# Optimisation of energy supply at off-grid healthcare facilities using Monte Carlo simulation

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## ABSTRACT

In this paper, we present a methodology for the optimisation of off-grid hybrid systems (photovoltaic-diesel-battery systems). A stochastic approach is developed by means of Monte Carlo simulation to consider the uncertainties of irradiation and load. The optimisation is economic; that is, we look for a system with a lower net present cost including installation, replacement of the components, operation and maintenance, etc. The most important variable that must be estimated is the batteries lifespan, which depends on the operating conditions (charge/discharge cycles, corrosion, state of charge, etc.). Previous works used classical methods for the estimation of batteries lifespan, which can be too optimistic in many cases, obtaining a net present cost of the system much lower than in reality. In this work, we include an advanced weighted Ah-throughput model for the lead-acid batteries, which is much more realistic.

The optimisation methodology presented in this paper is applied in the optimisation of the electrical supply for an off-grid hospital located in Kalonge (Democratic Republic of the Congo). At the moment, the power supply relies on a diesel generator; batteries are used in order to ensure the basic supply of energy when the generator is unavailable (night hours). The optimisation includes the possibility of adding solar photovoltaic (PV) panels to improve the supply of electrical energy. The results show that optimal design could achieve a 28% reduction in the levelised cost of energy and a 54% reduction in the diesel fuel used in the generator, thereby reducing pollution. Furthermore, we discuss possible improvements to the telecommunications of the hospital.

**Keywords:** Photovoltaic, Diesel, Batteries, Monte Carlo simulation, Off-grid hospital.

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## Introduction

Several renewable energy sources, such as Photovoltaic (PV), wind etc., can be used to generate electricity, and their application fields are numerous. In this paper, our study focuses on the area of health. In particular, our study case considers a hospital located far off the electric grid.

Previous studies from other authors show several factors that hinder rural electrification in some geographical locations [1–9]. In addition, systems based on renewable sources can be very useful in mobile health emergency systems [10]. These works have demonstrated that the use of renewable energies reduces economic costs and environmental impact, but there are surprisingly few studies of the energy supply to off-grid hospitals [11] in spite of the importance of this type of facility in the health and development of populations that need to receive suitable medical attention.

The simulation and optimisation of stand-alone (off-grid) hybrid systems (usually photovoltaic panels and/or wind turbines and/or diesel genset) with energy storage (usually batteries) have been studied in many works [12–16]. Usually, the optimisation is considered as a minimisation of the levelised cost of energy (LCE), but in some cases two or more variables have been considered in the optimisation [17].

In most of the previous works, the optimisation is used considering a deterministic approach (no randomness is considered in the data). However, some studies have used a stochastic approach to optimise the system, considering the uncertainties in renewable sources and, in some cases, in the load. For example, Kamjoo et al.[18], show a method based on chance-constrained programming (CCP) used to optimise a PV-wind-batteries system, including the uncertainties in renewable sources, using Monte Carlo simulation for validating the results. Arun et al. [19] perform the optimisation of a PV-batteries system using Monte Carlo simulation including the uncertainty associated with solar irradiation. Kamjoo et al. [20] use genetic algorithms to obtain multi-objective optimisation of PV-wind-batteries systems considering uncertainties by means of CCP, comparing the results with Monte Carlo simulation. Maheri, in [21], evaluates the reliability of different PV-wind-batteries-diesel systems obtained by deterministic design, considering two objectives, cost and reliability; in [22], the same author proposes two algorithms (using Monte Carlo simulation) to obtain the optimum margin of safety.

Those previous studies have correctly used the stochastic approach, but all of them use low-accuracy models for the estimation of the lifespan of the batteries, which usually are the most expensive components (considering the whole lifespan of the system). None of the previous works uses an accurate model for the ageing of the batteries, and the estimation of their lifespan can be too optimistic, implying that the total net present cost of the system (NPC) and the LCE can be very different from the real ones. The battery lifetime has always been estimated in fixed values or using classical models such as the number of equivalent full cycles or the cycle counting method; these models assume that operating conditions are those used in standard tests, and they can predict very high battery lifespans, much higher than real ones. In [23], Dufo-López and Bernal-Agustín compare different ageing models for lead-acid batteries, concluding that the weighted Ah-throughput model shown by Schiffer et al. in [24] is much more accurate than the classical models.

In the present paper, a new methodology for the optimisation of stand-alone hybrid systems is shown. The methodology includes a probabilistic optimisation by means of Monte Carlo simulation, in order to consider the uncertainties in the renewable sources and in the load. It allows stochastic optimisation of complex hybrid systems with a high level of accuracy in the model of the system, including a very accurate weighted Ah-throughput model for the lead-acid batteries [24].

This methodology is applied for the optimisation of the electrical supply of a hospital located far off the electric grid in Kalonge (Democratic Republic of the Congo), which is currently powered by a diesel-battery system. The results show that it is possible to improve the current system by adding photovoltaic solar energy, achieving lower total cost and pollutant emissions.

It is necessary to consider the consumption requirements when the main objective is to supply electric power for the needs of an off-grid hospital, its medical services and newer technologies which advance the services through lower-consumption devices (gateways, PCs, tablets, smartphones). In this last case, it would be possible to create a wireless sensor network (WSN), where several sensors record information regarding the physiological variables of the patient to send it to the medical specialist located in another hospital. These devices are sometimes placed in the body of the patient, forming a body sensor network (BSN). They can be machine to machine (M2M) and therefore work without human intervention. They are equipped with a small processor, a radio transceiver for communication and a sensor. Usually, these devices consume very low electrical power (in the range of mW) [25].

This work is presented as follows:

- Methodology
- Characteristics of the system to supply electricity to an off-grid hospital in Congo
- Simulation and optimisation results
- Conclusions and future works

## 1. Methodology

A new methodology for the simulation and optimisation of stand-alone hybrid systems (PV+diesel+batteries) has been applied, based on iHOGA software (developed by one of the authors [26]), adding Monte Carlo simulation to perform the stochastic approach.

The simulation and optimisation used in iHOGA software using a deterministic approach is shown in [26–28]. Recently, the advanced weighted Ah-throughput model for lead-acid batteries was added [24]. The software uses hourly time series for irradiation, temperature, load etc. during a whole year (8,760 values for each data series). With these data series, for each combination of components (number and type of PV panels, number and type of batteries, type of diesel generator, type of inverter-charger) and control strategies, it simulates the performance of the system. Furthermore, it obtains results on the series of energy delivered by the PV, the energy supplied by the diesel, fuel consumption, charge and discharge power of the batteries, remaining capacity of the batteries, etc. At the end of the simulation of each combination of components and control strategies, it evaluates the lifespan of the batteries (number of years to replace them), the total fuel consumption and all the costs involved in the system until it reaches its lifetime (usually 25 years, the PV panel expected lifespan). The costs include replacement of one of the components during the system lifetime. The cash flows of the different years are converted to the first year of the lifetime of the system (considering interest rate and inflation), calculating the NPC. This value divided by the total energy supplied to the load during the system lifetime yields the LCE. The combination of components and control strategies which has the lowest NPC (and also the lowest LCE) is the optimal system. In many cases, the number of possible combinations of components and control strategies is so high that evaluating all of them would imply an unacceptable computation time; in these cases, iHOGA uses a heuristic technique (evolutionary algorithm) to obtain the optimal solution (or a solution near the optimal) in a reasonable computation time [27].

Monte Carlo simulation adds to the software the availability to perform the stochastic approach. In PV-diesel-battery systems, the variability of the mean values of expected irradiation and load (consumption) is very important because it greatly influences the unmet load, the total cost and many other results. In general, the average values of irradiation and load vary from year to year so that its probability distribution follows a normal or Gaussian curve distribution. For example, in Fig. 1, the probability density function (PDF) of the annual average daily irradiation in a specific location is shown in red, and in green we can see the Gaussian curve which best fits. In this case, the mean of the annual average daily irradiation is 5 kWh/m$^2$/day, and the standard deviation is 0.2 kWh/m$^2$/day. That means that in most years, the average daily irradiation will be around 5 kWh/m$^2$/day; however, there may be years with a higher average value and others with a lower average value. For example, the annual average values during 10 consecutive years could be 5.1, 4.8, 5, 4.7, 4.5, 5.2, 5, 4.9, 5.05 and 5.1 kWh/m$^2$/day.

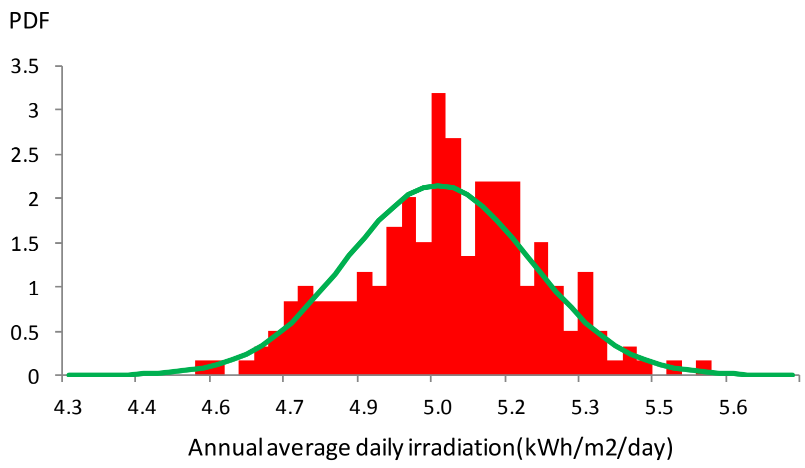


Fig. 1. PDF of the annual average daily irradiation

Therefore, if we know the mean and standard deviation of the average values of these variables, we can perform a probabilistic analysis using Monte Carlo simulation, carrying out different combinations that follow the probability curves of the average values of different variables.

With this analysis, for each combination of components and control strategy to study, there will be N samples of hourly series of the variables we want to analyse (in this case, load and irradiation). There are efficient methods for obtaining the sample, as, for example, the Monte Carlo variance reduction (MCVR) technique [29,30], but in this work the computing time is not too long, and it has not been necessary to apply these techniques. Each hourly series (8,760 h) of load and irradiation has an average value obtained according to a Gaussian probability distribution, with the mean the annual average value obtained from measures of many years (usually more than 10 years) and its standard deviation. During optimisation, each combination of components and control strategies is simulated N times. Each of these simulations includes an hourly series of load consumptions (with average value obtained randomly following the load Gaussian probability function) and a random series of irradiation (with average value obtained randomly following the irradiation Gaussian probability function). Each of these N simulations gives results of NPC, LCE, emissions, unmet load, energy delivered by PV, fuel consumption, etc. For each result, iHOGA calculates the mean and standard deviation of the N simulations. The optimal system will be the one with the lowest mean of the NPC.

Usually, the number of samples or trials (or sample size), N, is not a fixed number. There are many convergence thresholds for Monte Carlo simulation so that when the convergence threshold has been reached, the simulation finishes [31–33].

A widely used rule is to let the simulation run until the relative standard error of the NPC (standard error of the mean divided by the mean) reaches a specified value *RSE* (for example, 1%). This rule is indicated in Eq. (1).

$$100\frac{\frac{NPC_{\mathrm{SD}}}{\sqrt{n}}}{NPC_{\mathrm{mean}}} < RSE \qquad (1)$$

where $NPC_{\mathrm{mean}}$ and $NPC_{\mathrm{SD}}$ are the mean and standard deviation of the *NPC* obtained in the *n* samples evaluated until now. In this work, we have implemented this method.

Fig. 2 shows the optimisation flowchart that reflects the procedure described above.

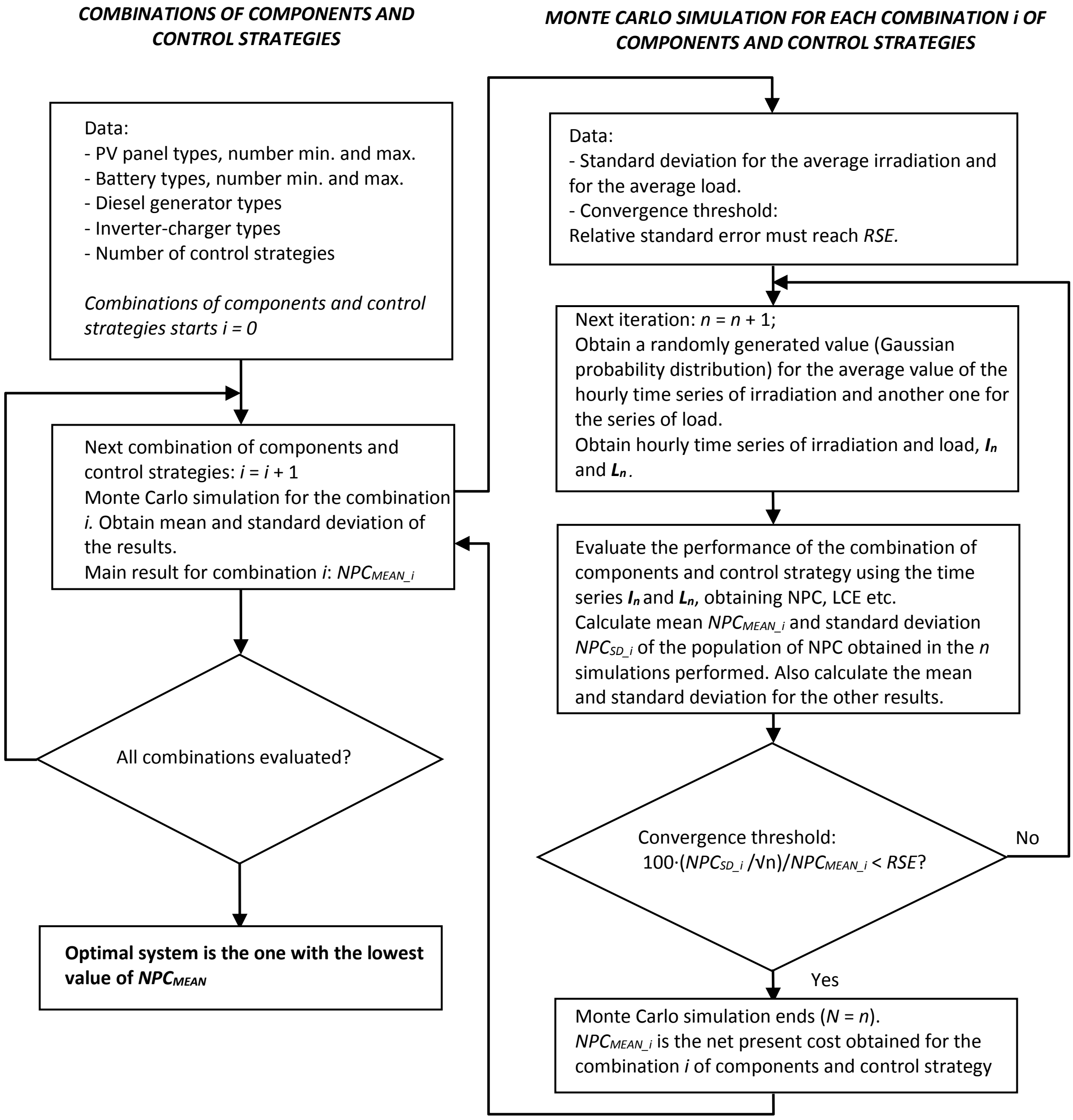


Fig. 2. Optimisation flowchart

## 3. Electrical supply of an off-grid hospital in Congo.

The methodology shown in section 2 has been applied in the optimisation of the electrical supply of an off-grid hospital located in Kalonge (Democratic Republic of the Congo, Sud Kivu, near Rwanda, latitude 2.33º S, longitude 28.75º E). There is no other hospital within 150 km; the nearest one is between 3 and 6 hours away, depending on road conditions. The electricity is currently supplied by a diesel generator during the day (which also charges the batteries) and batteries during night hours.

The work performed in this hospital by NGOs, such as Doctors Without Borders, is of great help to the population of the area, so it is of great interest to improve the conditions of power supply to the hospital.

We propose the PV-diesel-battery system shown in Fig. 3 to improve the power supply to the hospital. The system is currently composed of a diesel generator and batteries. Adding a PV generator will allow major flexibility and reliability. The load can be fed directly from the diesel generator or from the batteries (using an inverter). The charger function allows battery charging with the genset.

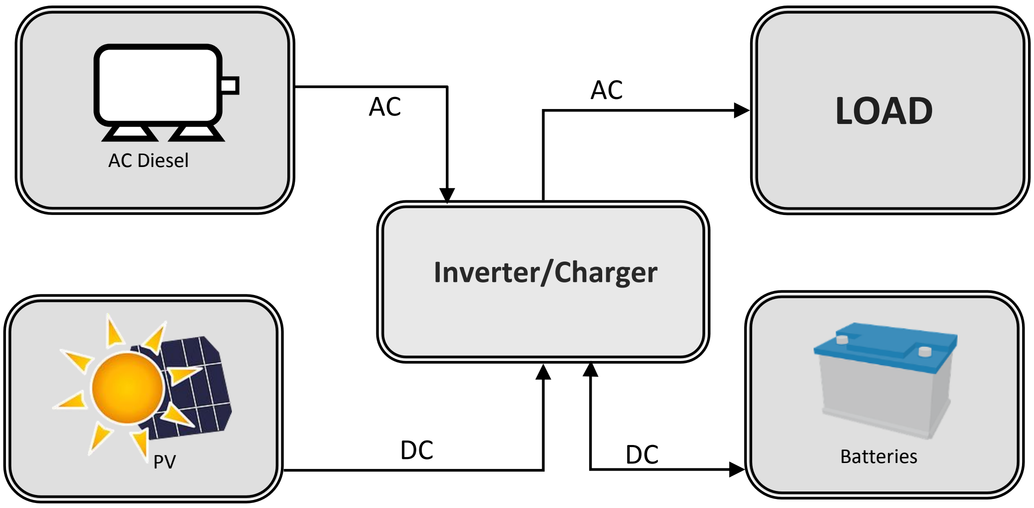


Fig. 3. Proposed PV-diesel-battery system

This system will be described in detail in the following subsections. Later, in section 4, the performances of the present system (diesel-battery), a proposed PV-diesel-battery system and an optimised PV-diesel-battery system (using the methodology of section 2) are shown.

### 3.1. Load

The load is between 1.8 and 2.8 kW for the hours of a typical full working day. However, there are some days where the load is much lower (due to few patients) or even close to zero. We have modelled it as 5 full working days followed by 2 days with no load. Fig. 4 shows the hourly load of 14 days. The power factor of the load is 0.9. The average daily load during the year is 36.23 kWh/day, and the total load of the year is 13,224 kWh/yr. We will consider a standard deviation for the average daily load Gaussian distribution curve of 5 kWh/day.

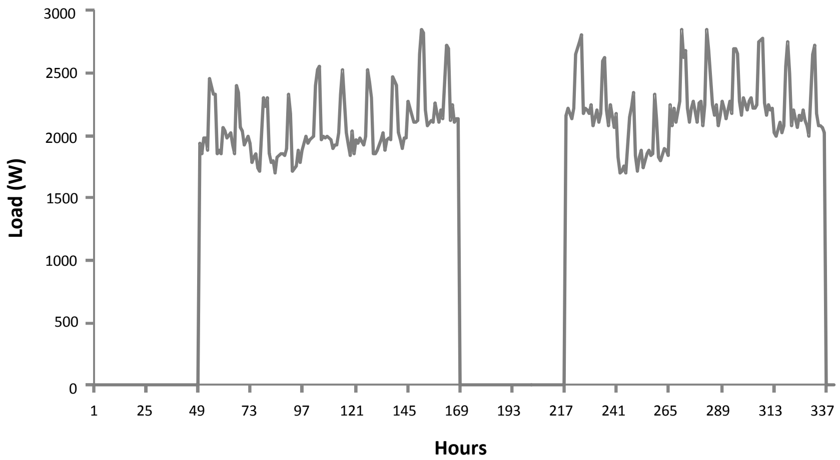


Fig. 4. Load (W)

### 3.2. Diesel generator

The rated continuous output power of the current genset is 8.5 kVA, its acquisition cost is 8,000 € and its operation and maintenance (O&M) cost is 0.14 €/h. Its expected lifespan is about 15,000 h in the conditions of the Congo. The fuel (gas-oil) price is 1.3 €/l, and we are considering only a 2% annual inflation rate (it is probable that it will be higher; however, we use a conservative value, as we are going to compare later with a hybrid system which includes a photovoltaic generator). Fuel consumption, FC (l/h), is modelled as dependant on the output power, *P* (kW), with Eq. (2).

$$FC = A{\cdot}P + B{\cdot}P_N \qquad (2)$$

where $P_N$ (kW) is the nominal output power, and *A* and *B* are the coefficients of the consumption curve. The values suggested by Skarstein and Ullen [34] have been used here: A = 0.246 l/kWh and B = 0.08145 l/kWh. The minimum output power recommended by the manufacturer is usually 30% of the rated power, the value used in the simulations. The genset is not available at night, from 10 p.m. to 4 a.m.

### 3.3. Batteries

There are three groups of four solar AGM lead-acid batteries of 200 Ah ($C_{10}$), 12 V (each battery of 2.4 kWh nominal capacity). Therefore, the total capacity of the batteries is equal to 28.8 kWh ($C_{bat}$). Each battery bank supplies the load of different services when the diesel genset is not ready to run. The four batteries of each group are in parallel. The minimum state of charge ($SOC_{\min}$) recommended by the manufacturer for all of them is 40%. Thus, the total available storage capacity is equal to 17.8 kWh (28.8·0.6), and the expected self-discharge coefficient is 5% monthly. The roundtrip efficiency is 80%. We have considered 12 years of floating life. Fig. 5 (AGM curve) shows the curve of cycles to failure vs. depth of discharge, and the average number of full equivalent cycles to failure is 605.

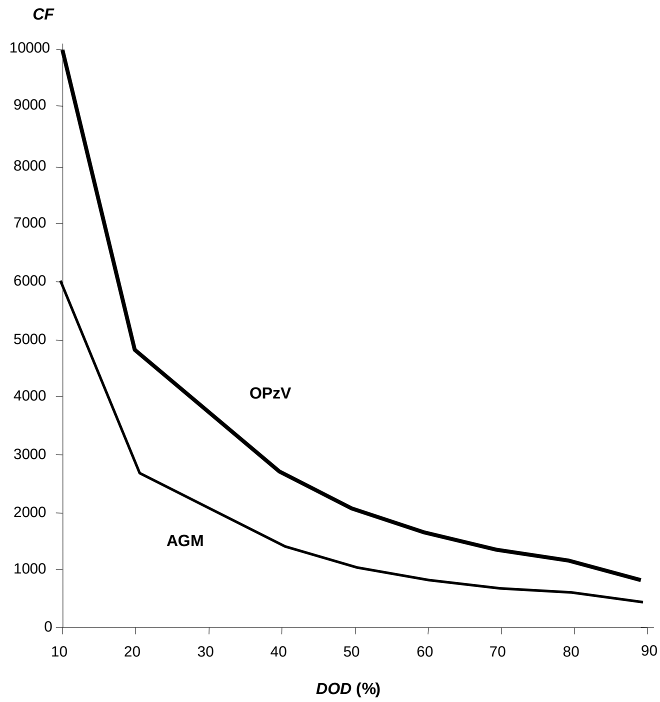


Fig. 5. Cycles to failure (CF) vs. depth of discharge (DOD)

The battery model considered is the weighted Ah-throughput model proposed by Schiffer et al. [24]. The acquisition cost of each battery is 230 € (i.e., 95.8 €/kWh), and its O&M cost is expected to be 1% of the acquisition cost (2.3 €/yr. for each battery) plus a fixed value of 50 €/year, for a total of 77.6 €/yr.

### 3.4. Inverter-chargers (bi-directional converter)

There are 3 inverter-chargers, one for each group of batteries. The output continuous power of each unit is 1,100 VA, and its acquisition cost is 2,000 €. The maximum continuous direct current for each unit is 40 A. Nominal DC voltage is 12 V. The diesel generator's inverter-chargers charge each group of batteries. When the generator is not allowed to work (at night or if it is unavailable), the three battery banks supply the load by means of the three inverter-chargers. The lifespan considered for the inverter-chargers is 15 years, the efficiency considered is 94% for the charger and the inverter efficiency is considered as dependant on the output power (Fig. 6). The battery charge includes four stages (bulk, absorption, float and equalisation). Each inverter-charger includes a built-in solar charge controller (maximum input current 30 A), but it does not include maximum power point tracking (MPPT).

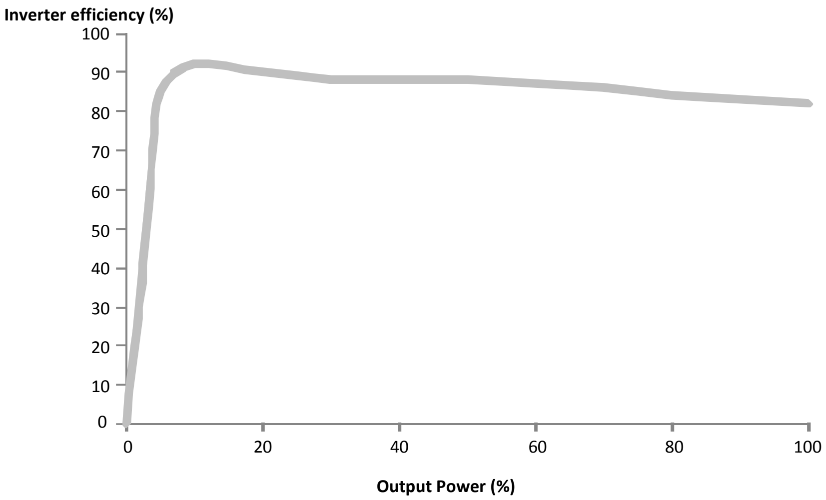


Fig. 6. Inverter efficiency

### 3.5. Control strategy

During daytime, energy is supplied by the diesel generator, which also charges the batteries. The batteries are used in order to ensure the basic supply of energy when the generator is unavailable (night hours) or under maintenance. The strategy used in the present system is the "cycle-charging strategy" [27]: when the generator must run, it will run at its rated power, so the extra power will charge the batteries.

### 3.6. Other data

The lifespan considered for the system is 25 years (to compare later with the hybrid PV-diesel-battery proposed systems). The annual nominal interest and general inflation rates are 4% and 2%, respectively. These rates are expected in European developed countries, as the components are manufactured there or their price is fixed there. These rates are applied to calculate the cost of replacement for the elements of the system when they reach the end of their lifespan, the remaining value of the elements (at the end of the lifetime of the system) and the total NPC of the system.

An installation cost of 300 € + 2% of total initial cost has been considered. A loan of 80% of initial cost has been considered as a loan with an interest of 10% annually for 10 years.

## 4. Simulation and optimisation results

In this section, the present system (diesel-battery) is simulated in a stochastic approach using Monte Carlo simulation (no optimisation is performed, as we just want to know the performance of the present system). Then the same is done for a proposed system composed of the present system plus a PV generator. Finally, the optimisation of a PV-diesel-battery system is performed using the methodology shown in section 2.

### 4.1. Present diesel-battery system

Monte Carlo simulation has been done to evaluate the performance of the present system. The convergence threshold of the Monte Carlo simulation is that the relative standard error (considering the results of NPC) must be lower than *RSE* = 0.2%, with a minimum of 2,000 samples.

The number of samples necessary to obtain a relative standard error lower than 0.2% has been lower than the minimum, so N = 2,000. A computer with 4 GB RAM and 2.4 GHz ran the necessary 130 seconds to perform the analysis (around 15 samples per second).

The results of the Monte Carlo simulation are the following (mean of each variable):

*NPC* is 281,940 €, and the *LCE* is equal to 0.87 €/kWh. During one year, the diesel generator runs 4,680 h (so its expected lifespan is 15,000/4,680 = 3.2 years), and it supplies 15,507 kWh (consuming 7,054 litres of gas-oil with emissions of 26,034 kg of $CO_2$). From this energy, 4,217 kWh are used to charge the batteries, and the rest is used to supply the load directly; the batteries are charged over 4,518 h and discharged over 1,555 h.

The batteries expected lifespan, calculated using the weighted Ah-throughput model proposed by Schiffer et al. [24], is 2.91 years.

We have also repeated the simulations using classical models to see the difference in the batteries expected lifespan: considering the average number of full equivalent cycles, the battery lifetime would be estimated at 4.27 years; using the rainflow cycle counting model, it would be 4.24 years. These values are much more optimistic and differ significantly from reality.

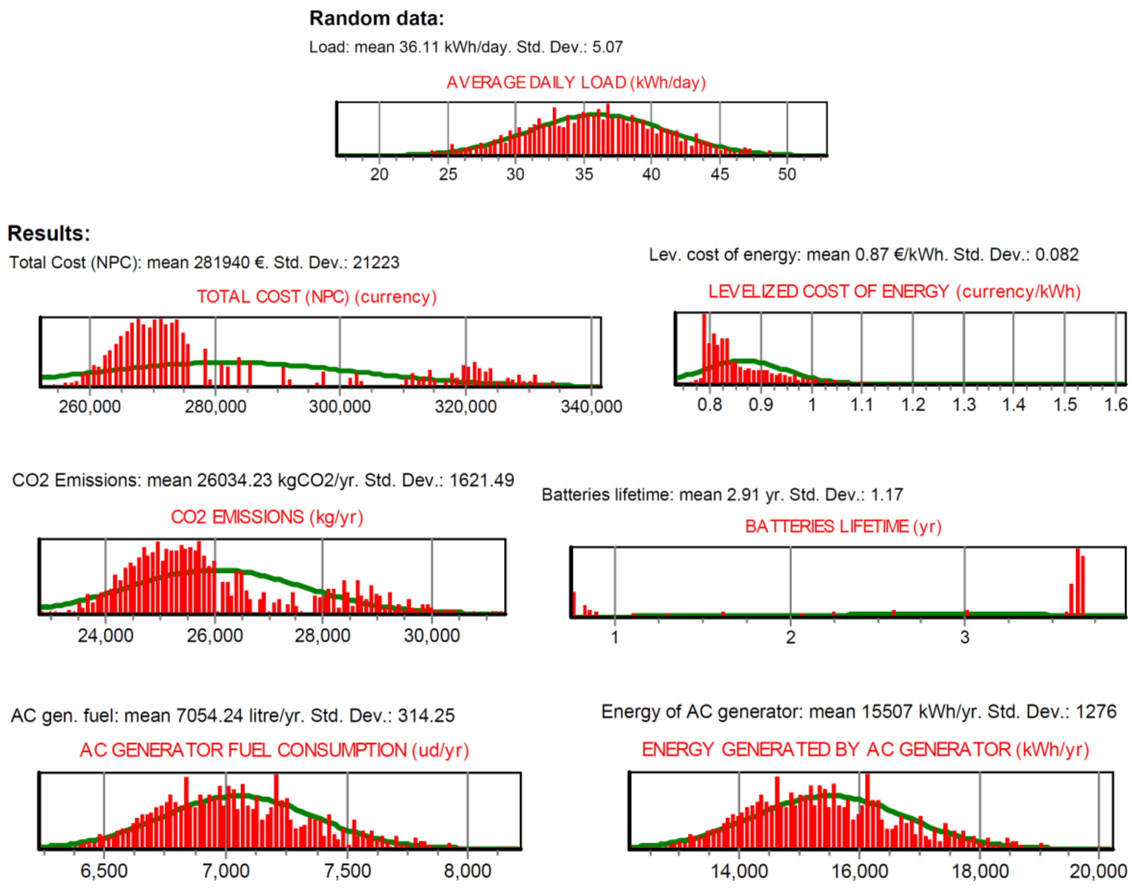


Fig. 7. Main results of current diesel-battery system

Fig. 7 shows the distribution curves of data (load) and main results (NPC, LCE, $CO_2$ emissions, batteries expected lifetime, diesel generator fuel consumption and energy supplied). In red, the probability distribution obtained can be seen, and in green, the normal curve which best fits is shown. In this case, we can see that NPC, LCE, $CO_2$ emissions and batteries expected lifetime probability distributions differ greatly from a normal distribution curve; however, diesel generator fuel consumption and energy are similar to a Gaussian curve. In addition, LCE has lower dispersion than NPC, as LCE is obtained by dividing NPC by the total energy load consumed during the 25 years. Samples with high loads imply very high NPC values (high fuel consumption and low battery lifetimes); however, as the LCE is calculated as NPC/load/25, although the NPC is very high, the load is also high, so the LCE has a lower dispersion.

Fig. 8 shows the simulation for the present diesel-battery system between January 23 and 29 in the 1$^{st}$ year.

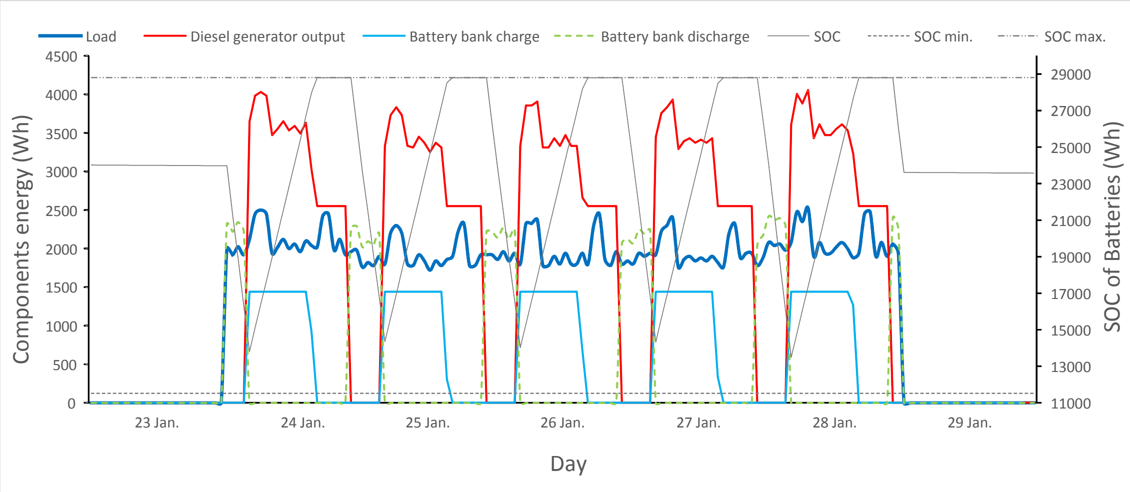


Fig. 8. Simulation of 7 days for the current diesel-battery system

## 4.2. PV-diesel-battery (original system plus PV generator)

We propose modifying the current diesel-battery system by adding a PV generator for each group of batteries. In this first study case, without applying any optimisation technique, a PV generator has been added to the current diesel-battery system.

The PV generator will be composed of mono-Si PV panels of $P_{PV}$ = 100 Wp, shortcut current $I_{SC}$ = 6.79 A, nominal voltage $V_{nom}$ = 12 V, open-circuit voltage 21 V, lifespan 25 years, acquisition cost 150 € (including support structure), O&M cost 2 €/yr. (plus 40 €/year for the whole PV system), NOCT 46º and power temperature coefficient -0.45%/ºC. As the maximum DC for the PV generator connected at each inverter-charger is 30 A, the number of panels in parallel cannot be higher than 30/6.79 = 4.41, or 4 panels in parallel. So for each inverter-charger, a PV generator of 400 Wp will be installed (total 1,200 Wp).

The panels have an inclination of 15º (the optimal for this location would be 0º, but a minimum slope is set to avoid dirtiness), 180º azimuth (north orientation). NASA's webpage has given the irradiation and temperature of the location [35]. We have obtained the average hourly time series of the irradiation using the Graham and Holland method, which gives the hourly irradiation over the tilted surface of the PV panels [36]. The ground reflectance considered is 0.2 (typical). The average total annual irradiation over the PV panels is 5.01 kWh/m$^2$/day. There is no data for that location for the standard deviation of the average irradiation. However, in [37], data on locations at several hundreds of km from the location, in Tanzania and Congo, can be found, with values around 0.2 kWh/m$^2$/day, which is the value we will use; in [38], values of around 0.13 kWh/m$^2$/day are obtained for several locations in Spain and Algeria. As the inverter-chargers do not include an MPPT system, the output current will be proportional to the shortcut current [10], so the output power from each PV panel will be $P_{PV}$ (W) = $G$(kW)/1kW·

$I_{SC}$(A) · $V_{nom}$(V) · *PR*, where *G* is the irradiance over the surface of the PV panel and *PR* is the performance ratio, considered here to be 0.83 (due to dirtiness, losses in cables and other problems).

The convergence threshold of the Monte Carlo simulation is that the relative standard error must be lower than 0.2%, with a minimum of 2,000 samples. In this case, N = 2,000 samples have been simulated.

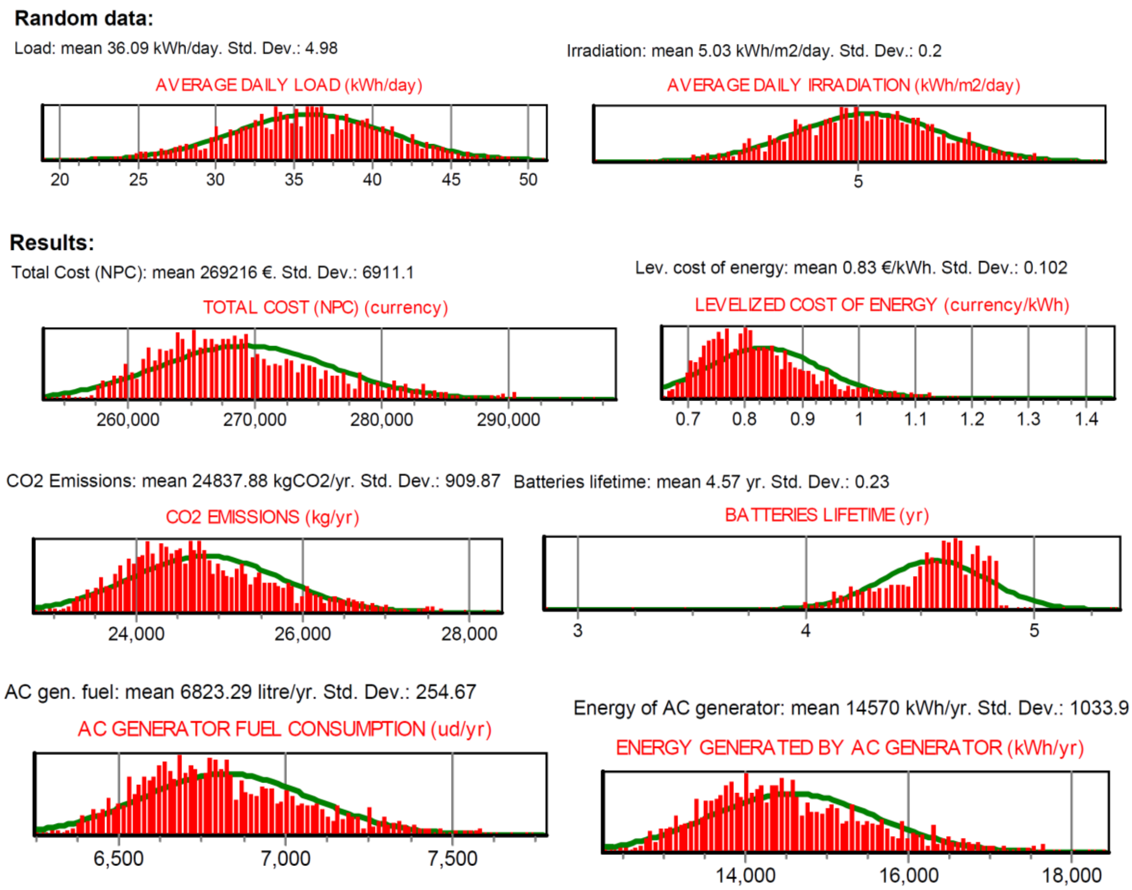


Fig. 9. Main results of PV-diesel-battery system (original system + PV)

Fig. 9 shows the results of the original system plus a 1,200 Wp PV generator. The reduction in the mean of *LCE* is quite low (0.83 vs. 0.87 €/kWh of the original system). However, the expected battery lifetime is much higher (mean of 4.57 vs. 2.91 years), and the dispersion is much lower (the standard deviation being 0.23 vs. 1.17 years).

### 4.3. PV-diesel-battery optimised system

A PV-diesel-battery system (using the actual 8.5 kVA diesel generator) has been optimised, comparing different combinations of systems and obtaining the one with the lowest *NPC* mean.

Next, the elements considered in the optimisation and the results are described.

### *4.3.1 Inverter-charger*

We have considered two new inverter-chargers. An inverter-charger composed of two units in parallel of a Xantrex XW6048-230-50 (6000 W, 131 A DC) + solar charger XW-MPPT60-150 (type A) and an inverter-charger composed of four units in parallel of the same Xantrex XW6048-230-50 (type B). The main characteristics of both types are detailed in Table 1.

Table 1. Inverter-chargers

| Type | A | B |
|---|---|---|
| Acq. cost (€) | 8,000 | 16,000 |
| Max. PV power (Wp) | 7,000 | 14,000 |
| Expected lifespan (yr) | 15 | 15 |
| Nominal DC voltage (V) | 48 | 48 |
| Efficiency | Same as actual system | Same as actual system |

### *4.3.2 PV panels*

We consider the same type of PV panels of 100 Wp and 12 V. As the PV generator of each solar charger is limited to 3,500 Wp, a maximum of eight groups of four panels of 100 Wp in parallel are allowed for each solar charger. For inverter-charger A, with two solar chargers, the maximum is 16 groups of four panels in parallel. For inverter-charger B, with four solar chargers, the maximum is 32 groups of four panels in parallel.

The software will try 33 combinations of PV generators (between 0 and 32 groups of four panels in parallel).

### *4.3.3 Batteries*

We have considered 2V OPzV batteries, so 24 batteries in serial will compose the battery bank. The software will try combinations of eight different batteries (Table 2), between 206 and 2020 Ah ($C_{10}$). The acquisition cost of the batteries is shown in Table 2, around 250 €/kWh. The minimum SOC recommended by the manufacturer is 20%, the self-discharge coefficient is 3% monthly and the roundtrip efficiency is 85%. The curve of cycles to failure vs. DOD is shown in Fig. 5 (OPzV), and the number of full equivalent cycles to failure is 1,174. The manufacturer datasheet shows 18 years of floating lifetime. A fixed cost of 50 €/yr. of O&M has been considered for the battery bank.

Table 2. OPzV 2 V batteries acquisition cost

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $C_{10}$ (Ah) | 206 | 258 | 309 | 361 | 505 | 1,030 | 1,515 | 2,020 |
| Acq. cost (€) | 166 | 192 | 218 | 235 | 301 | 525 | 700 | 991 |

### 4.3.4 Control strategies

Two possible control strategies have been considered: load following and cycle charging [27].

Load following strategy: In this strategy, when energy from the PV generator is not enough to meet the whole load, the rest of the energy is covered by the battery bank. If the batteries cannot cope with the demand, the diesel generator will run to cover the rest of the load.

Cycle charging strategy: When the generator must run because the load cannot be met by the batteries, it will run at its rated power, so the extra power will charge the batteries.

### 4.3.5 Results

We have evaluated a total of 33 combinations of PV generator x 8 combinations of battery bank x 2 combinations of control strategies = 528 combinations of components and control strategies. Combinations with PV power lower than 7,000 Wp use inverter type A, and combinations with PV higher than that value use inverter type B.

Considering that Monte Carlo simulation must consider around 2,000 samples for each combination, the number of total simulations would be around 2 million. The optimisation has taken around 22 hours, evaluating all the combinations of components and control strategies.

The optimal hybrid system found is a PV generator of 4x31 PV panels of 12 V, 100 Wp (total 12.4 kWp), the original diesel generator of 8.5 kVA, a battery bank of 24 batteries in serial of 2 V, 1,030 Ah (total 49.44 kWh) and the set of four inverter-chargers in parallel using the load-following strategy. Fig. 10 shows the main results of the optimal system.

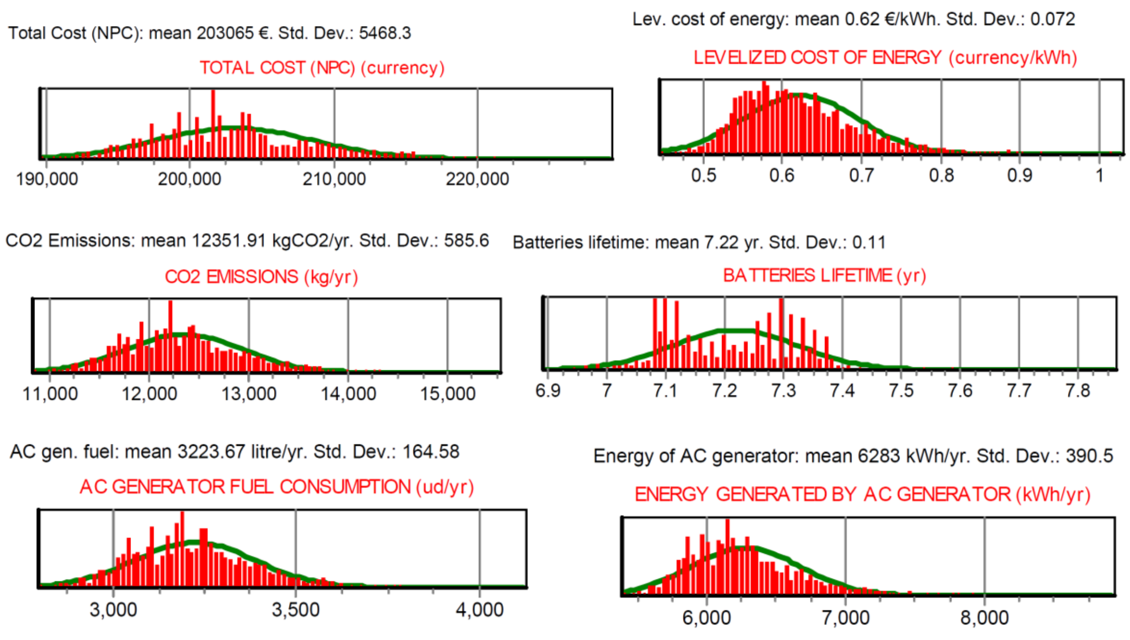


Fig. 10. Main results of the optimal PV-diesel-battery system

Table 3 summarises the results of the optimal hybrid system, and the simulation of 7 consecutive days is shown in Fig. 11. A more detailed simulation for a day (January 25) is shown in Fig. 12. The expected mean of LCE of the optimal hybrid system is 0.62 €/kWh, 28% lower than the current diesel-battery system. The diesel fuel consumption is reduced by 54%. We conclude that this optimal hybrid system is worth installing, as the cost of the energy will be much lower than for the current system, even considering a very low interest rate for the fuel price (2% annual; if this interest rate were higher, the difference in LCE would be higher).

Table 3. Results of the different cases

| | 1. Diesel-battery (current system) | | 2. Diesel-battery (current system) plus PV gen. of 1200 Wp | | 3. PV-diesel-battery optimal system | |
|---|---|---|---|---|---|---|
| Diesel rated power (kVA) | 8.5 | | 8.5 | | 8.5 | |
| Batteries: | | | | | | |
| Nominal capacity (kWh) | 28.8 | | 28.8 | | 49.44 | |
| Type | AGM | | AGM | | OPzV | |
| Inverter-charger: | | | | | | |
| Rated output power (kW) | 3.3 | | 3.3 | | 24 | |
| Max. PV peak power (kWp) | 1.2 | | 1.2 | | 14 | |
| PV peak power (kWp) | 0 | | 1.2 | | 12.4 | |
| Control strategy | Cycle charging | | Cycle charging | | Load following | |
| RESULTS: | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. |
| NPC (€) | 281,940 | 21,223 | 269,216 | 6,911 | 203,065 | 5,468 |
| LCE (€/kWh) | 0.87 | 0.082 | 0.83 | 0.102 | 0.62 | 0.072 |
| Diesel runs (h/yr.) | 4,680 | 0 | 4,680 | 0 | 2,424 | 101 |
| Diesel lifespan (yr.) | 3.2 | 0 | 3.2 | 0 | 6.2 | 0.25 |
| Diesel supplies (kWh/yr.) | 15,507 | 1,276 | 14,570 | 1,034 | 6,283 | 390 |
| Diesel consumption (litres/yr.) | 7,054 | 314 | 6,823 | 254 | 3,224 | 164 |
| $CO_2$ emissions | 26,034 | 1,621 | 24,838 | 910 | 12,352 | 585 |
| Energy cycled by batteries (kWh/yr.) | 4,217 | 535 | 4,071 | 552 | 3,798 | 494 |
| Batteries lifespan (yr.) | 2.91 | 1.17 | 4.57 | 0.23 | 7.22 | 0.11 |
| PV supplies (kWh/yr.) | - | - | 1,496 | 60 | 18,243 | 683 |

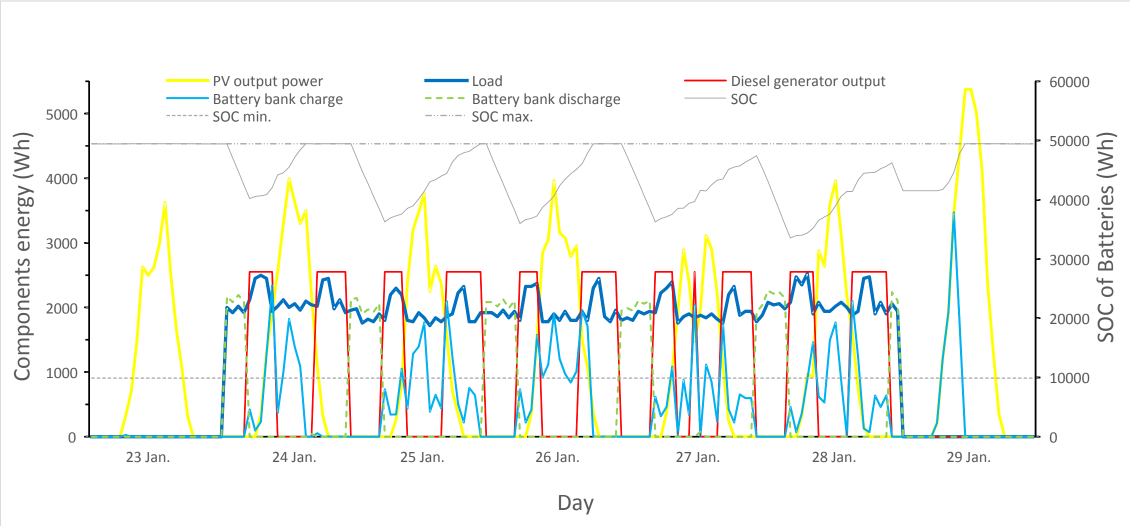


Fig. 11. Simulation of 7 days for the optimal PV-diesel-battery system

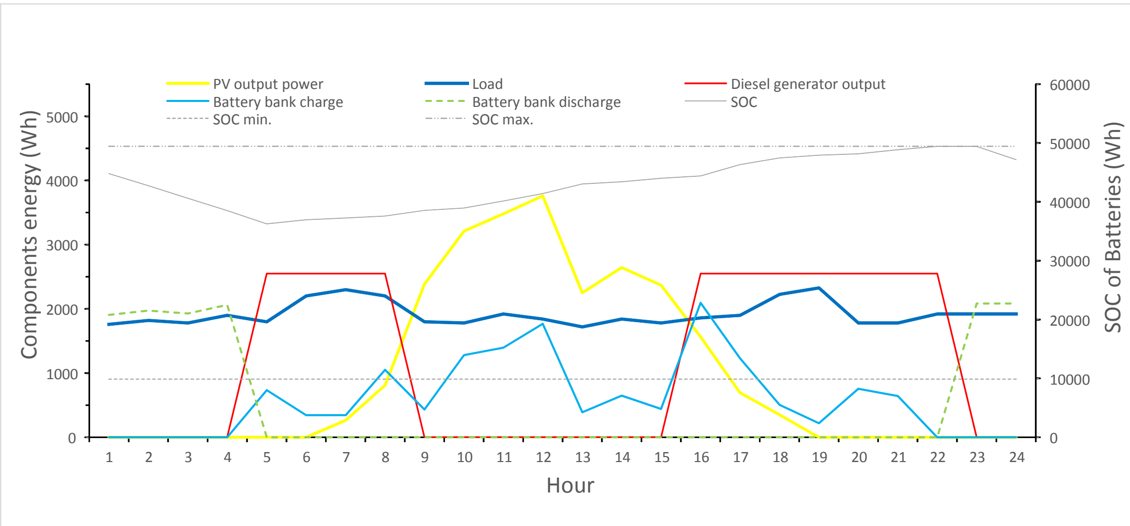


Fig. 12. Simulation of 24 hours for the optimal PV-diesel-battery system

After the optimisation of the energy production, the inclusion of a BSN with M2M could be of great interest in order to improve communications from the hospital. It would make it possible to send medical information from patients to other hospitals with more resources and medical specialists. The consumption of BSN devices is in the order of mW, as the device with more consumption is the M2M gateway that links with the outside. This consumption can be supplied without problems, using the renewable energy system proposed in this paper.

Taking into account the hospital's location and its orographic conditions, a potential difficulty in improving its telecommunications may be obtaining an Internet connection. Perhaps the best solution would be to install a very-small-aperture terminal (VSAT) antenna on the roof to obtain a satellite connection, but the initial investment and monthly cost would be prohibitive.

A more feasible solution would be to use the VSAT communications installed in the office of Doctors Without Borders [39], located 1.5 km from the hospital. If a WIMAX connection is installed from the hospital to this office, then it would be possible to use the VSAT service at the hospital. Although the connection speed is not very high (about 60 kB/s), it could be used to transmit noncritical patient data.

In summary, with an initial investment in M2M devices, an M2M gateway and WIMAX connection could begin transmitting certain vital signs of patients to other hospitals where they could be properly analysed. The process of adaptation to M2M technology is very simple because it relies on wearables (a BSN). If the experiment is successful and economically viable, it could increase energy production and provide the hospital with a satellite connection (Fig. 12). Obviously, this would increase energy consumption, but the PV-diesel-battery system ensures a supply of all the telecommunications system energy demands as well as scalability if the load must be increased.

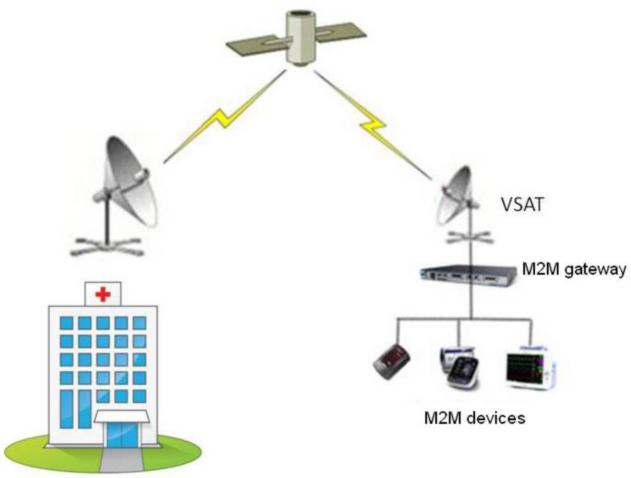


Fig 12. Proposed telecommunications system

## 5. Conclusions and future works

In this paper, a new methodology for the optimisation of off-grid hybrid systems (photovoltaic-diesel-battery systems) is shown. A Monte Carlo simulation is applied to consider the uncertainties of irradiation and load in the optimisation process. Previous works which use the stochastic approach use classical models for the batteries, obtaining values for the batteries lifetime which could be much higher than in reality, so the expected cost of the system is not correctly calculated. In this work, an advanced weighted Ah-throughput model for the lead-acid batteries is included in the model, obtaining results of batteries expected lifespan much closer to reality than those obtained using classical models of batteries, thus obtaining a much more accurate net present cost and levelised cost of energy (which includes the cost of batteries replacement during the system lifetime).

The probabilistic approach has been applied to the optimisation of the electricity supply to an off-grid hospital in Kalonge, Democratic Republic of the Congo, which currently uses a diesel-battery system. The optimisation of a PV-diesel-battery system is performed. The results show that the application of renewable energy systems in this Kalonge hospital, without the help of an optimisation tool, can lead to economically undesirable results. However, with the optimisation tool, cost reduction can be very significant (28%) and reduction in fossil fuel consumption even more so (54%), also reducing the pollutant emissions. Analysing these results and conducting further studies to improve the reliability of the supply both seem advisable, considering how critical these resources are and that in other hospitals, consumption is greater.

Furthermore, we have proposed possible improvements to the hospital's telecommunications.

Doctors Without Borders carries out its activities in other hospitals in Africa, such as in Batangafo and Kabo (Central African Republic), Shabunda (Congo), Deghabur (Ethiopia) and Madaoua (Niger). The results shown in this article could be extrapolated to others, offering potential energy- and cost-efficient improvements.

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