On the Design of an Optimal Hybrid Energy System for Base Transceiver Stations

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Abstract

The reduction of energy consumption, operation costs and CO_2 emissions at the Base Transceiver Stations (BTSs) is a major consideration in wireless telecommunications networks, while the utilization of alternative energy sources, such as solar or wind, having emerged as an attractive solution with numerous advantages. Nevertheless, the installation of BTSs with renewable energy, induces specific disadvantages such as the relatively higher costs and the high dependency on weather conditions. To this end, the deployment of hybrid BTSs and the optimal compromise between conventional and alternative energy sources is a very challenging problem with immense importance. In this paper, we propose a hybrid solar-wind-diesel/electricity grid system, which can efficiently feed the load of a BTS. In contrast to previous works, the seasonal effect on the BTS's electricity consumption is taken into account via considering (i) the radio transmitter and receiver operation strategy, based on the cells's traffic load, and (ii) the passive cooling. The main objective of the present work is the techno-economical optimization of the proposed hybrid system, via the development of a time-step simulation model, which takes into account the loss of load probability (LOLP) and levelized annual cost (LAC). Finally, considering the case-study of a BTS installed in the Greek island of Kea, it is shown that a combination of photo-voltaic, wind, diesel generators, batteries and electricity grid, for a grid-connected BTS, is the most cost-effective solution.

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1 Introduction

It is estimated that the telecom industry consumes about 1% of the global energy consumption of the planet [1, 2]. That is, the equivalent energy consumption of 15 million US homes and also the equivalent CO_2 emissions of 29 million cars. Over 90% of the wireless networks energy consumption is part of the operator's operating expenses. There are approximately 4 million installed Base Transceivers Stations (BTSs) in the world today. A BTS of a wireless communications network consumes 100 watts of electricity to produce only 1.2 Watts of transmitted radio signals. From a system efficiency perspective (output/input power), this translates into an energy efficiency of 1.2% [1]. In a typical BTS, radio equipment and cooling are the two major sections where the highest energy savings potential resides. To the best of our knowledge, the following techniques are proposed in the literaure [1] to reduce the power consumption of BTS:

- moving the RF converters and power amplifiers from the base of the station to the top of the tower close to the antenna and connecting them via fiber cables;
- turning radio transmitters and receivers off when the call traffic goes down (ECO Mode);
- passive cooling;
- advanced climate control for air conditioners;
- DC Power Sustem ECO Mode;
- use of higher efficiency rectifiers.

Renewable energy [3], such as wind and solar, is also used to reduce the operation costs in BTSs. These energy sources are intermittent, naturally available, environmental friendly and can be used to provide virtually free energy. Solar systems are a mature technology, used to power some remote BTSs for many years, replacing the expensive to run diesel generators. Hybrid solar-wind systems use two renewable energy sources, improving the system efficiency and reducing the energy storage requirements [4]. A solar-wind hybrid power generation system for remote BTSs is also proposed in [5]. However, the main problem of the renewable energy installations is that the generation of electricity cannot be fully forecasted and may not follow the trend of the actual energy demand [6]. In order to select an optimum combination for a hybrid system to meet the load demand, evaluations must be carried out on the basis of power reliability and system life-cycle cost.

Recently, several simulations have been performed in order to optimize hybrid energy systems and to fulfill the energy demands of a BTS. Hashimoto et al. [7] described a stand-alone hybrid power system, which is consisted of wind generators and photovoltaic modules for a BTS, comparing the produced energy during the worst month of the year with the consumed energy. In [8, 9] the software Homer (Hybrid optimizing model for electric renewables) is used to size a hybrid energy system for BTS [4]. Homer is a time-step simulator using hourly load and environmental data inputs for renewable energy system assessment. However, the limitation of this software is that algorithms and calculations are not visible or accessible. Ekren et al. [10] used ARENA 10.0, a commercial simulation software, to meet the electric power consumption of the global system for mobile communications (GSM) base station. One of the main objectives of Ekren et al. [10] is to show the use of the response surface methology (RSM) in size optimization of an autonomous PV/wind integrated hybrid energy system with battery storage. Furthermore, the same authors, in [11], developed a Simulated Annealing (SA) algorithm to optimize the size of a PV/wind integrated hybrid system with battery storage. They show that the SA algorithms give better results than the RSM. Furthermore, in [12], ARENA 12.0 was used to size a PV/wind integrated hybrid energy system with battery storage under various loads and unit cost of auxiliary energy sources. The optimum results were confirmed using loss of load probability and autonomy analysis. Finally, Hongxing et al. [13] proposed an optimal design model for designing hybrid solar-wind system employing battery banks for calculating the system optimum configurations and ensuring that the systems's annualized cost is minimized, while satisfying the custom required loss of power supply probability. The proposed method has been applied to design a hybrid system to supply power for a telecommunication relay station. The previous studies ignore the seasonal effect on the BTSs electricity consumption or they focus primarily on remote BTSs.

In this paper, we propose a hybrid solar-wind-batteries-diesel/electric grid system to reduce the operation costs in TBSs and an appropriate sizing model to evaluate them. The development of the time-step simulation model is based on the loss of load probability and levelized annual cost. The recommended algorithm is appropriate to size properly a hybrid system in order to meet all or a part of sustained load demands of a BTS and to evaluate the CO_2 emissions. The appropriate operation of a BTS supplied by hybrid system is described, modeled and simulated. The considered consumption model is a typical BTS, as presented by [14].

The contribution of this paper can be summarized as follows:

1. The proposed model is suitable both for remote and grid-connected BTSs.
2. The strategies of passive cooling and ECO Mode, which are responsible for the seasonal effect on the BTS's electricity consumption, are not ignored. The final BTS's load is determined during the time of simulation, via considering the indoor and outdoor temperature for the determination of the power consumption of the cooling equipments. In order to model the aforementioned techniques, we considered the separation of the total BTS's load in two parts:
   (a) the DC part, which includes the radio equipment, the feeder and the antenna, and
   (b) the AC part, which includes the cooling equipments.
3. An alternative use of cooling equipment is proposed. This new method is consisted of full operation of cooling equipments when there is a surplus of energy produced by the solar-wind system and limited operation when the energy provided by the solar-wind-batteries system almost meets the BTS's consumption.
4. Finally, the proposed algorithm is used to cost several configurations of hybrid system for a BTS, located in the Greek island of Kea. It is shown that a combination of photo-voltaic generators, wind generators, batteries and diesel generator or grid is the most cost-effective solution.

The rest of the paper is organized as follows. In Section 2, we introduce the hybrid system configuration. The model for BTS load is given in Section 3, while the power management is formulated in Section 4. The algorithm for the techno-economic analysis is presented in Section 5 and the simulation results are given in Section 6. Finally, the paper is concluded in Section 7.

2 The Hybrid System Configuration

2.1 Wind Turbine

The main factor that determines the power output of a wind turbine is the wind speed. Therefore, choosing a suitable model is very important for wind turbine power simulations. The most simplified model to simulate the power output, P_w of a wind turbine can be described by the following equation [15]:

$$P_w(u) = \begin{cases} 0, u \leq U_c \\ P_r \frac{u-U_c}{U_r-U_c}, U_c < u < U_r \\ P_r, U_r \leq u \leq U_f \\ 0, u > U_f \end{cases} \tag{1}$$

where P_r is the rated power, U_c is the cut-in wind speed, U_r is the rated wind speed and U_f is the cut-off wind speed.

Wind speed varies with height, while wind data of different sites are measured at different levels. The wind speed, u, corresponding to a height, H, is given by the wind power law for the case of known value of wind speed, u_0, for the specific height H_0, as

$$u = u_0 \left(\frac{H}{H_0}\right)^{\xi}, \tag{2}$$

where ξ is the power law exponent. The one-seventh is a good reference number for flat surfaces where a BTS is usually located, far away from tall trees or buildings. Here, H and H_0 denote the height of the turbine and measuring above the ground, respectively.

2.2 Photo-Voltaic Generator

There are three main factors that determines the power output of a PV generator, namely the PV cell material, the cell temperature and the solar radiation incident on the PV modules. An appropriate model to simulate the power output of a PV generator is described by [15]

$$P_p = n_p E_p G_t, \tag{3}$$

where n_p represents the PV generator efficiency, E_p (in m^2) the area of the PV generator and G_t (in W/m^2) the solar radiation that incidents on the PV module. The PV generator efficiency is given by

$$n_p = n_m n_e[1 - b(T_c - T_r)], \tag{4}$$

where n_m is the reference module efficiency, n_e is the power conditioning efficiency, b is the generator efficiency temperature coefficient, T_r is the reference cell temperature and T_c is the cell temperature given by

$$T_c = T_a(t) + \frac{T_n - 20}{800} G_t, \tag{5}$$

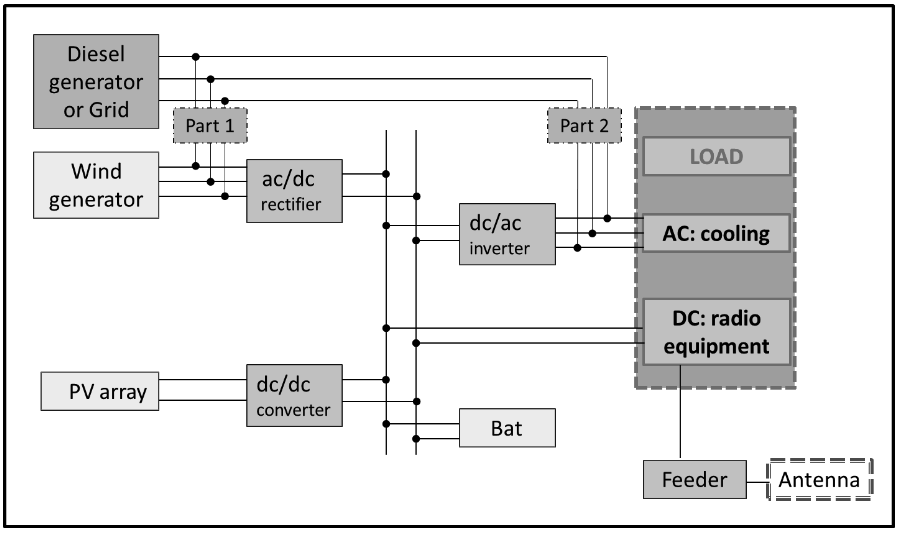

Figure 1 System configuration.

with T_a being the ambient temperature and T_n the nominal cell operating temperature.

The solar radiation incident G_t on a PV module is a function of time, orientation and slope angle. However, the solar radiation is usually measured only at a horizontal plane. Thus, a technique to transfer the radiation measured at horizontal plane to the desired slope angle β of the PV module is needed. Such a technique is described in detail in [16].

2.3 Diesel Generator – Grid

The majority of the BTSs already has a diesel generator, which can also be used as a backup to the hybrid system, reducing the installed size of the described wind/PV/battery system. At the same time, grid connection could be used as a back up too, when possible. Moreover, the grid should be used as a storage system, by giving the surplus of energy to the grid or taking from it when there is a shortfall. The aforementioned technique leads to great financial benefits, such as the nulling of the batteries required. However, the unique disadvantage associated with this technique is the increase of the CO_2 emissions.

The operation of the diesel generator can be described as $P_n = n_t P_d$, where P_d is the nominal power of the diesel generator and $n_t = n_0 n_g$ [17].

The factor n_0 is used to show that the total efficiency of the diesel generator depends on the load factor. Diesel generators work more efficiently when they are operated at 70–90% of full load. Since the proposed hybrid energy system will include batteries, it is recommended that they charge when the diesel generator is already on.

By means of the algorithm we describe in Section 5, the CO_2 emissions of every solution can be computed. Obviously on a system that relies only on green sources of energy the emissions are null. But when diesel generator or grid is used, CO_2 emissions per year, F, can be defined as

$$F = E_m X_i, \tag{6}$$

where E_m is the energy that the BTS takes from diesel generator, while in the case of grid connection, it is the energy that the BTS takes from it without to return it later, considering that BTS can sell energy back to the grid. The parameter X_i (in [kgCO_2/KWh]), is the carbon emissions of the not green source of energy (diesel generator/grid) that occasionally feeds the BTS. However, in the case of grid connection, the increase of CO_2 emissions may be balanced with an equivalent corresponding decrease, when the surplus of energy given to the grid is equal to the energy taken previously from it.

2.4 Battery System

According to the previous section, the cooling power (AC load) is not only a function of the power that consumes the radio equipment (DC power), but it also depends on the operation of passive cooling. For this reason, it has to be considered as a different part of consumption during the simulation. Note that during discharging process, the energy that the batteries can offer is around 20% of their nominal capacity, and the maximum depth of discharge is around 30–50%, according to the specifications of the manufacturers [16]. Furthermore, before the power reaches the air conditioner, it passes trough an inverter. In fact, it is not a simple inverter, but its study is not on the purpose of this article. We only care of its efficiency and cost.

When $K < 0$ and the capacity in the time t is higher than the minimum allowable, the batteries are in discharging process and the storage capacity in the instant $t + \Delta t$ is given by

$$C_b(t + \Delta t) = \begin{cases} C_b(t) + \frac{K}{n_d}, \frac{|K|}{n_d} < \frac{C_m}{5}\Delta t \\ C_b(t) - \frac{C_m}{5}\Delta t, \frac{|K|}{n_d} \geq \frac{C_m}{5}\Delta t. \end{cases} \tag{7}$$

When $K > 0$ and the batteries are not full, then they are in charging process and the storage capacity is given by

$$C_b(t+\Delta t) = \begin{cases} C_b(t) + Kn_h,\ Kn_h < \frac{C_m}{5}\Delta t \\ C_b(t) + \frac{C_m}{5}\Delta t,\ Kn_h \geq \frac{C_m}{5}\Delta t, \end{cases} \tag{8}$$

where $C_b(t+\Delta t)$ is the available battery bank capacity at time $t+\Delta t$, $C_b(t)$ is the available battery bank capacity at time t, n_h is the battery charging efficiency, n_d is the battery discharging efficiency, C_m is the nominal batteries' capacity and Δt is the time-step (in hours) of the simulation. For the parameter K, it holds that

$$K = (P_{p1} + P_w)n_r + \frac{P_{p2} - A_C}{n_i} + P_p n_c - D_C, \tag{9}$$

where variable A_C is used to describe the AC part of consumption, D_C is the DC part, n_i is the efficiency of the inverter, n_r is the rectifier efficiency and n_c is the converter efficiency. Note that P_{p1} is the power that goes from diesel generator or grid to DC or to batteries trough Part 1 and P_{p1} is the power that goes from diesel generator or grid to AC trough Part 2. The two parts of consumption, DC and AC, are described in more detail in the following section.

In the case of discharging, the offered energy (P_b) by the batteries at time $t+\Delta t$ can be expressed as

$$P_b = (C_b(t+\Delta t) - C_b(t))n_d. \tag{10}$$

3 BTS Load

As mentioned previously, the two major consumers of energy on a BTS are the radio and the cooling equipment. In more details, the radio equipment consumes about 68% of the total energy to produce the RF power, the air conditioner is responsible for the 30% of the consumption, 1% is losses on the feeder and only 1% goes to the final signal [1].

3.1 DC Load

In order to define the DC load of a BTS, namely the consumption of RF, feeder and antenna, a strategy called ECO Mode has to be taken into account during the technical and economic assessment of the hybrid system. This

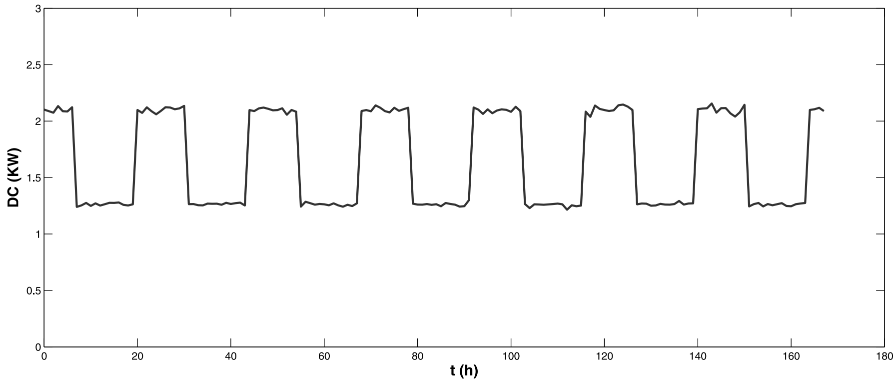

Figure 2 DC load.

strategy consists of turning radio transmitters and receivers off when the call traffic goes down. This typically happens during the night (see Figure 2), reducing the power consumption of DC up to 40% [1].

3.2 AC Load

A strategy that reduces the power consumption of a BTS is the operation of the air conditioner at higher temperature. It has been calculated that by allowing a wider fluctuation between 31 and 26°C, the total cooling cost which can be saved is about 14% [1].

In this paper, an appropriate modification of the aforementioned strategy is adopted, in order to better taking the advantage of the output power of the hybrid energy system. Particularly, we suggest that (i) when the produced energy of the BTS hybrid system exceeds consumption and the batteries are full, the surplus of energy should be used to cool the BTS up to a lower temperature, and (ii) when the produced energy is not enough, consumed energy on the air condition could be eliminated. The only restriction of this strategy is that the temperature level must not exceed the maximum desirable one. Using the two aforementioned strategies, wind or PV generators of lower nominal power can meet the electric power consumption, reducing the total costs of the hybrid system and making the approach of hybrid energy system for BTSs more attractive. Furthermore, it needs to be emphasized that the cooling requirements do not exclusively depend on the power which is consumed on the radio equipment. Especially in the BTSs where the technique of passive cooling is used, the cooling requirements also depend on the weather conditions, such as temperature.

Hourly AC load, which is mainly consisted of the consumption of the air-condition, is given by $A_C(t) = Q_L(t)/n_a$, where n_a is the efficiency of the air-condition and $Q_L(t)$ is the total cooling load per hour. For the parameter Q_L, it holds [18] that

$$Q_L(t) = Q_I(t) + Q_A(t) + Q_E(t) + Q_S(t), \tag{11}$$

where Q_I is the heat production from the RF, which is taken as a percentage of DC consumption, Q_A the air leakage, Q_E the heat transfer through envelope of BTS and Q_S the solar radiation transferred trough envelope, which in this paper is considered to be equal to zero. The parameters Q_A, Q_E are defined as

$$Q_A = GdC_p(T_0 - T_r) \tag{12}$$

and

$$Q_E = KF(T_0 - T_r), \tag{13}$$

assuming that G is the air leakage flow rate through envelope, d density of air, C_p the specific heat capacity of air, K the envelope heat transfer coefficient, F the total envelope's surface area, while T_0 and T_r are hourly outdoor and indoor temperatures respectively [18].

Hence, cooling load of BTS depends on the outside temperature and during the winter, which is fairly considered as the worst period for a hybrid wind/PV system, the final load of is lower. Considering the previous statement, the solution of hybrid power system for BTSs can be regarded much more feasible.

If a fluctuation of temperature is allowed, the indoor temperature of BTS can be given by

$$T_{in}(t + \Delta t) = \frac{Q(t + \Delta t)}{m_a C_p} + T_{in}(t), \tag{14}$$

where

$$Q(t) = Q_L(t) - Q_I(t) - Q_E(t) - Q_A(t) \tag{15}$$

and T_{in} is the indoor temperature.

4 Power Management

There are some basic principles that have to be taken into account for an efficient power management during the operation of a BTS. The load of BTS must use the available green sources of energy as much as possible. The diesel generator and grid provide power on priority to AC. If a fluctuation of the temperature is not unacceptable, the use of a diesel generator or grid should be avoided. When the diesel generator is already on and its load factor is lower than 90%, the diesel generator should be used to charge the batteries, if the batteries are not full.

A_C is the air condition consumption that the internal cabinet temperature will remain constant and equal to a default temperature. A_{Cn} is the down limit of air condition consumption. Air condition consumption cannot be considered smaller than A_{Cn}, because that would provoke an increase of indoor temperature larger than the desirable one. So the essential air condition consumption, A_{Cn} is defined by the upper limit, T_{upl}, and under limit, T_{unl}, of the indoor temperature. The exact operation of the hybrid system is described in Figure 3.

5 Techno-Economic Analysis

5.1 Description of the Algorithm that Controls the Suitability of the Solution

Reliability is a very important factor for a hybrid system that feeds a BTS. On the other hand, the generation of energy by wind turbines and PV generators is a stochastic process and thus, time to time simulation is needed to check which are the components of the hybrid system and the characteristics of the BTS in order to secure the reliability of the system. Reliability is controlled by the number of loss of load probability. Loss of load probability (LOLP) is the probability – the percentage of time – that the hybrid system does not satisfy the load of BTS. So LOLP can be defined as

$$\mathrm{LOLP} = \frac{\tau}{T}, \tag{16}$$

where T is the number of hours in this study with weather data input and

$$\tau = \sum_{t=0}^{T} \mathscr{D}\left[(P_{p1} + P_w)n_r + \frac{(P_{p2} - A_{Cn})}{n_i} + P_p n_c + P_b - D_C < 0 \right]. \tag{17}$$

In (17), $\mathscr{D}[x]$ denotes the time duration where the x event is true.

A high value of LOLP means that system is not reliable. A solution is unsuitable when LOLP is larger than an upper limit, which is defined by L.

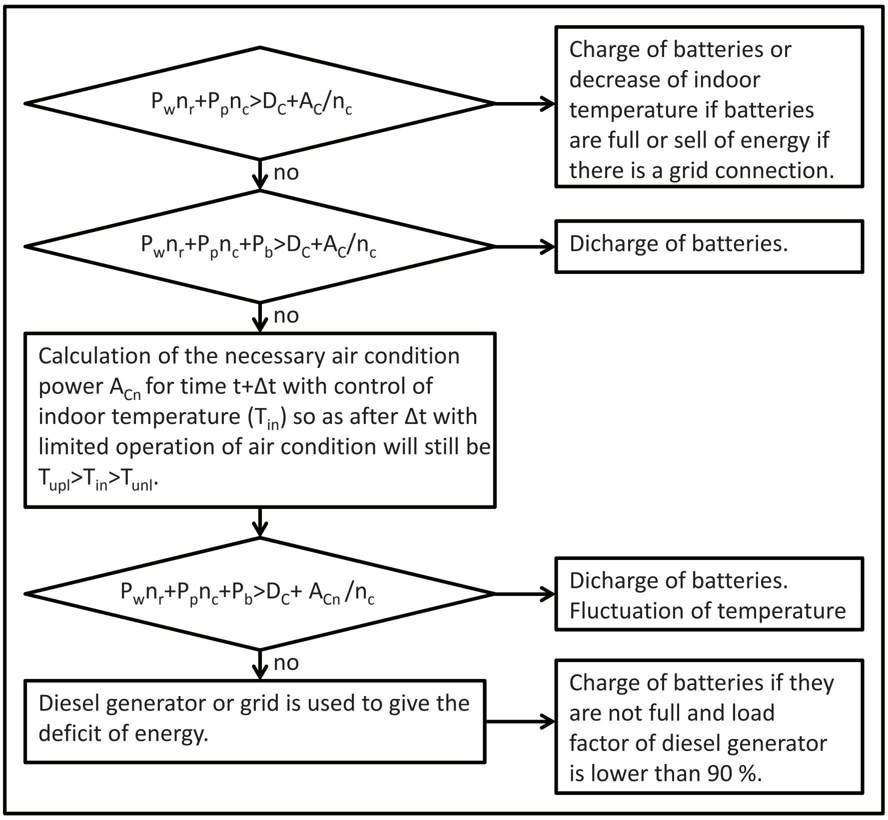

Figure 3 Power management.

5.2 Economic Evaluation of the Solution

The cost of a hybrid system depends on the following factors: the nominal power of wind and PV generators, the number of batteries, the life time of the hybrid system, the usage of diesel generator or grid, the replacement cost of batteries batteries, the maintenance cost of the hybrid system. From all the suitable combinations of parts of hybrid system, optimum is the one with the lower cost. The present value of the total cost [13] can be given by

$$V_p = V_c + V_m + V_i + V_r, \tag{18}$$

where V_c is the initial capital cost of the system, which depends on the nominal power of wind turbines (P_r), the number of PV generators (N_p), the nominal power of diesel generator (P_d), the number of batteries (N_b) and their

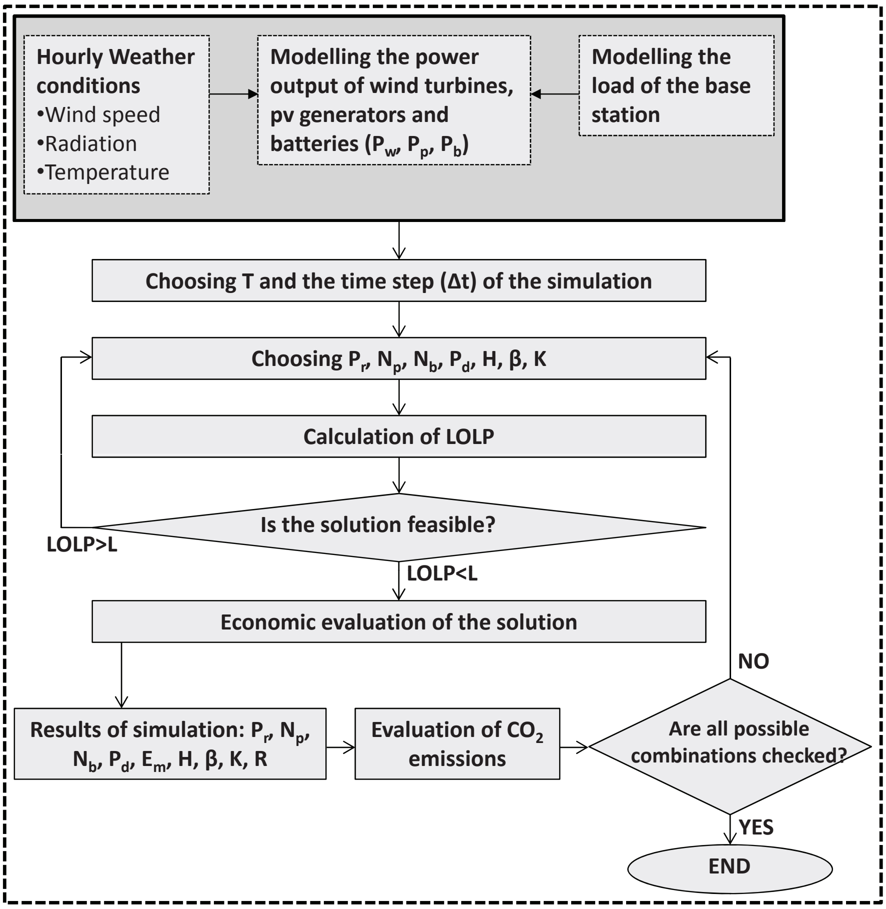

Figure 4 Simulation process.

costs, V_m is the present value of the total maintenance cost of the system, V_i is the present value of the cost of energy produced by diesel generator or taken from grid and V_r the present value of total replacement cost of batteries and during the life time of hybrid system. The total maintenance cost of hybrid system in the first year can be defined as

$$M_t = M_p + M_w + M_b, \tag{19}$$

where M_p, M_w, M_b is the maintenance cost of PV generators, wind turbines and batteries in the first year respectively. The maintenance cost of system every next year is higher because of the annual inflation rate. The present value of the total maintenance cost for all the lifetime of the system can be given by the present value of uniform inflation series factor, f.

$$f_s = \frac{1 - (\frac{1+a}{1+i})^n}{i - a}, \tag{20}$$

where i is the interest rate, a is the inflation rate and n the useful lifetime of the system. So the present value of the total maintenance cost for all the years is given as $V_m = M_t f_s$.

Assuming that B is the total cost of energy, which is provided either from diesel generator or grid, for the first year, the present value of the aforementioned cost of energy for all the years is $V_i = B f_s$. Considering that only batteries need replacement, the present value of the total replacement cost for all the lifetime of the system is given by

$$V_r = \sum_{j=1}^{y} (V_{cb} f_p), \tag{21}$$

where y is the total number of replacements of the batteries' system for all the years and V_{cb} the initial capital cost of the batteries.

$$f_p = \frac{1}{(1+i)^x}, \tag{22}$$

with x being the year of every one replacement. Knowing the present value of the investment, V_p, the levelized annual cost, R, can be calculated by the Capital Recovery Factor, f_r, as $R = V_p f_r$, where

$$f_r = \frac{i}{1 - (1+i)^{-n}}. \tag{23}$$

6 Results and Discussion

In this section, we present results of the techno-economic analysis of the hybrid system, for the use case of a BTS in the Greek island of Kea. In case study, we consider that the useful lifetime of the system is 25 years, while the upper limit of LOLP, L, must be equal to 0. Real hourly weather data for the year of 2011 were used for the simulation, which are obtained from Meteorological Institute of National Observatory of Athens. We assume that wind speed, solar radiation and temperature are constant during the time step.

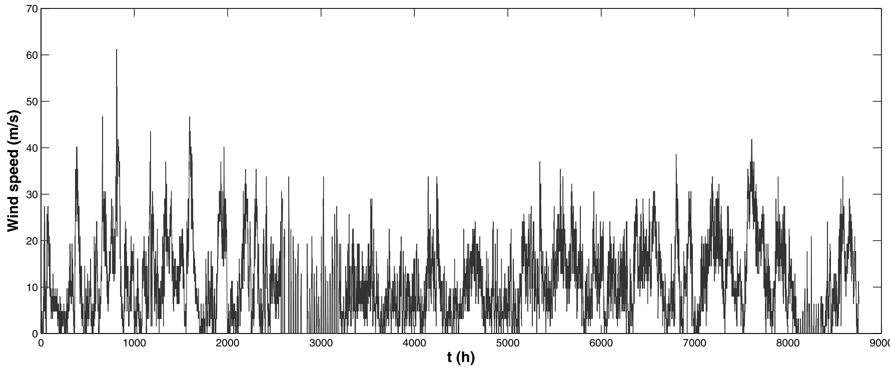

Figure 5 Hourly data of wind speed.

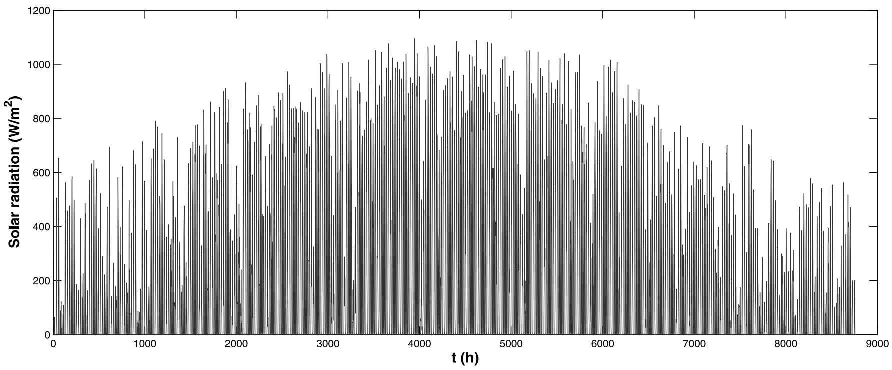

Figure 6 Hourly data of solar radiation.

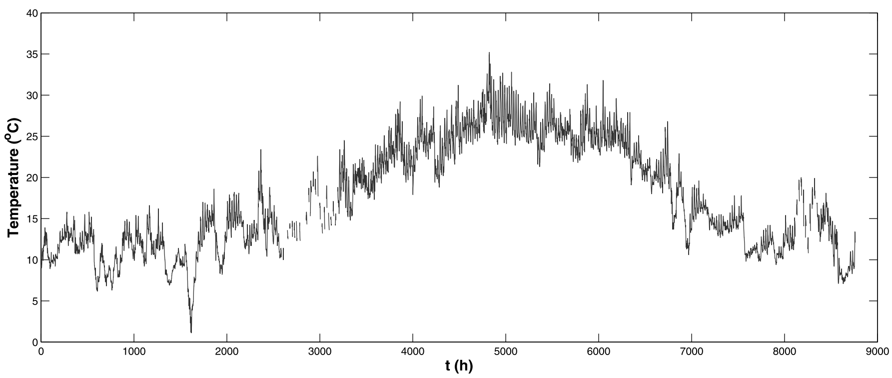

Figure 7 Hourly data of temperature.

Table 1 Levelized annual cost for autonomus BTS (normalized to the cost of the exclusive use of diesel generator).

System Configuration	*LAC (EUR)*
PV-Wind turbines-Batteries-Diesel generator	0.472
Wind turbines-Batteries-Diesel generator	0.585
PV-Batteries-Diesel generator	0.792
Diesel generator	1

The considered hourly wind speed, solar radiation and temperature profiles are shown in Figures 5, 6 and 7.

Due to the high availability of wind and solar potential in Kea, the installation of systems based on renewable sources of energy shows to be a promising solution for BTSs. In order to clarify the previous statement, both the cases of autonomous and grid-connected BTS are simulated and analyzed.As shown at Tables 1 and 2, a combination of PV generators, wind turbines, batteries and diesel generator or grid, for grid connected BTSs, is the most cost-effective solution both for autonomous and grid connected BTSs. Note that we get the used values for PV, wind wind generators, diesel, etc from the current market. Particularly, for the case of remote BTS, the autonomous diesel generator system leads to 1 levelised (normalized) annual system cost (R), while PV-Wind turbines-Batteries-Diesel generator system leads to R equal to 0.472, using the diesel generator only for 20% of the total time. This translates into 52.8% reduction of operation costs of system and 80% reduction of the CO_2 emissions. For the case of grid-connected BTS, utilizing a hybrid PV-wind turbines-grid system leads to 12% reduction of R and 64% reduction of CO_2 emissions, compared to the case of the conventional grid-connected system. In this study we considered that BTSs can sell energy back to the grid at half the price as they buy it. In Tables 1 and 2, we also show that a configuration of system based on the combination of the two renewable sources of energy, solar and wind energy, is the most cost effective solution. Moreover, as we have observed, stand-alone PV/wind energy systems, without a diesel generator or electric grid for back up, are not reliable, as they cannot guarantee the zero loss of load probability. At both the cases of autonomous and grid connected BTS, the load of BTS mostly relies on the production of wind turbines, as shown in Figure 8. However, the existence of PV generators is cost effective, because these two green sources of energy are complimentary.

Table 2 Levelized annual cost for grid connected BTS (normalized to the cost of the exclusive use of grid).

System Configuration	*LAC (EUR)*
PV-Wind turbines-Grid	0.879
Wind turbines-Grid	0.907
PV-Grid	0.915
Grid	1

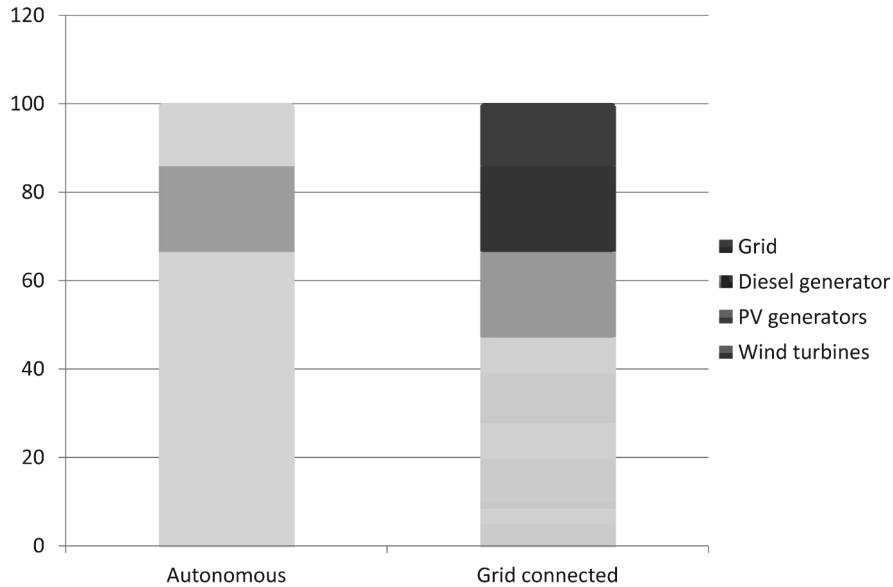

Figure 8 Distribution of energy to different systems (%).

7 Conclusions

The operational costs of BTSs can be effectively reduced through the utilization of renewable energy sources. Nevertheless, despite their significant benefits, such as their environmental impact and their substantial availability, they also induce specific disadvantages such as the high initial capital cost and the dependency on weather conditions. In this paper, we presented a hybrid system, which uses renewable energy sources (solar and wind energy), diesel power and the electric grid. This system has been optimized for minimizing the operational costs of BTS, while promising high reliability. Moreover, the proposed time-step simulation is appropriate for all BTSs, either connected to the grid or not. The seasonal effect on the BTS's electric energy consumption, as well as the smarter operation of air-conditioner and diesel generator are taken into account for the technical and economical analysis. According to numerical results, for the use case of the Greek island of Kea, we confirmed that hybrid energy system is a promising, cost-effective option for both remote and grid-connected BTSs, via reducing remarkably the total annualized cost of energy system and CO_2 emissions.

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