load-demand hours [5-9].

The electric networks installed in remote islands are usually non-interconnected and they are typically characterized by a small generation capacity, high electric energy generation costs and frequent system disturbances that lead to load shedding. The installation of wind farms is usually favored in remote islands because of their significant wind potential. However, the main obstacles which limit the wind-energy penetration in isolated electric power grids are the following: (i) the stochastic variation of the wind speed, leading to a significant mismatch between the wind energy generation and the electricity demand, (ii) the technical minima of the electric grid thermal energy-generation units and (iii) the transmission line instability problems. These factors lead to rejection of the excess wind-generated energy, although during the peak load-demand time intervals additional gas-turbine generators of high operating cost are usually introduced to cover the corresponding power demand [10].

Aiming towards the increment of the wind energy penetration and the improvement of the grid stability in isolated electric power systems, a technical and economic analysis of a pumped hydro storage system is presented in [3]. This system is coupled with wind farms in order to store the rejected energy and provide it back to the electric grid during the peak demand hours. The main disadvantage of the pumped hydro storage systems is the high installation cost, which mainly depends on the construction costs of the water reservoirs and the nominal power rating of the hydroelectric turbines. The construction works required for the creation of the higher and lower water reservoirs are extensive, they have ground morphology limitations and they create a permanent impact on the landscape.

In this paper, a methodology for the optimal sizing of a Battery Energy Storage System (BESS) targeting to supply a predefined and constant (guaranteed) amount of power to an isolated electric grid during the peak load demand hours (i.e. from 11:00 to 15:00) on a daily basis during the whole year, is presented. The proposed BESS battery bank is either charged using the wind-generated energy surplus which is rejected by the isolated electric network, or the energy stored in the battery bank is injected to the electric grid during the peak demand hours. The application of the proposed configuration results in both increment of the wind energy penetration in the isolated electric grid and reduction of the thermal power stations power contribution during the peak demand hours. Because of the minimal requirements for civil engineering works, the proposed BESS configuration has the following advantages compared to the pumped hydro storage solution described above: (i) the construction of the battery energy storage system can be implemented in a shorter time interval (ii) it does not influence the environmental topography of the installation area and (iii) in case that the interconnection of the isolated electric network with another electric power system results in significant reduction of the available rejected wind-generated energy, thus eliminating the necessity of further use of any previously installed BESS, then the proposed energy storage system can be easily transferred to another installation area. Additionally, the operation of the BESS does not depend on extra natural resources, such as water, which is frequently unavailable in remote islands.

The block diagram of the BESS system under study is depicted in Fig. 1. It consists of a battery bank and multiple bidirectional DC/AC power converters (inverters) connected to a common DC-Bus. Using multiple inverters operating in parallel in order to achieve the necessary power capability has the advantages of maintainability and improved reliability [11]. A control unit is used to control the operation of each DC/AC converter based on measurements of the battery bank current and voltage. In case of an autonomous BESS system the battery bank charging process is implemented using only the rejected wind energy, while during the operation of a non-autonomous BESS system additional electric energy is absorbed from the electric grid in order to fulfill the battery bank charging requirements. In the latter case, the electric grid energy import is implemented during the night (i.e. form 00:00 to 08:00) in order to reduce the load imposed on the thermal units during the rest of the day, while simultaneously achieving a low buying price of the imported energy. The BESS optimal sizing methodology presented in this paper targets to calculate the optimal values of the total number of DC/AC power converters, the total number of battery strings connected in parallel and the constant (guaranteed) power that can be supplied from the

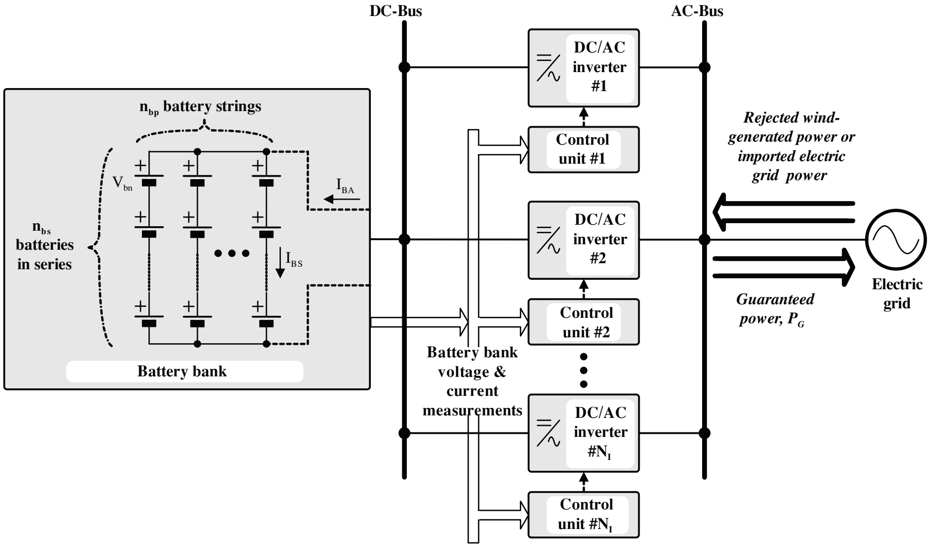

Figure 1: The block diagram of the proposed Battery Energy Storage System.

BESS to the electric grid from 11:00 to 15:00 every day of the year, such that the economic benefit resulting from the BESS energy sales to the electric grid is maximized. The resulting economic benefit is calculated according to the system components total capital and maintenance costs, the cost of purchasing the complementary energy required from the electric grid and the total revenues achieved from the BESS energy sales to the electric grid during the system operational time period. In case of optimal sizing of an autonomous BESS system, complementary energy is not purchased from the electric grid and the corresponding cost is not included in the total cost function. The maximization of the economic benefit function is implemented employing Genetic Algorithms (GAs), which compared to the conventional optimization methods, such as the dynamic programming and the gradient techniques, have the ability to handle complex problems with linear or nonlinear cost functions both, accurately and efficiently.

This paper is organized as follows: the proposed methodology is outlined in Section 2, the BESS modeling and operation simulation is described in Section 3, the system economic benefit maximization using genetic algorithms is analyzed in Section 4, the economic analysis methods are described in Section 5 and the simulation results are presented in Section 6.

2. THE PROPOSED METHODOLOGY

The flowchart of the proposed BESS optimal sizing procedure is illustrated in Fig. 2. The optimal sizing algorithm inputs are the technical specifications of the batteries and the DC/AC power converters, the hourly mean load demand of the target electric system on a yearly basis and the hourly mean values of the rejected wind-generated power, also on a yearly basis. All the above inputs are stored in suitable text files for easy maintenance. The required technical specifications of each battery are the following:

- The model number,
- The storage capacity, C_b (Ah),
- The nominal voltage, V_{bn} (Volt),
- The variation of the battery internal resistance with the state of charge, or the battery round-trip efficiency values during charging and discharging, respectively,

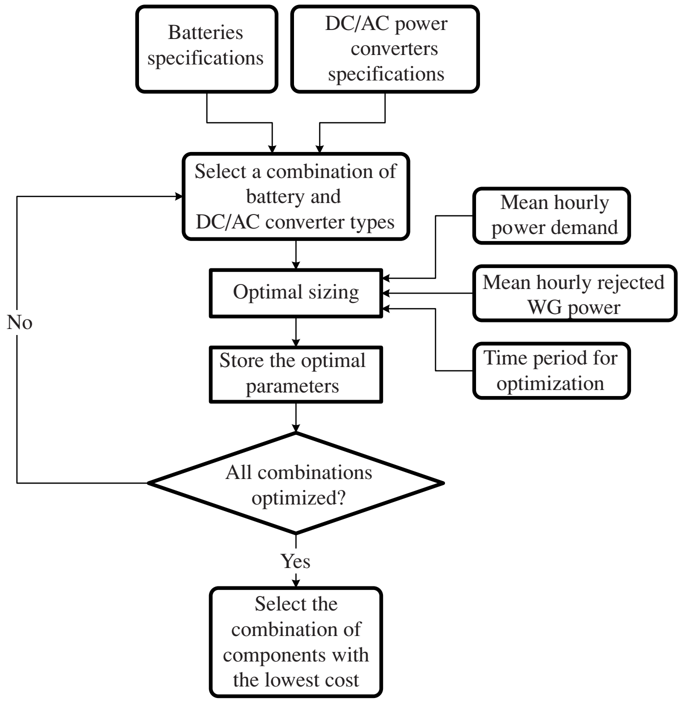

Figure 2: The flowchart of the proposed optimization methodology.

in case that the battery manufacturer does not provide the internal resistance values,

- The maximum permissible depth of discharge, DOD_{max} (%),
- The capital cost, C_{CB} (€), including the market price and the installation cost,
- The annual maintenance cost, C_{MB} (€/year),
- The battery ampere-hour throughput, Q_{life} (Ah), which is calculated using the technical specifications provided by the manufacturer and
- The battery maximum lifetime period, $L_{B,max}$ (years).

The technical specifications of each DC/AC power converter, input to the optimal sizing algorithm are the following:

- The DC/AC power converter model number,
- The power conversion efficiency, n_{inv} (%),
- The nominal AC power rating, P_{nom} (W),
- The mean time between failures (MTBF) in hours,
- The capital cost, C_{CI} (€), including the market price and the installation cost,
- The annual maintenance cost, C_{MI} (€/year),
- The DC input nominal voltage rating, V_{op} (Volt),
- The capital cost of the DC/AC power converter control unit, C_{CU} (€) and
- The repair cost of each power converter, R_{CI} (€).

The BESS operating lifetime period (in years) is specified by the user as an algorithm input parameter. During the evolution of the GA dynamic search process for the optimal solution, various combinations of total battery capacity and guaranteed power values, comprising a system configuration, are generated. For each combination, a system simulation for a one year time period is performed in order to verify that the battery capacity under consideration is adequate to provide the corresponding amount of guaranteed power to the electric grid, according to the rejected wind-generated power profile during the year. The optimal system configuration consists of the number of batteries and the corresponding guaranteed power level values which satisfy this constraint, while simultaneously achieve the highest economic benefit during the battery energy storage system lifetime.

The process described above is repeated for each combination of battery and DC/AC power converter types stored in the input database. After all device type combinations have been optimally sized, the combination achieving the highest economic benefit and the corresponding devices mixture are displayed as the overall optimal system configuration.

3. THE BESS MODELING AND OPERATION SIMULATION

In the proposed method, the system operation is simulated for one year with a time step of one hour. The power produced by the BESS and the rejected WG power are both assumed to be constant during that time interval. The total number of batteries, n_{bs}, that should be connected in series in order to implement one battery string is dictated by the DC-bus nominal voltage, V_{op} and the nominal voltage of each battery, V_{bn}:

$$n_{bs} = \frac{V_{op}}{V_{bn}} \tag{1}$$

The DC-bus nominal voltage is equal to the DC/AC converter DC input nominal voltage rating.

The total nominal capacity of the battery bank, C_{nom} (Ah), depends on the nominal capacity of each battery, C_b (Ah) and the total number of battery strings forming the battery bank, n_{bp}:

$$C_{nom} = n_{bp} \cdot C_b \tag{2}$$

The battery bank is assumed to be initially partially charged and the corresponding initial capacity, C_{init}, is calculated using the following equation:

$$C_{init} = \left(1 - \frac{DOD_{max}}{2}\right) \cdot C_{nom} \tag{3}$$

where DOD_{max} (%) is the batteries maximum permissible depth of discharge, which is either specified by the manufacturer, or, in case that this information is not available, its value is set equal to 80%.

The total number of batteries composing the BESS battery bank, N_B, is calculated as follows:

$$N_B = n_{bp} \cdot n_{bs} \tag{4}$$

The battery bank initial state of charge on day 1 and at hour 0, $SOC^1(0)$ (%), is equal to the ratio of the battery bank initial and nominal capacity values:

$$SOC^1(0) = \frac{C_{init}}{C_{nom}} \cdot 100\% \tag{5}$$

The total number of DC/AC power converters, N_I, required to implement the BESS scheme under consideration is calculated according to the guaranteed power value, P_G(W) and the nominal AC power rating of each DC/AC converter, P_{nom}:

$$N_I = \frac{F_O \cdot P_G}{P_{nom}} \tag{6}$$

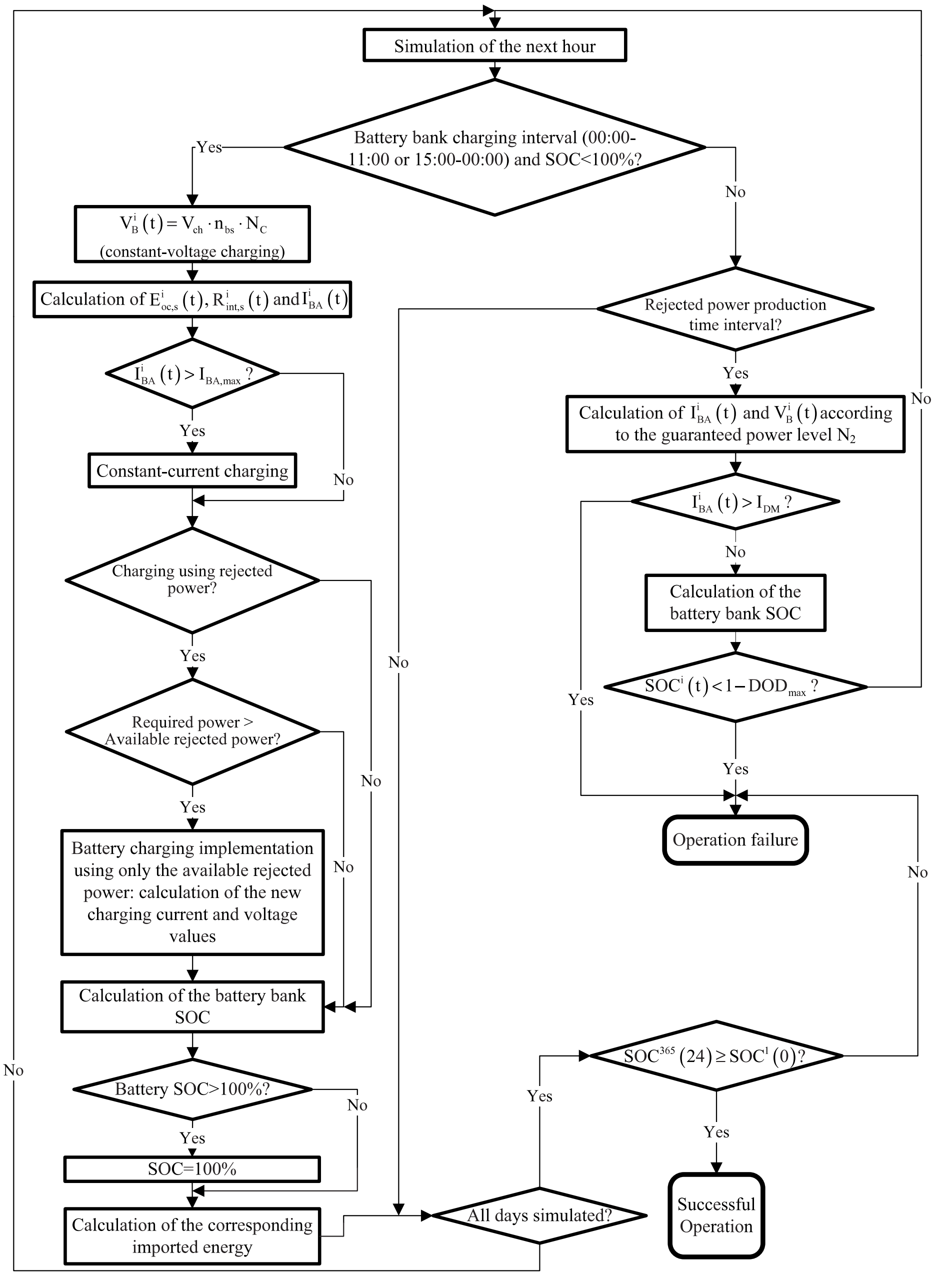

Figure 3: The flowchart of the algorithm simulating the operation of the proposed BESS.

where $F_o = 1.2$ is an over-sizing factor, which is incorporated in order to enhance the power converters reliability in case of increased operating temperature conditions, while simultaneously provides the capability to cover the electric-grid load variations for small time intervals.

The parameters P_G and n_{bp} correspond to genes of the GA chromosomes and their values are random integer numbers produced by the GA during the optimization process.

The battery charging process is performed in case that either rejected wind-generated energy is available, or additional power is imported to the BESS from the electric grid in order to cover the battery bank charging requirements during the low load demand time interval. The flowchart of the algorithm simulating this process is depicted in Fig. 3. Initially, the battery bank state of charge is examined. If the batteries are fully charged (SOC = 100%) then the battery charging process is suspended, else the battery bank is charged through the DC/AC power converters according to the constant-voltage charging method. In order to simulate this process, each battery string is modeled as a voltage source, corresponding to the battery string open-circuit voltage, $E^i_{oc,s}(t)$, which is connected in series with the battery string internal resistance, $R^i_{int,s}(t)$ [12,13]. Both $E^i_{oc,s}(t)$ and $R^i_{int,s}(t)$ depend on the battery state of charge, $SOC^i(t)$ and their values are provided by the battery manufacturer. Thus, the open-circuit voltage of each BESS battery string on day i ($1 \le i \le 365$) and at the beginning of hour t ($1 \le t \le 24$), $E^i_{oc,s}(t)$, is modeled to depend linearly on the corresponding state of charge [12], according to the following formula:

$$E^i_{oc,s}(t) = \left[v_1 + v_2 \cdot SOC^i(t)\right] \cdot n_{bs} \tag{7}$$

The values of v_1 and v_2 are calculated according to the information provided by the battery manufacturer about the variation of $E^i_{oc,s}(t)$ with $SOC^i(t)$. Then, the internal resistance, $R^i_{int,s}(t)$ and the corresponding charging current, $I^i_{BS}(t)$, of each battery string are calculated using the following relationships:

$$R^i_{int,s}(t) = \left[r_1 - r_2\left(SOC^i(t)\right)\right] \cdot n_{bs} \tag{8}$$

$$I^i_{BS}(t) = \frac{V_{ch} \cdot n_{bs} \cdot N_C - E^i_{oc,s}(t)}{R^i_{int,s}(t)} \tag{9}$$

where, N_C is the number of series-connected cells forming each battery and V_{ch} is the voltage applied during the constant-voltage charging process (V/cell).

Equation (8) is used to model the dependence of $R^i_{int,s}(t)$ with the corresponding state of charge, $SOC^i(t)$. In this equation, the values of r_1 and $r_2(SOC^i(t))$ are calculated according to the information provided by the manufacturer of the target battery about the variation of the battery internal resistance with the corresponding state of charge. The value of the applied voltage, V_{ch}, during the constant-voltage charging mode is specified by the battery manufacturer. The value of the battery bank total charging current, $I^i_{BA}(t)$, is derived using equation (9) as follows:

$$I^i_{BA}(t) = I^i_{BS}(t) \cdot n_{bp} = \frac{V_{ch} \cdot n_{bs} \cdot N_C - E^i_{oc,s}(t)}{R^i_{int,s}(t)} \cdot n_{bp} \tag{10}$$

The charging current $I^i_{BA}(t)$ must be lower than the maximum permissible charging current specified by the battery manufacturer, I_{CM} (A). Additionally, the maximum value of the charging current which can be supplied by the DC/AC power converter to the battery bank, $I_{DC,max}$, is limited by the converters total nominal power capability:

$$I_{DC,max} = \frac{N_I \cdot P_{nom}}{V_{ch} \cdot n_{bs} \cdot N_C} \tag{11}$$

Considering the last two limitations, the maximum battery bank charging current, $I_{BA,max}$, is calculated as follows:

$$I_{BA,max} = \min\left(I_{CM}, I_{DC,max}\right) \tag{12}$$

In case that the value of $I^i_{BA}(t)$ calculated using eqn. (10) exceeds $I_{BA,max}$, then its value is set equal to $I_{BA,max}$ and the battery bank charging process is implemented according to the constant-current charging principle. During this process, the charging current is set to $I_{BA}^{i}(t)=I_{BA,max}$, while the battery bank voltage is a function of the corresponding open-circuit voltage, charging current and internal resistance values:

$$V_{B}^{i}(t)=E_{OC}^{i}(t)+I_{BS}^{i}(t)\cdot R_{int,s}^{i}(t) \tag{13}$$

This charging procedure is applied until the battery bank voltage value is increased to $V_{B}^{i}(t)=V_{ch}\cdot n_{bs}\cdot N_{C}$. Then, the constant-voltage charging procedure is re-initiated and the corresponding charging current value, dictated by the applied voltage and the battery state of charge according to eqn. (10), is progressively reduced during the time evolution of the charging process.

The power which must be transferred to the battery bank during the charging processes described above, $P_{chA}^{i}(t)$, is evaluated using the following relationship:

$$P_{chA}^{i}(t)=I_{BA}^{i}(t)\cdot V_{B}^{i}(t) \tag{14}$$

According to the energy management plan implemented by the proposed BESS, the power $P_{chA}^{i}(t)$ is either acquired using the rejected wind-generated power, $P_{R}^{i}(t)$, which is rejected by the electric grid during the 00:00–11:00 and 15:00–00:00 time intervals, or it is imported to the BESS from the electric grid during the low load demand time interval (00:00–08:00), in case that rejected power is not available during an hour of that time period. If the rejected wind-generated power is not adequate to fulfill the BESS battery charging power requirements $\left[P_{chA}^{i}(t)>P_{R}^{i}(t)\cdot n_{inv}\right]$, then the charging process is implemented using only the available amount of rejected power:

$$P_{chA}^{i}(t)=P_{R}^{i}(t)\cdot n_{inv}=V_{B}^{i}(t)\cdot I_{BA}^{i}(t) \tag{15}$$

where $V_{B}^{i}(t)=E_{OC}^{i}(t)+I_{BS}^{i}(t)\cdot R_{int,s}^{i}(t)$.

This operation is performed until the battery bank voltage is increased to $V_{B}^{i}(t)=V_{ch}\cdot n_{bs}\cdot N_{C}$. Then, the constant-voltage charging phase is initiated and it is practically implemented by controlling the DC/AC converters such that the power transferred to the battery bank is progressively reduced in order to maintain the battery voltage equal to $V_{B}^{i}(t)=V_{ch}\cdot n_{bs}\cdot N_{C}$. Thus, during this process the power used to charge the battery bank is less than the available rejected power. Such an operation is feasible under practical conditions, assuming that the rejected power is produced by wind farms employing pitch-controlled and variable-speed wind-generators. Else, the excess rejected power could be injected to an auxiliary (dummy) load.

The total energy imported from the electric grid during the year, E_S, is calculated as follows:

$$E_{S}=\sum_{i=1}^{365}\sum_{t=1}^{8}E_{S}^{i}(t)\cdot H\left(P_{chA}^{i}(t)\right)=\sum_{i=1}^{365}\sum_{t=1}^{8}\frac{P_{chA}^{i}(t)}{n_{inv}}\cdot 1h\cdot H\left(P_{chA}^{i}(t)\right) \tag{16}$$

where the function $H\left(P_{chA}^{i}(t)\right)$ is defined as follows: $H\left(P_{chA}^{i}(t)\right)=1$ if the power $P_{chA}^{i}(t)$ is imported form the electric grid during the 00:00–08:00 time interval and $H\left(P_{chA}^{i}(t)\right)=0$ if the power $P_{chA}^{i}(t)$ is acquired using the rejected wind-generated power during that time interval. This calculation is indispensable during the subsequent stages of the optimal sizing process, in order to estimate the cost of the additional energy imported from the electric grid.

The battery bank state of charge is modified during charging, according to the values of the corresponding charging current and nominal capacity:

$$\begin{aligned} &SOC^i(t) = SOC^i(t-1) + \frac{I^i_{BA}(t)\cdot\Delta t}{C_{nom}} \\ &SOC^i(24) = SOC^{i+1}(0) \end{aligned} \tag{17}$$

where Δt is the simulation time step, set to $\Delta t = 1$ hour.

If the value of $SOC^i(t)$ resulting according to eqn. (17) is higher than 100%, then the value of $SOC^i(t)$ is set to 100%. In this case, the energy imported from the electric grid during that time interval, $E^i_S(t)$, is calculated as follows:

$$E^i_S(t) = \frac{P^i_{chA}(t)}{n_{inv}}\cdot\Delta t' = \frac{P^i_{chA}(t)}{n_{inv}}\cdot\frac{\left[1-SOC^i(t-1)\right]\cdot C_{nom}}{I^i_{BA}(t)} \tag{18}$$

This procedure is necessary in order to calculate the precise amount of energy transferred to the battery bank, since under practical conditions the 100% battery bank state of charge would be achieved before the end of that simulated hour. Then, the simulation algorithm proceeds to the simulation of the BESS operation during the next hour.

During the electric grid peak load demand hours, i.e. from 11:00 to 15:00, the BESS supplies constant power, P_G, to the electric grid and the battery bank is discharged. In this case, the direction of the battery bank and battery string currents depicted in Fig. 1, $I^i_{BA}(t)$ and $I^i_{BS}(t)$, respectively, is reversed. The simulation algorithm flowchart in this case is illustrated in Fig. 3. The battery bank open-circuit voltage and internal resistance are initially calculated using equations (7) and (8), respectively. Then, the battery bank discharging current, $I^i_{BA}(t)$ and the corresponding discharging current of each string of the battery bank, $I^i_{BS}(t)$, are calculated as follows:

$$I^i_{BA}(t) = \frac{\frac{P_G}{n_{inv}}}{V^i_B(t)} \tag{19}$$

$$I^i_{BS}(t) = \frac{I^i_{BA}(t)}{n_{bp}} \tag{20}$$

The battery bank voltage, $V^i_B(t)$, during the discharging process, is a function of the battery bank open-circuit voltage, $E^i_{OC}(t)$, the internal resistance of each string, $R^i_{int,s}(t)$ and the battery string discharging current, $I^i_{BS}(t)$:

$$V^i_B(t) = E^i_{OC}(t) - I^i_{BS}(t)\cdot R^i_{int,s}(t) \tag{21}$$

In case that the resulting value of $I^i_{BA}(t)$ is higher than the maximum permissible battery discharging rate, I_{DM} (A), then the simulation algorithm fails and the specific GA chromosome is rejected.

Before proceeding to the BESS operation simulation during the next hour that the BESS provides power to the electric grid, the battery bank state of charge at the end of hour t is calculated:

$$\begin{aligned} &SOC^{i}(t)=SOC^{i}(t-1)-\frac{I_{BA}^{i}(t)\cdot\Delta t}{C_{nom}} \\ &SOC^{i}(24)=SOC^{i+1}(0) \end{aligned} \tag{22}$$

If , $SOC^i(t) < 1 - DOD_{max}$ indicating that the battery bank has been completely discharged, thus it is not able to provide the required power to the electric grid, then the simulation algorithm terminates with failure and the specific GA chromosome is rejected. In case that the value of the state of charge at the last hour of the year is higher than its initial value [$SOC^{365}(24) \geq SOC^1(0)$], indicating that the corresponding value of P_G ensures the reliable transfer of guaranteed power equal to P_G from the battery bank to the electric grid during the whole year, then the simulation algorithm terminates successfully, otherwise it fails and the specific GA chromosome is rejected.

The procedure described above is also applied to simulate the operation of an autonomous BESS, but in this case the battery bank charging process is implemented using exclusively the rejected wind-generated power. Thus, during the electric grid low load demand time period (00:00–08:00) any power is transferred from the electric grid to the BESS and the battery bank state of charge remains constant during that time interval.

In case that there is no available information from the battery manufacturer regarding the internal resistance of the batteries then an alternative procedure can be used to simulate the battery bank operation, presented here only for completeness purposes, as follows: the battery bank voltage is assumed to be constant during the entire time period of the charging and discharging processes and its value is set equal to the DC-Bus nominal voltage, V_{op}. Additionally, the battery bank state of charge at the beginning of hour t of day i, $SOC^i(t)$, during the charging/discharging process is calculated using a simplified model:

$$\begin{aligned} &SOC^{i}(t)=SOC^{i}(t-1)+\frac{n_B\frac{P_{chA}^{i}(t-1)}{V_{op}}\Delta t}{C_{nom}} \\ &SOC^{i}(24)=SOC^{i+1}(0) \end{aligned} \tag{23}$$

where n_B = 80% is the battery round-trip efficiency during charging and n_B = 100% during discharging [14] and $P_{chA}^{i}(t-1)$ is the battery bank input/output power at hour t-1 [$P_{chA}^{i}(t-1)<0$ during discharging and $P_{chA}^{i}(t-1)>0$ during charging].

4. THE SYSTEM ECONOMIC BENEFIT MAXIMIZATION USING GENETIC ALGORITHMS

The optimization variables are the total number of battery strings, n_{bp}, and the hourly guaranteed power offered by the BESS to the electric grid during the 11:00–15:00 time interval, P_G. These two genes comprise a GA chromosome having the format c = [P_G | n_{bp}]. The number of power converters, N_I, has not been incorporated in the GA chromosome structure since, according to eqn. (6) its value is defined by the hourly guaranteed power level. However, the number of DC/AC power converters participates in the optimization process, since the corresponding capital and maintenance costs have been included in the total system cost function.

The purpose of the optimization process is to calculate the optimal values of the total number of battery strings connected in parallel and the constant (guaranteed) power that can be supplied from the BESS to the electric grid from 11:00 to 15:00 every day of the year, such that the economic benefit resulting from the BESS energy sales to the electric grid is maximized. Thus, the objective function to be minimized in case of a non-autonomous system is calculated according to the values of the total investment capital, CC_n, the total maintenance cost of the system batteries and DC/AC power converters, MC_n, the cost of the additional energy imported from the electric grid in order to fulfill the battery bank charging requirements, EC_n and the total revenues achieved from the electricity sales for n years of BESS operation, ER_n, as follows:

$$g(N_I, P_G, n_{bp}) = CC_n + MC_n + EC_n - ER_n \tag{24}$$

The impact of taxation has not been incorporated in eqn. (24), since the corresponding expenses depend on the investor tax rate, the State taxing system and the Renewable Energy promotion policies, which are characterized by a significant variation worldwide.

The total investment capital for the purchase of the necessary equipment, after n years of system operation (future value), CC_n, depends on the State subsidization ratio, s (%), the initial total investment capital (on year n = 0), CC_0, and the discount rate, i (%):

$$CC_n = (1-s) \cdot CC_0 \cdot (1+i)^n \tag{25}$$

The value of the initial total investment capital is equal to the sum of the batteries, DC/AC power converters and control units capital costs:

$$CC_0 = n_{bp} \cdot n_{bs} \cdot C_{CB} + N_I \cdot C_{CI} + N_I \cdot C_{CU} \tag{26}$$

The system total maintenance cost, MC_n, after n years of the BESS operation consists of the batteries and DC/AC power converters maintenance, replacement and repair costs and it is defined as:

$$MC_n = (n_{bp} \cdot n_{bs} \cdot C_{MB} + N_I \cdot C_{MI}) \cdot (1+g_I) \cdot (1+i)^n \cdot \frac{1-\left(\frac{1+g_I}{1+i}\right)^n}{i-g_I} + B_C + IN_C \tag{27}$$

The lifetime of the batteries, L_B (years) is calculated each time the BESS operation simulation is performed. It depends on the selected battery type and the values of the hourly guaranteed power offered by the BESS to the electric grid:

$$L_B = \min\left(L_{B,max}, \frac{Q_{life}}{Q_{actual}}\right) = \min\left(L_{B,max}, \frac{\text{Average}\{C_{nom} \cdot DoD \cdot C(DOD)\}_{DOD=DOD_{min}}^{DOD_{max}}}{Q_{actual}}\right) \tag{28}$$

where $L_{B,max}$ is the battery maximum lifetime period (years) under floating conditions, specified by the manufacturer, Q_{actual} is the battery bank ampere-hour throughput during the year, Q_{life} is the value of the total ampere-hours that can be stored and used during the battery lifetime and C(DOD) is the number of charging/discharging cycles that can be achieved during the selected battery lifetime period in case that the corresponding depth of discharge is equal to DoD, both provided by the battery manufacturer [15, 16].

The value of Q_{actual} is calculated during the BESS operation simulation using the computed values of the battery bank discharging current [17]:

$$Q_{actual} = \sum_{i=1}^{365}\sum_{t=1}^{24} I_{BA}^i(t) \cdot S\left(I_{BA}^i(t)\right) \cdot \Delta t \tag{29}$$

where the function S(x) is defined as:

$$\begin{aligned} &S(x) = 0, \text{ if } x \geq 0 \\ &S(x) = -1, \text{ if } x < 0 \end{aligned} \tag{30}$$

The resulting total replacement cost of the batteries, B_C, during the BESS operating time period, n, is calculated as follows:

$$B_C = C_{CB} \cdot n_{bp} \cdot n_{bs} \cdot \left[\sum_{\forall j = k_1^*} \frac{(1+g_I)^j}{(1+i)^j} \right] \cdot (1+i)^n \tag{31}$$

Since the batteries are replaced only in specific years during the BESS lifetime, the sum in equation (31) is evaluated only for the specific values of year numbers, k_1^*, that the battery bank replacement is required. For example if the calculated battery lifetime is 4 years and the study is performed for n = 15 years then the sum in equation (31) is evaluated for $k_1^* = 4{,}8 \text{ and } 12$.

Similarly, the total repair cost of the power converters, IN_C, after n years of operation is calculated using the following formula:

$$IN_C = N_I \cdot R_{CI} \cdot \left[\sum_{\forall j = k_2^*} \frac{(1+g_I)^j}{(1+i)^j} \right] \cdot (1+i)^n \tag{32}$$

The parameter k_2^*, in this case, is a function of the total number of DC/AC power converter operating hours during the BESS lifetime, T_n and the power converter mean time between failures, MTBF (h), provided by the manufacturer:

$$k_2^* = \frac{T_n}{MTBF} = \frac{n \cdot 365 \cdot 24}{MTBF} \tag{33}$$

The total revenues achieved from the electricity sales after n years of BESS operation, ER_n, are calculated using the following equation:

$$ER_n = ER_o \cdot (1+e) \cdot (1+i)^n \cdot \frac{1 - \left(\frac{1+e}{1+i} \right)^n}{i - e} \tag{34}$$

The present value of the annual revenues, ER_o, is derived as follows:

$$ER_0 = 365 \cdot 4 \cdot P_G \cdot c_G \tag{35}$$

where c_G is the BESS electric energy selling price (€/kWh).

The total cost required to purchase the additional energy imported from the electric grid in order to fulfill the battery bank charging requirements, EC_n, is calculated as a function of the amount of the total annual imported energy per year, E_S (kWh), which is calculated during the BESS operation simulation and the cost of the energy imported from the electric grid, c_I (€/kWh):

$$EC_n = E_S \cdot c_I \cdot (1+e) \cdot (1+i)^n \cdot \frac{1 - \left(\frac{1+e}{1+i} \right)^n}{i - e} \tag{36}$$

In case of an autonomous system the objective function is calculated using equations (24)-(35) and setting $EC_n = 0$.

In order to investigate the effect of the objective function type on the optimal sizing results produced by the GA optimal sizing process, an additional objective function in the case of the non-autonomous system has been implemented. It is defined as the ratio of the total annual energy imported to the BESS from the electric grid during the battery charging process, to the total annual energy transferred from the BESS to the electric grid during the guaranteed power supply time intervals, i.e. from 11:00 to 15:00:

$$g(P_G) = R_E = \frac{E_S}{P_G \cdot 4 \cdot 365} \tag{37}$$

This type of objective function has been used in [18] for the size optimization of a pumped hydro storage system.

The BESS cost (objective) function minimization is performed by maximizing the GA fitness function as follows:

$$f(\mathbf{X}) = \begin{cases} C_{max} - g(\mathbf{X}), \text{ if } C_{max} - g(\mathbf{X}) > 0, \\ 0, \text{ otherwise} \end{cases} \tag{38}$$

where $f(\mathbf{X})$ is the fitness function used by the GA for the selection of the chromosomes that will participate in the GA mutation and crossover operations and $\mathbf{X} = [N_I, P_G, n_{bp}]$ or $\mathbf{X} = [P_G]$, depending on the objective function type.

The variable C_{max} is the absolute minimum of function $g(\mathbf{X})$ and it is calculated at each GA generation. The objective function minimization is performed subject to the following constraints:

$$\begin{aligned} & N_I \geq 1 \\ & 0 < P_G \leq P_{L,min} - P_{T,min} \\ & n_{bp} \geq 1 \end{aligned} \tag{39}$$

where $P_{L,min}$ is the minimum power demand of the electric grid load during the guaranteed power production time intervals (11:00–15:00) throughout the whole year and $P_{T,min}$ is the technical minimum of the electric network thermal power stations.

In case that any of the optimization problem constraints described above is not satisfied, then the specific chromosome containing the corresponding genes is rejected.

The GA optimization process flowchart is illustrated in Fig. 4. An initial population of chromosomes, comprising the 1st generation, is generated randomly. In case that any of the initial population chromosomes violates the problem constraints, then it is replaced by a new chromosome, which is generated randomly and fulfils these constraints. The first step of each algorithm iteration is the fitness function evaluation for all chromosomes of the corresponding population. If any of the resulting fitness function values is lower than the lowest value obtained at the previous iterations, then this value is considered to be the optimal solution of the minimization problem and the corresponding chromosome consists of the BESS optimal operational parameter values. This optimal solution is replaced by better solutions, if any, produced in subsequent GA generations during the program evolution. The selection of the chromosomes which will be subject to the crossover and mutation operations, thus producing the next generation population, is based on the roulette wheel method [19]. The crossover mechanism uses the Simple Crossover, Simple Arithmetical Crossover and Whole Arithmetical Crossover operators. Next, the selected chromosomes are subject to the mutation mechanism, which is performed using the Uniform Mutation, Boundary Mutation

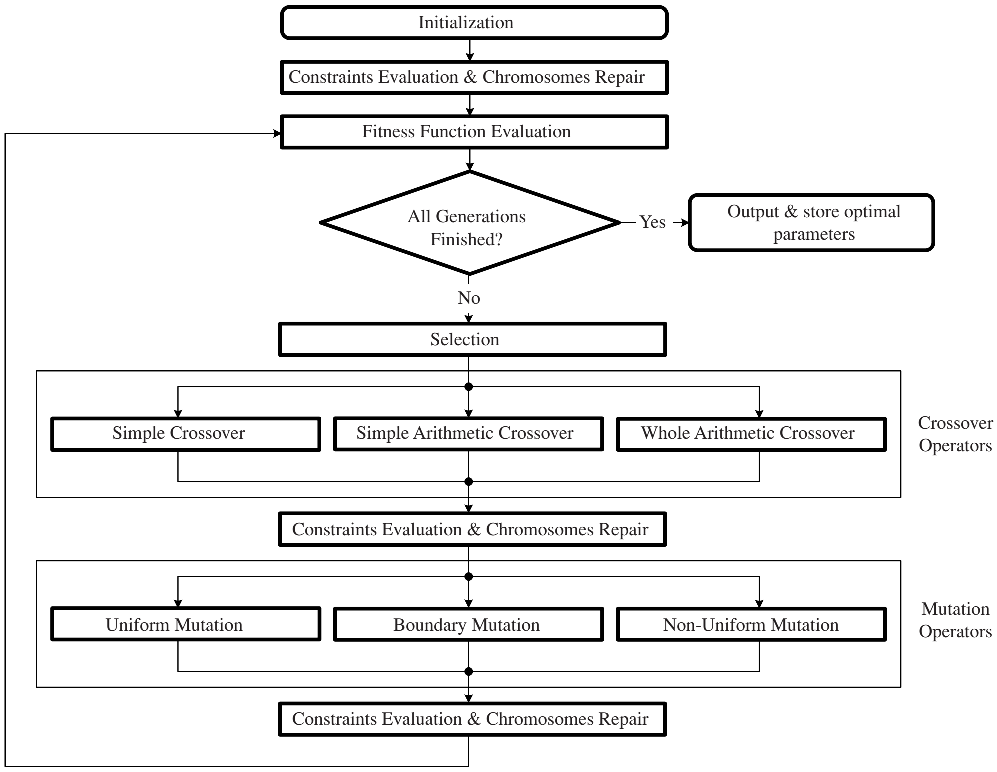

Figure 4: The GA optimization process flowchart.

and Non-Uniform Mutation operators. In case that the application of the crossover or mutation operators results in a chromosome which does not satisfy the optimization problem constraints, then a "repair" procedure is performed and that chromosome is replaced by the corresponding parent. In case of the Simple Crossover operation, where each new chromosome is generated by two parents, then the chromosome is replaced by the parent with the best fitness function value. The GA optimization process described above is repeated until a predefined number of population generations have been evaluated. The GA parameters used in the proposed methodology have the following values:

- Number of generations: $G = 10000$,
- Number of chromosomes $N = 30$,
- Simple crossover probability $p_{sc} = 0.1$,
- Simple arithmetic crossover probability $p_{sac} = 0.1$,
- Whole arithmetic crossover probability $p_{wac} = 0.1$,
- Uniform mutation probability $p_{um} = 0.1$,
- Boundary mutation probability $p_{bm} = 0.03$ and
- Non-uniform mutation probability $p_{nm} = 0.35$.

5. ECONOMIC ANALYSIS

The total economic benefit, EB (€), which can be achieved during the operational lifetime of an optimally sized BESS configuration is equal to the opposite of the system total cost function:

$$EB = -g(N_I, P_G, n_{bp}) \tag{40}$$

The economic viability of the proposed BESS is investigated by calculating the system discounted payback period (DPP) and the internal rate of return (IRR) [20]. The discounted payback period, n*, is defined as the time period that sets the system net present value (NPV) to zero:

$$NPV = \frac{-g(N_1, P_G, n_{bp})}{(1+i)^n} = \frac{ER_n - CC_n - MC_n - EC_n}{(1+i)^n} = 0 \quad ,\text{for } n = n^* \tag{41}$$

The internal rate of return (IRR) is equal to the discount rate value that sets the system NPV to zero:

$$NPV = \frac{-g(N_1, P_G, n_{bp})}{(1+i)^n} = \frac{ER_n - CC_n - MC_n - EC_n}{(1+i)^n} = 0 \quad ,\text{for } i = IRR \tag{42}$$

The values of n* and IRR are calculated by solving eqns. (41) and (42), respectively, using numerical analysis methods. In case of an autonomous system, the values of n* and IRR are calculated by setting $EC_n = 0$ in eqns. (41) and (42), respectively. An investment is considered to be economically viable when NPV > 0, n* < n and the corresponding IRR value is above an acceptance limit, which is set according to the market conditions.

6. SIMULATION RESULTS AND DISCUSSION

The proposed methodology has been applied in order to design a BESS which is using the rejected power of wind farms installed in the island of Crete, Greece. The electric network of this island is autonomous. According to the data provided by the Greek Public Power Corporation, the installed capacity of the conventional generation units of the electric network of Crete is 837MW. However, the maximum power which can be generated during the summer period is 750MW, due to increased temperature operating conditions. The technical minimum of the electric network thermal power stations is 151MW. In Spring 2008, the minimum load power demand was 175MW. The maximum load power demand during the year 2007 was 675MW and it is expected that this value will be increased to 720MW during the year 2008.

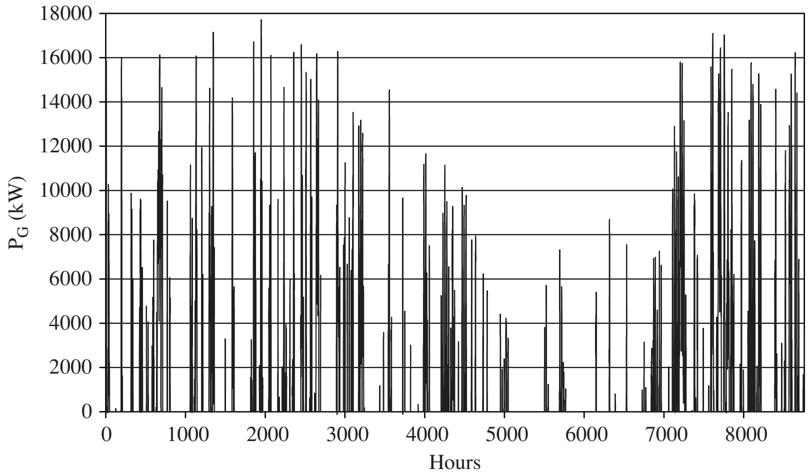

Figure 5: The estimated hourly distribution of the rejected power of three wind farms during the year 2005.

Table 1: The battery specifications

V_{bn} (V)	C_b (Ah)	DOD (%)	C_{CB}(€)	Q_{life} (Ah)	$L_{B,max}$ (years)
12	185	0.8	280	228870	7

Table 2: The DC/AC converter specifications

P_{nom} (kW)	n_{inv} (%)	V_{op} (V)	MTBF (h)	C_{CI} (€)	C_{CU} (€)
100	0.94	360	87600	15650	50

The estimated hourly distribution, during the year 2005, of the rejected wind-generated power of three wind parks installed on this island is depicted in Fig. 5. The rated power of these wind parks is 25MW, while the total rejected energy during the year 2005 is E_R = 9774MWh, corresponding to approximately 13% of the produced energy.

The BESS battery bank is composed of lead-acid batteries, which have been used in a wide variety of energy-storage installations for utility applications [6, 7]. The charging current has been limited to $I_{CM} = C_{nom}/5h$ in order to avoid the battery performance degradation under practical operating conditions. The value of I_{DM} has been set equal to $C_{nom}/5h$ since the battery nominal capacity is significantly reduced at higher discharge rates. The battery bank charging and discharging procedures have been simulated using equations (1)-(22). The technical and economical characteristics of the batteries and the DC/AC converters input to the optimal sizing algorithm are presented in Tables 1 and 2, respectively. The annual maintenance cost of the batteries has been set equal to 1.5% of the corresponding capital cost. The repair and annual maintenance costs of the DC/AC power converters have been set equal to 1% and 1.5%, respectively, of the corresponding capital cost.

According to the local market conditions, the values of the economic parameters used for the analysis are:

- Discount rate i = 8%,
- Inflation rate g_I = 3%,
- Electricity price annual escalation rate e = 2% and
- The IRR value acceptance limits have been set to 5%, 8% and 12% in case that the BESS operational lifetime is 5, 10 and 15 years, respectively.

The State subsidization rate, s (%), for the proposed configuration is possible to range between 30% and 50%. The BESS optimal sizing software was developed using the Microsoft Visual C++ language and the CPU time required for the optimal sizing of each combination of input device types is approximately one hour, using a PC with a 2.08GHz CPU and 768MB RAM.

The proposed methodology has been applied for the optimal sizing of an autonomous BESS system. The economic viability of the resulting BESS configurations was investigated by calculating the corresponding net present values. According to the economic analysis results, an autonomous BESS is not economically viable (i.e. NPV < 0) even in case that the electric energy selling price is equal to c_G = 0.45€/kWh and the subsidization ratio is s = 50%, which occur under the most favorable local market conditions. This is due to the rejected power hourly variability, exhibiting large spikes of available power during short time intervals, while for long time periods there is any available rejected energy. Thus, a large number of batteries is required in order to capture and store such a large amount of energy, increasing the total cost of the autonomous BESS such that its installation is not economically viable.

The economic viability of a non-autonomous BESS configuration has been investigated for various values of the parameter r_C, which is defined as the ratio of the imported energy cost, c_I (€/kWh), to the BESS electric energy selling price, c_G (€/kWh):

Table 3: The BESS optimal configuration and economic parameters in case of a non-autonomous system with s=30% and r_C = 0.1

n (years)	N_I	N_B	P_G (kW)	R_E	CC_n (€)	MC_n (€)	EC_n (€)	ER_n (€)	EB (€)	IRR (%)	n* (years)
5	2	330	134	0.81	127330	11851	12847	157920	5890	10	4.7
10	2	270	114	0.78	161700	150150	26976	345740	6903	8.3	9.7
15	2	270	114	0.78	237600	376760	52416	671770	4999.5	8	14

$$r_C = \frac{c_I}{c_G} \tag{43}$$

For c_G < 0.13€/kWh the optimally sized BESS configurations are not economically viable, since either NPV < 0 or the resulting IRR values are below the corresponding acceptance limit. If the guaranteed electric energy selling price is equal to 0.13 €/kWh then an economically viable solution for this configuration can be achieved only in case that s ≥ 30%. Furthermore, if c_G = 0.13€/kWh and the subsidization rate is s = 30%, then economically viable solutions can be achieved only in case that r_C = 0.1 According to the optimally sized BESS operation simulation results for c_G = 0.13€/kWh, s = 30%, r_C = 0.1 and n = 5, 10 or 15 years, respectively, the battery bank operational lifetime is L_B = 5 years. The corresponding results of the optimization process including the optimal numbers of DC/AC converters, the total number of batteries, the total investment capital, the total maintenance cost, the cost of the additional energy imported from the electric grid and the total revenues achieved from the electricity sales for n = 5, 10 and 15 years, respectively, of BESS operational lifetime, are summarized in Table 3. It is observed that due to the limited operational lifetime of the batteries and the periodic battery bank replacements required, the maintenance expenses, MC_n, are highly increased for n = 10 and 15 years. Thus, although the installation cost, CC_n, is much lower than the total revenues achieved from the electricity sales, ER_n, for n = 10 and 15 years, the resulting total economic benefit, EB, is very low and the IRR value is below the corresponding acceptance limit for n = 15 years. Thus, the economic viability requirements are satisfied only in case that the BESS operational lifetime period is 5 or 10 years, respectively.

The values of the optimal number of power converters (N_I), the optimum total number of batteries (N_B) and the optimum guaranteed power level (P_G) only for those values of the parameter r_C which result in an NPV value such that NPV > 0, in case that the electric energy selling price is equal to 0.13€/kWh and s = 50%, are illustrated in Figs. 6, 7 and 8, respectively. It is observed that the optimal numbers of batteries and DC/AC power converters, the optimal guaranteed power level and the corresponding values of the initial investment capital, depicted in Fig. 9, are decreased with an increase of the r_C ratio value, because of the corresponding increment of the imported energy cost. Thus, for higher values of r_C any further exploitation of the available rejected energy results in BESS configurations which are not economically viable. The maximum values of N_I, P_G, n_{bp} and CC_o are produced in case that the BESS operational lifetime is n = 5 years, because the system maintenance cost is highly increased for higher values of n. The system maintenance costs are mainly influenced by the periodic battery bank replacements required, since according to the optimally sized BESS operation simulation results for c_G = 0.13€/kWh and s = 50%, the battery bank operational lifetime is L_B = 6 years for n = 5 years and r_C = 0.1 or r_C = 0.2, while L_B = 5 years for the rest of the combinations. Thus, in case that n > 5, any further exploitation of the available rejected energy achieved by the installation of more power converters and batteries results in BESS configurations which produce a

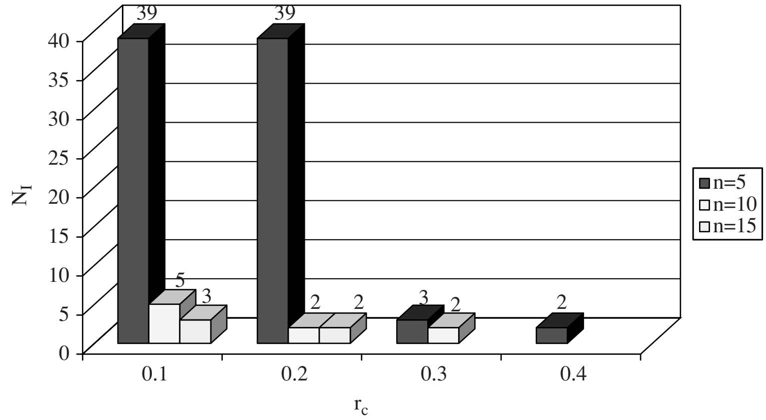

Figure 6: The variation of the optimal number of power converters versus the ratio r_C in case of c_G = 0.13€/kWh and s = 50%.

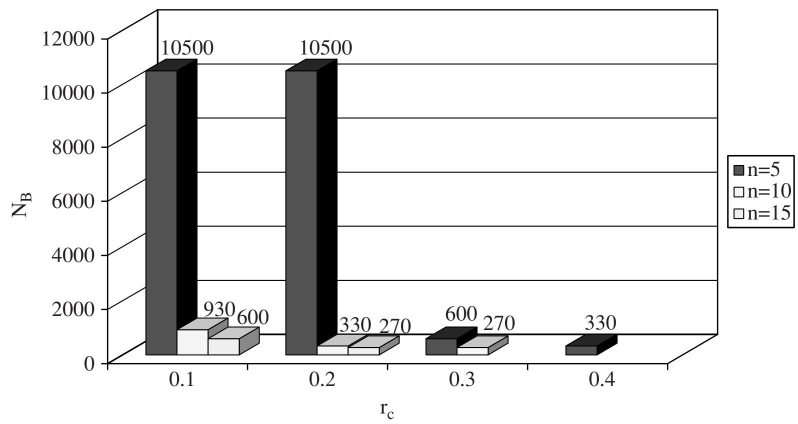

Figure 7: The optimal total number of batteries for various values of r_C in case of c_G = 0.13€/kWh and s = 50%.

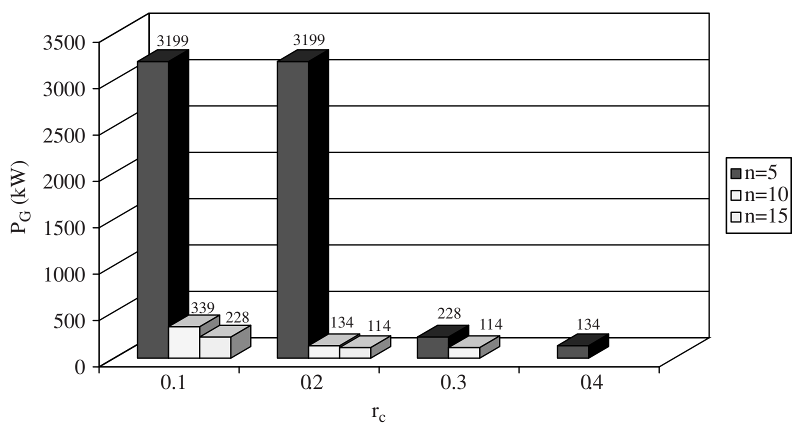

Figure 8: The optimal guaranteed power level for c_G = 0.13€/kWh and s = 50%.

drastically lower total economic benefit. The total cost of the batteries is 82% of CC_o for n = 5 years, while the total cost of the DC/AC power converters and control units is 18% of CC_o for n = 5 years. The specific turnkey price of the installation $[\, CC_o/(N_I \cdot P_{nom}) \,]$ is 535-910 €/kW for $0.1 \le r_C \le 0.4$ if the electric energy selling price is equal to 0.13€/kWh and s = 50%.

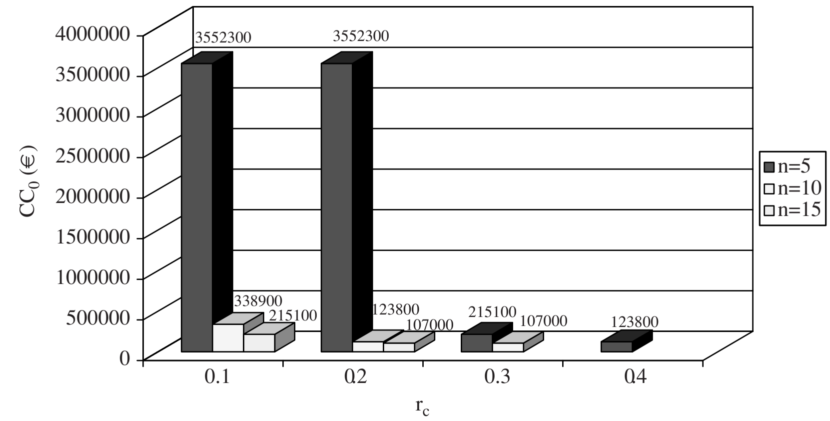

Figure 9: The variation of CC_0 versus r_C in case of c_G = 0.13€/kWh and s = 50%.

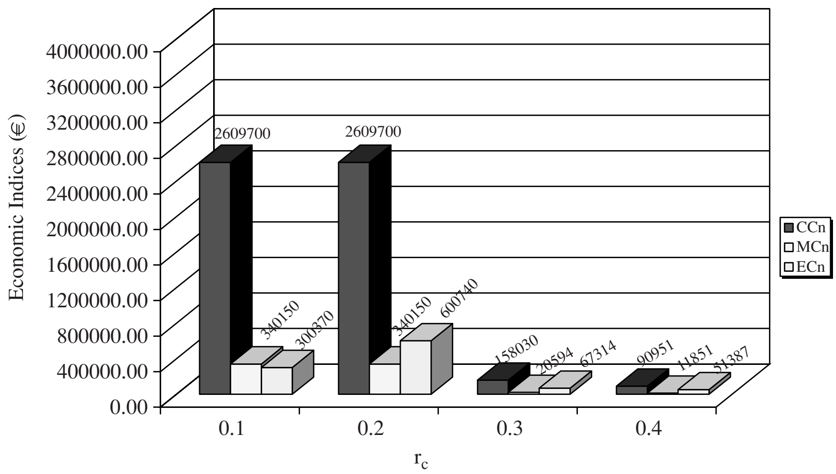

Figure 10: The economic indices CC_n, MC_n and EC_n for c_G = 0.13€/kWh, n = 5 years and s = 50%.

These values are significantly lower than the corresponding values of a pumped hydro storage system (1500-2000 €/kW) [3].

The economic indices of the optimally sized BESS in case that c_G = 0.13€/kWh, n = 5 and s = 50% are depicted in Figs. 10 and 11. The total revenues, ER_n, remain high when $r_C < 0.2$ but decrease significantly when r_C increases. It is worth noted here that in all cases the total revenues are higher than the total investment capital. The total maintenance expenses, MC_n, are approximately 13% of the installation cost, CC_n, while the imported electric energy cost, EC_n, is 11-56% of CC_n.

The economic viability of the optimally sized BESS configurations with NPV > 0 has been investigated by calculating the discounted payback period and the IRR for various values of r_C. The discounted payback period and the IRR for various values of n, s and r_C in case that c_G = 0.13€/kWh, are illustrated in Figs. 12 and 13, respectively. Their variability is due to the different values of the optimal guaranteed power produced in each case, which also affects the resulting total economic benefit of the installation, depicted in Fig. 14. In case that n = 5 the discounted payback period is 4.2-4.7 years, while in case that n = 10 and 15 years the resulting discounted payback period is higher than 8.8 years and 13 years, respectively. The calculated IRR values of the optimally sized BESS configurations in case that n = 5, s = 50% and $0.1 \leq r_C \leq 0.4$

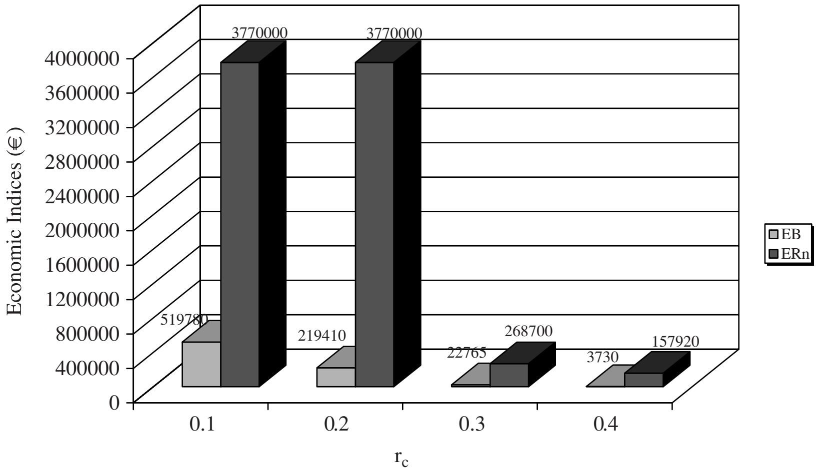

Figure 11: The economic indices ER_n and EB for c_G = 0.13€/kWh, n = 5 years and s = 50%.

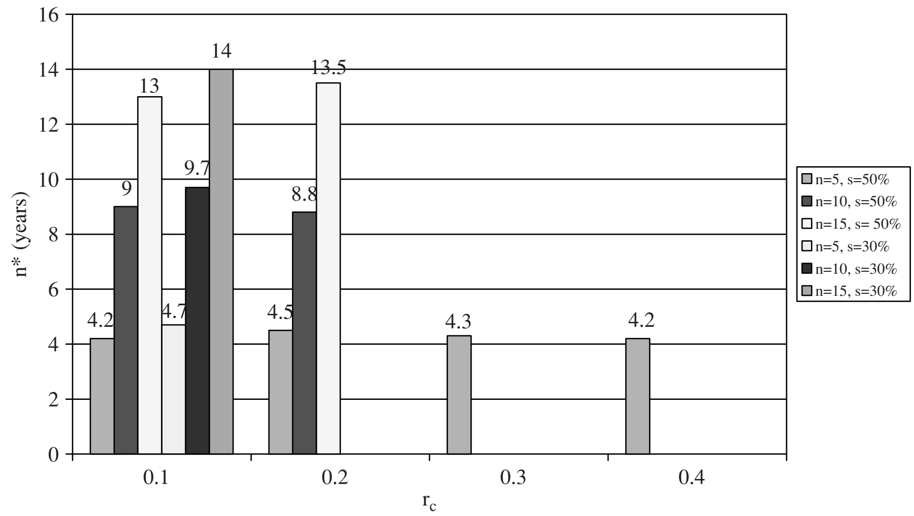

Figure 12: The variation of the discounted payback period for various values of r_C and n in case that c_G = 0.13€/kWh.

range from 10% to 15%. These values are above the acceptance limit of 5% for a 5 years BESS operational lifetime. In case that n = 10 years, the calculated IRR values are above the corresponding acceptance limit in case that $r_C < 0.3$. Also, for a 15 years BESS operational lifetime the IRR value is never above the 12% acceptance limit. It is observed that increasing the BESS operational lifetime period results in a restriction of the economic conditions which are required in order to achieve the system economic viability. This is due to the necessary battery bank replacements during the system lifetime, which result in a significant increase of the system maintenance cost. Thus, the resulting economic benefit, EB, presented in Fig. 14, is significantly reduced for n > 5. The amount of the annual energy imported from the electric grid in order to support the BESS guaranteed power production depends on the rejected power hourly variability. The calculated optimal values of R_E are equal to 0.78–0.84, thus contributing towards the reduction of the air pollution caused by the thermal power stations, while in case of a pumped hydro storage system the additional energy imported during the year is of the order of the annual guaranteed energy exported to the electric grid [18].

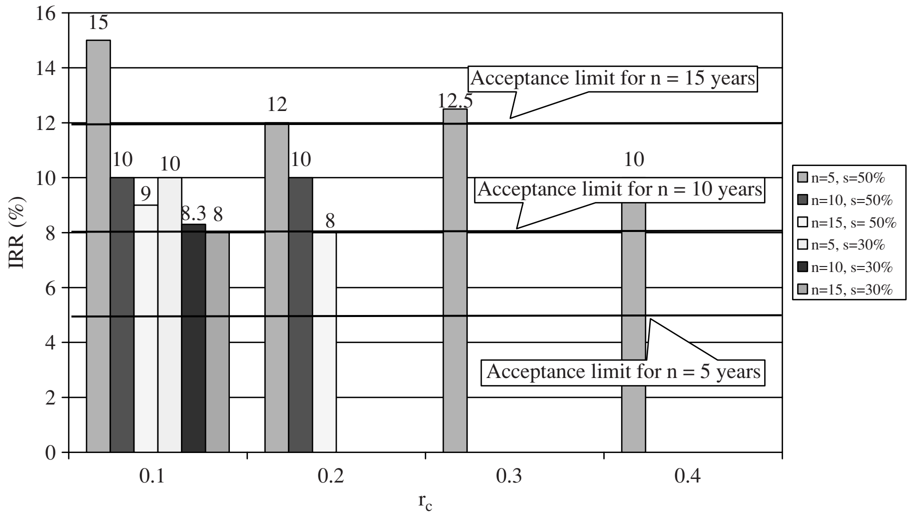

Figure 13: The IRR for various values of r_C, n and s (%) in case that c_G = 0.13€/kWh.

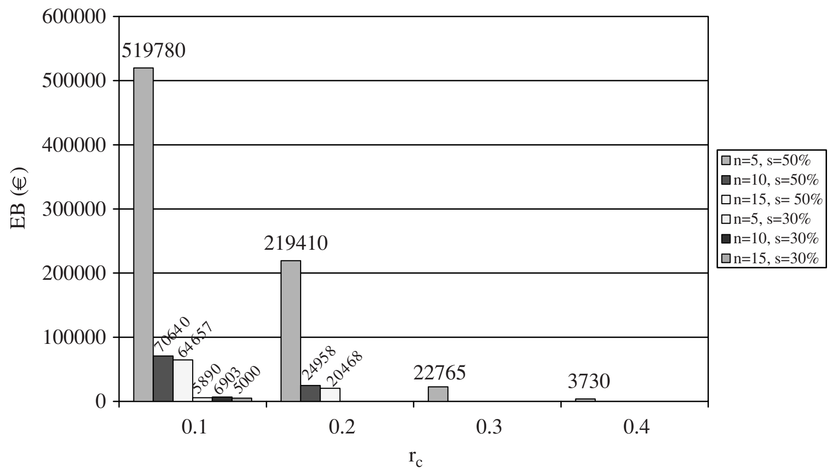

Figure 14: The EB for various values of r_C, n and s (%) in case that c_G = 0.13€/kWh.

The proposed optimal sizing procedure and the economic analysis have been performed for $c_G > 0.13$€/kWh and for various values of n, s and r_C such that n = 5, 10, and 15 years, $0\% \le s \le 50\%$ and $0.1 \le r_C \le 0.8$. According to the corresponding results, the value of the battery bank lifetime, L_B, varies in the range of 5 to 7 years, depending on the guaranteed power level and the total number of batteries composing each optimally sized BESS. The ranges of the calculated operational parameters corresponding to economically viable configurations (i.e. NPV > 0 and IRR value above the corresponding acceptance limit) are summarized in Table 4. It is observed that both the total economic benefit and the guaranteed power level are highly increased for values of c_G in the 0.29–0.45 €/kWh range. The specific turnkey price of the economically viable BESS installations $[CC_o/(N_I \cdot P_{nom})]$ is 535–1562 €/kW. These values are lower than the corresponding values of a pumped hydro storage system (1500–2000 €/kW) [3]. The optimal values of R_E are equal to 0.78–0.88, thus contributing towards the reduction of the air pollution caused by the thermal power stations, while in case of a pumped hydro

Table 4: The optimal sizing and economic analysis results for c_G > 0.13€/kWh

c_G (€/kWh)	s (%)	n (years)	r_C	P_G (kW)	n* (years)	IRR (%)	R_E	EB (k€)
0.29	0	5	0.1–0.5	114–11698	3.8–4.7	10–18	0.78–0.85	89.20–3537.8
		10	0.1–0.6	114–11698	4.3–9	10–14	0.78–0.85	29.03–14537
		15	0.1–0.3	3397–11698	4.3–4.5	12–16	0.79–0.85	7296–53642
	50	5	0.1–0.8	2737–11698	2–4.6	10–50	0.78–0.85	163.1–15100
		10	0.1–0.8	114–11698	2–8.8	10–24	0.78–0.85	24.2–31507
		15	0.1–0.6	3199–11698	3–3.5	15–25	0.78–0.85	7112.8–78576
0.35	0	5	0.1–0.6	339–11698	3.8–4.7	10–23	0.8–0.85	28.7-9360
		10	0.1–0.7	114–11698	3.5–8.6	10–19	0.78–0.85	41.3–29500
		15	0.1–0.5	3397–11698	3–4	12–22	0.78–0.85	5816.3–82800
	50	5	0.1–0.8	3397–16538	2.4–3.7	18–40	0.79–0.88	779.37–22035
		10	0.1–0.8	2737–11698	1.7–9.4	9–30	0.78–0.85	391.98–46491
		15	0.1–0.7	3397–11698	2–3	12–33	0.79–0.85	3360.5–107690
0.45	0	5	0.1–0.8	114–11698	2.5–4.7	10–35	0.78–0.85	7.31–19100
		10	0.1–0.8	114–11698	2.5–8	12–26	0.78–0.85	68.6–54500
		15	0.1–0.6	5908–11698	2.5–4.5	16–30	0.79–0.85	21223–131000
	50	5	0.1–0.8	8973–16538	1.8–3.8	19–55	0.82–0.87	11817.6–31096.3
		10	0.1–0.8	3397–16538	1.8–2.8	15–26	0.79–0.88	3058.8–75580
		15	0.1–0.8	3397–13738	2–2.7	12–35	0.79–0.86	4751.4–168820

storage system the additional energy imported during the year is of the order of the annual guaranteed energy exported to the electric grid [18].

According to [3], the operational cost of the existing gas-turbine generators of the isolated electric network of Crete is 0.18-0.20 €/kWh, while it has been substantially increased since that time due to the large increment of the oil price. Also, the typical price of the electric energy offered by the Greek Public Power Corporation (PPC) to the electric network consumers from 00:00 to 08:00 is 0.031-0.049 €/kWh, depending on the AC voltage rating and the type of the electric energy consumer. Thus, according to the optimal sizing and economic analysis results presented above, the installation of the proposed BESS even with the minimum economically viable electric energy selling price c_G = 0.13€/kWh, 0.2 < r_C < 0.4, s = 50% and n = 5 years would be economically beneficial for both the BESS investor and the local electric network operator. Considering that in Greece the photovoltaic-generated electricity is sold to the electric network operator at a selling price of up to 0.45 €/kWh, the electric energy selling price of the proposed BESS could be substantially increased above the minimum economically viable limit of c_G = 0.13€/kWh, resulting in substantial increments of both the total economic benefit and the economically viable BESS operational lifetime period.

The proposed optimal sizing methodology has also been applied in the case of a non-autonomous system, using the $g(P_G)$ as the objective function to be minimized. The corresponding BESS optimal configuration consists of N_I = 2 power converters and N_B = 390 batteries. The optimal guaranteed power level is P_G = 128kW and the corresponding value of R_E is equal to 0.75. These optimal values do not depend on c_G and c_I, since the total system cost in not taken into consideration during the optimal sizing procedure. However, the parameters c_G and c_I affect the economic viability of the resulting configuration, i.e. the values of NPV, n* and IRR. According to the economic analysis results, economically viable solutions are produced only in the following cases:

- c_G = 0.13€/kWh, s = 50% and n = 5 or 10 years or
- c_G = 0.29-0.45€/kWh, s = 0-50% and n = 5, 10 or 15 years.

Table 5: The economic analysis results using the $g(P_G)$ as the objective function

c_G (€/kWh)	s (%)	n (years)	r_C	n* (years)	IRR (%)	EB (€)
0.13	50	5	0.1–0.2	4–4.4	12–16	11467–22781
		10	0.1	9.9	8.4	2322.8
0.29	0	5	0.1–0.4	3.3–4.6	11–23	15508–91222
		10	0.1–0.5	3.3–9.15	9.5–20	32704–292496
		15	0.1–0.4	3.3–4.5	12–17	225485–604071
	50	5	0.1–0.8	1.6–4.2	14–65	17849–194516
		10	0.1–0.7	1.5–8.15	12–32	54580–444268
		15	0.1–0.6	1.5–2.5	12.5–24	196098–827075
0.35	0	5	0.1–0.6	2.65–4.9	8–33	3324–155623
		10	0.1–0.6	2.6–8.4	11–26	66298–458226
		15	0.1–0.5	2.5–4.1	13–22	316868–926087
	50	5	0.1–0.8	1.3–3.3	23–81	45698–258917
		10	0.1–0.8	1.3–3.25	12–40	61299–609998
		15	0.1–0.7	1.3–2.5	13–30	235262–1149091
0.45	0	5	0.1–0.7	2–4.3	13–48	27982–262958
		10	0.1–0.8	2–9.2	9.5–35	28971–734442
		15	0.1–0.7	2–4.2	12.5–29	287858–1462780
	50	5	0.1–0.8	1–2.4	38–110	92113–366251
		10	0.1–0.8	1–2.4	18–52	180743–886214
		15	0.1–0.8	1.2–2.4	15–38	315041–1685783

The corresponding ranges of n*, IRR and EB are presented in Table 5.

It is observed that the total economic benefit, EB, achieved using the optimally sized configurations produced using this method is less compared to the values of EB achieved using the optimal BESS configurations which are produced using the $g(N_I, P_G, n_{bp})$ objective function. This is due to the fact that using the $g(P_G)$ as the objective function to be maximized, the total system cost in not taken into consideration during the optimal sizing procedure. Therefore, it is concluded that the objective function $g(P_G)$ is not a reliable criterion to be used during the optimal sizing procedure of the proposed BESS system.

An example of the objective function $g(P_G)$ variation versus the guaranteed power level, P_G, in case of a non-autonomous system with $N_I = n_{bp} = 1$, $c_G = 0.13$€/kWh, $r_C = 0.1$, $s = 50\%$ and $n = 5$, is plotted in Fig. 15. It is observed that the function $g(P_G)$ exhibits both local and global minimum points, since the available rejected wind-generated power is exploited differently for each value of the produced guaranteed power. The application of linear programming techniques for the minimization of this objective function could result in convergence to a local minimum point, instead of the global minimum solution. In the proposed method, the GA algorithm convergence to the global optimum solution has been verified, using a properly developed simulation program, by linearly changing the values of all decision variables included in the optimization process and calculating the corresponding system cost during the n years of system operation. This procedure is repeated for each combination of system components types. The resulting optimal solution, for each combination of system components types, is equal to the solution derived using the proposed GA optimization method, in terms of both the total system cost and the values of the decision variables, thus proving the GA optimization procedure capability to converge to the global optimum solution. However, the CPU time required by this simulation program to derive the optimal solution for each combination of system components types is approximately 48 hours, while using the GA-based process the corresponding time required is approximately 1 hour.

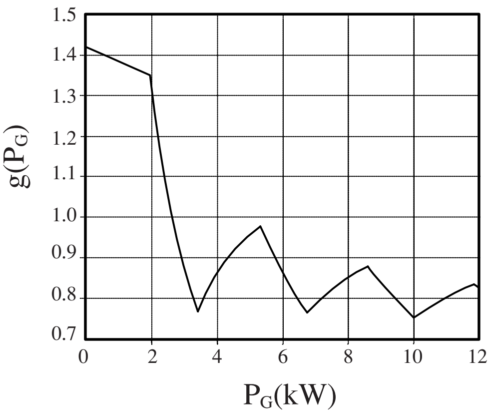

Figure 15: The variation of the objective function $g(P_G)$ versus the guaranteed power level in case that $N_I = n_{bp} = 1$, $c_G = 0.13€/kWh$, $r_C = 0.1$, $s = 50\%$ and $n = 5$ years.

7. CONCLUSIONS

In this work, a methodology for the optimal design and the economic evaluation of a battery energy storage system used to increase the wind energy penetration in isolated electric grids is presented. A part of the energy produced by wind farms interconnected with an isolated electric system is rejected by the power system due to grid stability barriers. This energy is initially stored in the proposed BESS in the form of chemical energy and then it is released back to the electric grid during the peak load-demand hours, thus enabling the reduction of the thermal power stations power contribution during that time interval. Compared to the pumped hydro storage solution, the proposed BESS configuration is characterized by minimal requirements for civil engineering works, resulting in lower installation cost. Additionally, it can be implemented in a shorter time interval, it does not influence the environmental topography of the installation area, it can be easily transferred to another installation area and its operation does not depend on extra natural resources, such as water, which is frequently unavailable in remote islands.

The BESS optimal sizing methodology presented in this paper targets to calculate the optimal values of the total number of DC/AC power converters, the total number of battery strings connected in parallel and the constant (guaranteed) power that can be supplied from the BESS to the electric grid from 11:00 to 15:00 every day of the year, such that the economic benefit resulting from the BESS energy sales to the electric grid is maximized. The maximization of the economic benefit function is implemented employing Genetic Algorithms (GAs), which compared to the conventional optimization methods have the ability to obtain the global optimum solution with relative computational simplicity.

The proposed method has been applied for the optimal design of a BESS supporting the isolated electric network of a remote island with significant wind potential. According to the optimal sizing and economic analysis results, the economical viability of the proposed BESS is highly restricted by the short operational lifetime of the batteries, which increases the system maintenance cost due to the necessary battery bank replacements. The installation of the proposed BESS even with the minimum economically viable electric energy selling price $c_G = 0.13€/kWh$, $0.2 < r_C < 0.4$, $s = 50\%$ and $n = 5$ years would be economically beneficial for both the BESS investor and the local electric network operator. Compared to the pumped hydro storage systems, the proposed BESS installations have the advantages of lower specific turnkey price and lower requirements of importing additional energy from the electric grid, thus contributing towards the reduction of the air pollution caused by the thermal power stations.

ACKNOWLEDGEMENT

The authors would like to thank their former graduate student Mr. D. Papadopoulos for his contribution during the development of the optimal sizing program code.

NOMENCLATURE

B_C	Total replacement cost of the batteries
C_b	Nominal capacity of each battery
C_{CB}	Capital cost of each battery
C_{CI}	Capital cost of each power converter
C_{CU}	Capital cost of each control unit
C_{init}	Initial capacity of the battery bank
C_{MB}	Annual maintenance cost of each battery
C_{MI}	Annual maintenance cost of each power converter
C_{nom}	Total nominal capacity of the battery bank
CC_n	Total investment capital for n years
CC_0	Total investment capital on year 0
C(DOD)	Number of battery charging/discharging cycles that can be achieved in case that the corresponding depth of discharge is equal to DOD
c_G	BESS electric energy selling price (€/kWh)
c_I	Cost of the energy imported from the electric grid
DOD_{max}	Batteries maximum permissible depth of discharge
$E^i_{oc,s}(t)$	Open-circuit voltage on day i and at the beginning of hour t
E_R	Total rejected energy during the year
EB	Total economic benefit
EC_n	Cost of the additional energy imported from the electric grid in order to fulfill the battery bank charging requirements for n years
ER_n	Total revenues achieved from the electricity sales for n years
e	Electricity price annual escalation rate
F_O	Over-sizing factor
$f(\mathbf{X})$	Fitness function
g_I	Inflation rate
$g(N_I, P_G, n_{bp})$	Objective function
$I^i_{BA}(t)$	Battery bank total charging current on day i and at the beginning of hour t
$I_{BA,max}$	Maximum battery bank charging current
$I^i_{BS}(t)$	Batteries charging current on day i and at the beginning of hour t
I_{CM}	Maximum permissible charging current specified by the battery manufacturer
$I_{DC,max}$	Maximum value of the charging current which can be supplied by the DC/AC power converter to the battery bank
I_{DM}	Maximum permissible battery discharging rate
IN_C	Total repair cost of the power converters
IRR	Internal rate of return
i	Discount rate
L_B	Lifetime of the batteries (years)
$L_{B,max}$	Battery maximum lifetime period (years)
MC_n	Total maintenance cost of the system batteries and DC/AC power converters for n years
MTBF	Mean time between failures of the power converter

N_B	Total number of batteries composing the BESS battery bank
N_C	Number of series-connected cells forming each battery
N_I	Total number of DC/AC power converters
n_B	Battery round-trip efficiency during charging
n_{bp}	Total number of battery strings forming the battery bank
n_{bs}	Total number of batteries connected in series
n_{inv}	DC/AC power converter efficiency
n^*	Discounted payback period
$P_{chA}^{i}(t)$	Power which must be transferred to the battery bank during the charging process on day i and at the beginning of hour t
P_G	Guaranteed power
$P_{L,min}$	Minimum power demand of the electric grid load during the guaranteed power production time intervals throughout the whole year
P_{nom}	Nominal AC power rating of each DC/AC converter
$P_R^i(t)$	Rejected wind generated power on day i and at the beginning of hour t
$P_{T,min}$	Technical minimum of the electric network thermal power stations
Q_{actual}	Battery bank ampere-hour throughput during the year
Q_{life}	Total ampere-hours that can be stored and used during the battery lifetime
R_{CI}	The repair cost of each power converter
R_E	The ratio of the total annual energy imported to the BESS from the electric grid during the battery charging process, to the total annual energy transferred from the BESS to the electric grid during the guaranteed power supply time intervals
$R_{int,s}^{i}(t)$	Internal resistance of battery on day i and at the beginning of hour t
r_C	Ratio of the imported energy cost to the BESS electric energy selling price
$r_1, r_2(SOC^i(t))$	Parameters calculated according to the information provided by the battery manufacturer about the variation of the internal resistance with the battery state of charge
$SOC^i(t)$	Battery bank state of charge at the beginning of hour t of day i
$SOC^1(0)$	The battery bank initial state of charge on day 1 and at hour 0
s	State subsidization ratio
T_n	Total number of DC/AC power converter operating hours during the BESS lifetime
V_{bn}	Nominal voltage of each battery
V_{ch}	Applied voltage during the constant-voltage charging process (V/cell)
V_{op}	DC-bus nominal voltage
v_1, v_2	Parameters calculated according to the information provided by the battery manufacturer about the variation of $E_{oc,s}^{i}(t)$ with $SOC^i(t)$

REFERENCES

[1] McDowall J. Nickel-Cadmium Batteries for Energy Storage Applications. The Fourteenth Annual Battery Conference on Applications and Advances 1999; 303–308.

[2] Kashem MA, Ledwich G. Energy requirement for distributed energy resources with battery energy storage for voltage support in three-phase distribution lines, Electric Power Systems Research 2007;77:10–23.

[3] Kaldellis JK, Kavadias KA, Papantonis DE, Stavrakakis GS. Maximising wind generated electricity with hydro storage: case study Crete. Wind Engineering 2006; 30:73–92.

[4] Korpas M, Holen AT. Operation Planning of Hydrogen Storage Connected to Wind Power Operating in a Power Market. IEEE Transactions on Energy Conversion 2006; 21:742–749.

[5] Papic I. Simulation Model for Discharging a Lead-Acid Battery Energy Storage System for Load Leveling. IEEE Transactions on Energy Conversion 2006; 21:608–615.

[6] Parker CD. Lead-Acid battery energy-storage systems for electricity supply networks. Journal of Power Sources 2001; 100:18–28.

[7] Wagner R, Schroeder M, Stephanblome T, Handschin E. A multifunctional energy-storage system with high-power lead-acid batteries. Journal of Power Sources 1999; 78:156–163.

[8] Ibrahim H, Ilinca A, Perron J. Energy storage systems — Characteristics and comparisons. Renewable and Sustainable Energy Reviews. In Press.

[9] Lu B, Shadidehpour M. Short-tem scheduling of battery in a grid-connected PV/Battery System. IEEE Transactions on Power Systems 2005; 20:1053–1061.

[10] McDowall J. Integrating energy storage with wind power in weak electricity grids. Journal of Power Sources 2006; 162: 959–964.

[11] Wu TF, Hsieh HM, Wu YE, Chen YK. Parallel-inverter system with failure isolation and hot-swap features. IEEE Transactions on Industry Applications 2007; 43: 1329–1340.

[12] Chiasson J, Vairamohan B. Estimating the State of Charge of a Battery. IEEE Transactions on Control Systems Technology 2005; 13: 465–470.

[13] Dürr M, Cruden A, Gair S, McDonald J.R. Dynamic model of a lead acid battery for use in a domestic fuel cell system. Journal of Power Sources 2006; 161: 1400–1411.

[14] Borowy BS, Salameh ZM. Methodology for Optimally Sizing the Combination of a Battery Bank and PV Array in a Wind/PV Hybrid System. IEEE Transactions on Energy Conversion 1996; 11: 367–373.

[15] Sauer D, Wenzl H. Comparison of different approaches for lifetime prediction of electrochemical systems — using lead-acid batteries as example, Journal of Power Sources 2008; 176: 534–546.

[16] Wenzl H, Baring-Gould I, Kaiser R, Liaw BY, Lundsager P, Manwell J, Ruddell A, Svoboda V. Life prediction of batteries for selecting the technically most suitable and cost effective battery. Journal of Power Sources 2005; 144: 373–384.

[17] Svoboda V, Wenzl H, Kaiser R, Jossen A, Baring-Gould I, Manwell J, Lundsager P, Bindner H, Cronin T, Norgard P, Ruddell A, Perujo A, Douglas K, Rodrigues C, Joyce A, Tselepis S, Borg N, Nieuwenhout F, Wilmot N, Mattera F, Sauer D. Operating conditions of batteries in off-grid renewable energy systems. Solar Energy 2007; 81: 1409–1425.

[18] Anagnostopoulos JS, Papantonis DE. Simulation and size optimization of a pumped-storage power plant for the recovery of wind-farms rejected energy. Renewable Energy 2008; 33:1685–1694.

[19] Michalewicz Z. Genetic Algorithms + Data Structures = Evolution Programs, 2nd ed. Springer-Verlag; 1994.

[20] Karagiannis FE. Wind energy investments in Greece — An economical approach. 10th Mediterranean Electrotechnical Conference 2000; 3: 1141–1144.