Economic Evaluation of Degradation by Corrosion of an On-Grid Battery Energy Storage System: A Case Study in Algeria Territory

Fouzia Brihmat

Abstract**—**Economic planning models, which are used to build microgrids and Distributed Energy Resources (DER), are the current norm for expressing such confidence. These models often decide both short-term DER dispatch and long-term DER investments. This research investigates the most cost-effective hybrid (photovoltaic-diesel) renewable energy system (HRES) based on Total Net Present Cost (TNPC) in an Algerian Saharan area, which has a high potential for solar irradiation and has a production capacity of 1 GW/h. Lead-acid batteries have been around much longer and are easier to understand, but have limited storage capacity. Lithium-ion batteries last longer, are lighter, but generally more expensive. By combining the advantages of each chemistry, we produce cost-effective high-capacity battery banks that operate solely on AC coupling. The financial implications of this research describe the corrosion process that occurs at the interface between the active material and grid material of the positive plate of a lead-acid battery. The best cost study for the HRES is completed with the assistance of the HOMER Pro MATLAB Link. Additionally, during the course of the project's 20 years, the system is simulated for each time step. In this model, which takes into consideration decline in solar efficiency, changes in battery storage levels over time, and rises in fuel prices above the rate of inflation, the trade-off is that the model is more accurate, but the computation takes longer. We initially utilized the optimizer to run the model without multi-year in order to discover the best system architecture. The optimal system for the single-year scenario is the Danvest generator, which has 760 kW, 200 kWh of the necessary quantity of lead-acid storage, and a somewhat lower Cost Of Energy (COE) of $0.309/kWh. Different scenarios that account for fluctuations in the gasified biomass generator's production of electricity have been simulated, and various strategies to guarantee the balance between generation and consumption have been investigated.

Keywords**—**Battery, Corrosion, Diesel, Economic planning optimization, Hybrid energy system, HES, Lead-acid battery, Li-ion battery, multi-year planning, microgrid, price forecast, total net present cost, wind.

I. Introduction

THIS research used a black box approach to analyze the anodic behavior and corrodibility of pasted and unpasted grids as well as different lead alloys. The estimation of battery deterioration and cycle life for on-grid hybrid energy systems, as well as the effects this has on battery performance and cost, were given special attention. Corrosion is considered a side reaction that takes place in the positive plate. It is largely possible to understand the corrosion that appears during battery storage as the continuation of the first assault that was sparked by low density sulfuric acid production.

The deterioration rate is influenced by operating circumstances. The following battery aging variables have received the most attention: temperature, SOC (state of charge), voltage, Depth of Discharge (DOD), and current density.

Prior findings indicated potentially major corrosion problems. It is one of the sector's principal enemies. The cost of corrosion, which includes all preventative measures, replacing damaged parts or buildings, and both the direct and indirect consequences of accidents due to corrosion, are estimated at 5,2% of world gross product in 2020, which corresponds to approximately 150 million tones/year or even 5 tones/second. We focus on the battery corrosion as it was mentioned on the § 1. According to predictions [2], corrosion will contribute 6.2% of the world's gross product in 2026, or around 150 million tons annually or even 5 tons per second. We focus on battery corrosion.

It will be necessary to lower the cost of their energy storage technology if rural regions are to be brought on-grid or electrified on a broad scale. In truth, producers rent battery packs to consumers with the assurance that they would replace them if they stop functioning as least as well as required.

In Algeria, there are a lot of rural villages that are not connected to the main grid. They generally fulfill their electrical demands with standalone diesel generators. Diesel generators are surrounded by social and financial problems. Giving individuals without access to power safe, cheap energy is quite challenging. Even though extending the grid is favored to provide power to rural regions, there are situations when isolated settlements cannot be reached by the national grid. Alternatives for off-grid HRES may be quite useful in these situations. A single usage of renewable resources like solo PV or standalone wind is problematic due to the intermittent nature of the energy supply. A hybrid energy system that combines solar electricity and a diesel generator can dependably meet demand. The system may produce power with a lot less emissions compared to standalone diesel generators. Designing a HRES with reduced net present cost system components is the problem.

We determine the most practicable energy system design after doing simulation, optimization, and sensitivity analysis, taking into consideration the different configurations that would fulfill the load requirement.

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We need to be certain that this activity will be lucrative before we take a financial risk. The development of methods to improve battery packs' endurance and efficiently manage their warranties is made possible by modeling the performance evolution of battery packs over time. This model looks at when it makes sense to supplement a diesel power supply with wind turbines or batteries. The system consists of two diesel generators of 150 kW and 75 kW. The wind turbine under consideration is a 50 kW model.

Both varying diesel fuel costs and wind speeds are taken into consideration. The ideal system type shows that under conditions of high wind speeds and high gasoline costs, wind power does make sense.

The Modified Kinetic Battery Model (or ASM) employed in this work takes into consideration temperature variations based on capacity, calendar life, and rate of losses. The model makes an estimate of cycle lifetime using the Rainflow Counting approach.

We consider a battery whose interior temperature is constant. Otherwise, a lumped thermal model is used to calculate the interior temperature of the battery bank.

II. Methodology

This study investigates the most economically viable HRES based on the TNPC for the Ouargla area of the Algerian Sahara (31°56°.952N 5°19.5012E). An appropriate site must be chosen, the available energy resources must be assessed, the energy system must be modeled, and the energy system must be optimized. A wind turbine, diesel generator, and battery energy system are created to satisfy a specified electrical demand.

We have developed a model of the economics and behavior of a power system that accounts for the expenses of setup and maintenance. The Modified Kinetic Model, which incorporates series resistance, the effects of temperature on capacity and degradation rate, as well as cycle-by-cycle deterioration depending on discharge depth (DOD), was the main focus of our study.

The combination of HOMER and MATLAB is used for all computations [1].

A. System under Study

Fig. 1 demonstrates the system under study. It comprises of a single wind turbine (WT) and a power conditioning system (converter, filters, and step-up transformer) coupled at the point of common connection (PCC). The grid or the WT may be used to charge the battery energy storage system (BESS), which can also discharge electricity to the grid. It is equipped with a battery management system (BMS), which measures the voltages of the battery cells, makes sure that they are charged uniformly, and determines the battery system's SOC, state of health (SOH), and remaining usable life (RUL). The BMS also monitors battery cell temperatures and controls the cooling system to maintain the BESS at the ideal operating temperature. The WT-battery, often referred to as an enhanced WT, is powered by an AWT controller. The AWT controller receives information from the PCC on the actual WT power generation. It also gets information from the BMS on the battery's current SOC, SOH, and RUL. The predicted WT power for the application under consideration is sent to the AWT controller. The AWT controller determines the optimum operating strategy and determines how much power the BESS must provide or absorb based on all of this information. The BESS converter is then directed by the AWT controller to generate or consume the required power.

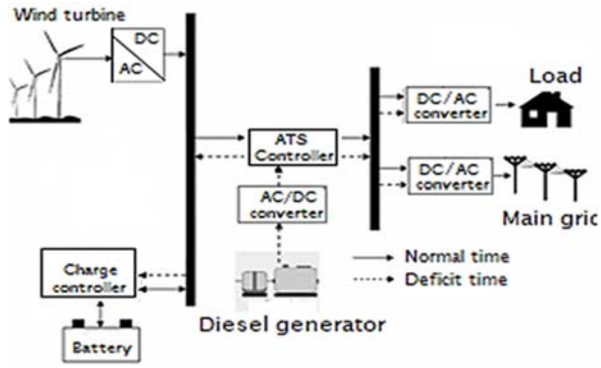


Fig. 1 General scheme of the studied system

B. The Benefits of Long-Term Plans

Between 1995 and 2025, retail electricity rates and natural gas prices rose by factors of 3 and 4, respectively (Fig. 3 (a)).

A model of economic planning that overlooks these tendencies is obviously working with incomplete information. However, most models take that year as a stand-in for the whole project lifespan and base their judgments only on the energy environment in that year. As a result, depending on the year (abscissa) in which an analysis is performed, a different recommendation for the installation of DERs may be given (Fig. 3 (b)). In this situation, research carried out in 2020 is flawed since less fuel-based generation is optimal only five years later, in 2025. Similar to this, if the research is done in 2025, it will not be optimal five years later since the cheapest approach requires wind farms.

From 1995 to 2025, electricity retail rates and natural gas prices have increased significantly by a factor of 3 and 4 respectively (Fig. 3 (a)).

Clearly, an economic planning model which does not consider such trends is working with incomplete information. Yet, most models use a single year as representative of the entire project lifetime, making decisions based on the energy landscape solely in that year. As observed in Fig. 3 (b), the year (abscissa) in which an analysis is run can change the recommendation for the DERs to be installed. In this scenario, an analysis run in 2020 is incorrect just five years later in 2025, since less fuel-based generation is optimal. Similarly, if the analysis is run in 2025, it is sub-optimal five years later, as the lowest-cost solution requires wind turbines.

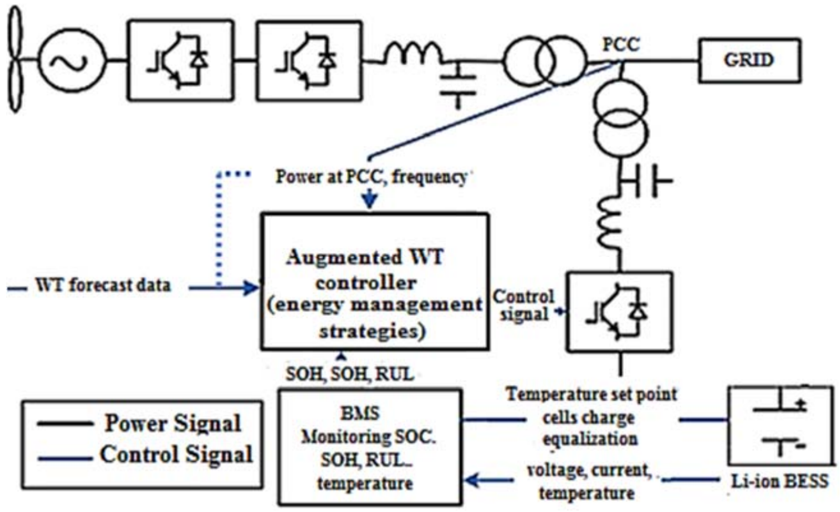
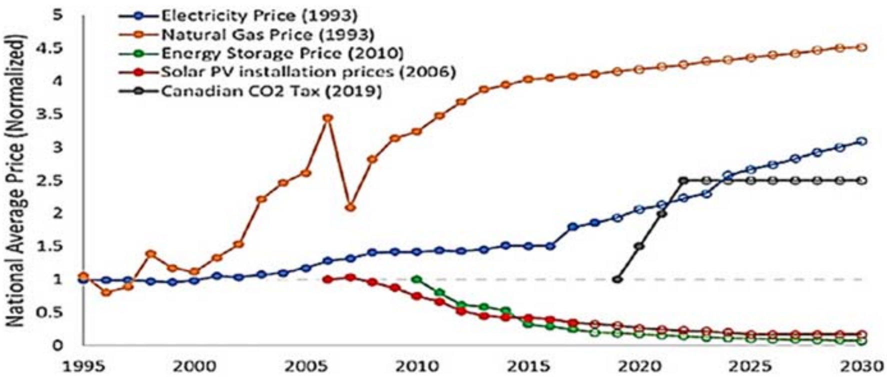
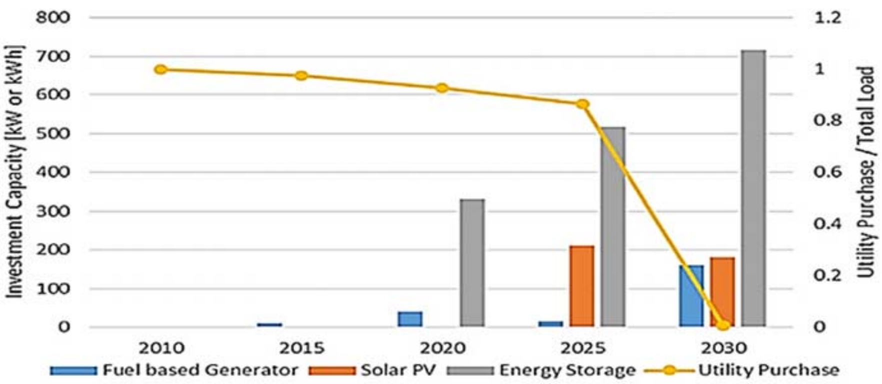


Fig. 2 Block diagram of the system under study



(a)



(b)

Fig. 3 (a) The average national price of energy sources, technology installation costs, and carbon taxes [2]-[6]; (b) Comparison of investment decisions determined using a single year optimization approach considering the historic and forecasted prices from years 2010–2030 displayed in (a)

C. Background of the Economic Analysis

The prices for the available WT power production data and the pricing for ancillary services data were only accessible for a year. However, it was assumed that throughout a 20-year period, the prices for auxiliary services and WT output power would be constant in order to determine the investment profitability (the typical lifespan of the WT). The earnings from the FEB service were calculated using the West Denmark balancing market pricing for 2010 [7], [8].

In the present study, the investment profitability in Li-ion BESS for delivering the forecast error balancing (FEB) service was examined using the NPV approach. A Li-ion BESS investment should be undertaken in this case if the approach can show that the NPV will be greater than zero (i.e., NPV 0). In the investment year, the NPV approach compares all cash flows against one another (i.e., year 0). The NPV accounts for the fact that future investment earnings will be less valued than in year 0 of the investment and is computed on the assumption of a given interest rate. The main goal of the simulations was to determine the investment's net present value (NPV) for the Li-ion BESS that was being utilized to provide FEB service.

The NPV is determined in accordance with (1), which offers the formula to be used on the sum of all cash flows happening in the same year [8].

$$NPV = \sum_{n=1}^{j} P = F_n \cdot \frac{1}{(1+i)^n} \tag{1}$$

where P is the present worth, F is the future worth, i is the interest rate, n is the year in which the cash flow occurs and j is the number of years for the NPV analysis.

The research system shown in Fig. 2 was modified, and a simulation benchmark was created using the flowchart shown in Fig. 4.

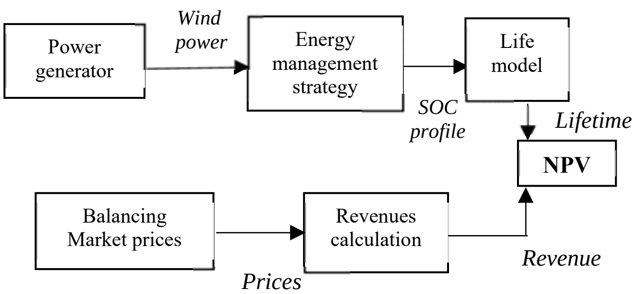


Fig. 4 Flowchart of the simulation benchmark

1. Inflation Rates and Nominal Discount Factor

Annual inflation is included into the project at a rate of 5.71%. Using a discount factor of 10.70%, all renewable energy technologies have been considered.

2. Project Lifetime

As noted in the introductory section, developing a hybrid energy system based on annual demand increase presents a number of challenges when taking both technical and financial factors into account. In this study, the project life is 20 years due to all of these issues.

Accurately estimating the power drop over time and the accompanying different economic aspects is crucial for all stakeholders, including governments, utility companies, investors, and academics, in the design of any project using RES. Therefore, evaluating the potential annual changes during a project might help to ascertain its economic sustainability. The following factors will lead to reduced cash flows or less power generation: rising grid pricing, rising loads, volatile fuel prices, battery and WT deterioration. It goes without saying that a techno-economic analysis of a system with RES that disregards these elements is doing an inadequate job of studying the system. To ascertain how long the project will survive, the bulk of analyses, however, simply take the energy situation in a single year into account. The objective of this work is to fully account for the multi-year changes in the component characteristics of the project at the selected site in order to determine the most cost-effective alternative.

3. Sensitivity

To assess the effects of altering different system setup settings, sensitivity analysis is employed. Sensitivity analysis makes it possible to assess how adaptable a system is.

This research used sensitivity analysis to examine the effects of modifying the fuel price and solar irradiation on the levelized cost of electricity and the TNPC.

III. The Advanced Battery Storage BESS

A. Battery Degradation Estimation Methods

Batteries can degrade while in storage for a number of different chemical reasons, including the limited thermal stability of materials (such as silver oxide in silver-zinc batteries) or the corrosion of metal electrodes (such as lead in lead-acid batteries or lithium in lithium-thionyl chloride batteries). Due to parasitic processes such lithium metal/battery electrolyte reactions in lithium metal rechargeable batteries, battery performance might deteriorate while in use. Degradation rates may be influenced by a variety of elements, including temperature fluctuations or storage temperature. To find this, battery standards call for testing after different storage temperature cycles. By using accelerated aging at high temperatures or real-time storage measures, one may assess the impact of performance loss. Thermal measurements are one of the additional techniques for estimating deterioration rates (microcalorimetry). Increased battery deterioration rates can be attributed to improper charging voltage management, for example, overcharging lead-acid batteries can lead to overheating and excessive electrolyte loss through gassing [8], [9].

B. Degradation Mechanisms

Most conventional batteries and certain specialist batteries both employ aqueous electrolytes. Corrosion may cause these batteries to deteriorate in a number of different ways. Despite the fact that lead is a metal that is generally inert, lead-acid batteries contain a rather concentrated acid that will eventually corrode the lead. Batteries with more lead loss have less capacity. Lead sulfate, a corrosion byproduct, may also make it challenging to recharge batteries, which would reduce both short-term and long-term battery capacities.

Another problem with lead-acid batteries is lead sulphate discharges from the lead-negative and lead-dioxide-positive electrodes. When a battery is allowed to stand whereas being drained (when both plates are coated with lead sulphate), lead sulphate recrystallizes, forming crystals that will not recharge and permanently lowering the battery's capacity [9].

IV. Results and Discussion

Both hourly wind speed and 75 W diesel fuel constitute two model inputs. Their representative profiles are superposed in Fig. 5. We present the 150 W diesel fuel profile in Fig. 6.

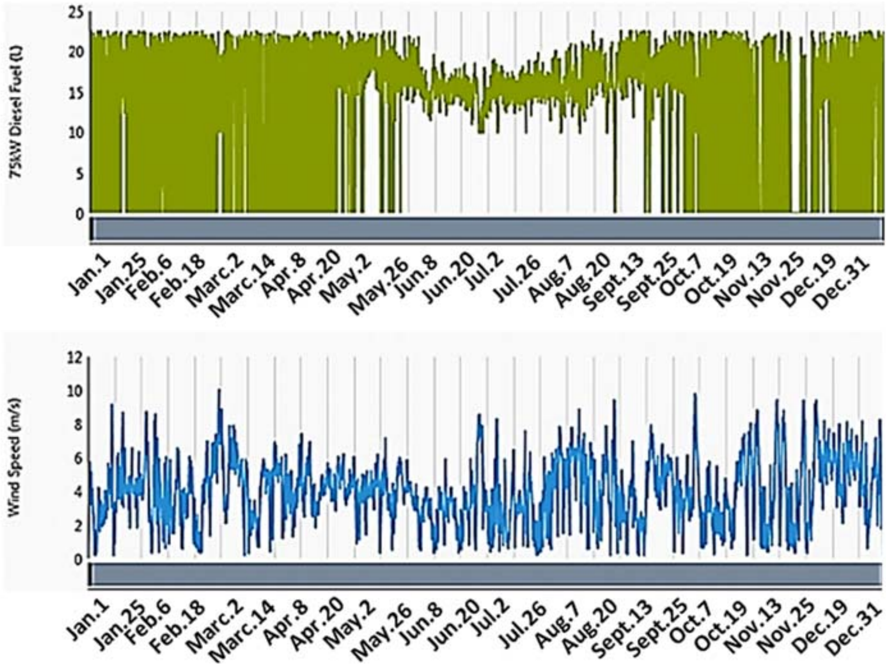


Fig. 5 Hourly Wind speed and 75 W diesel fuel profile

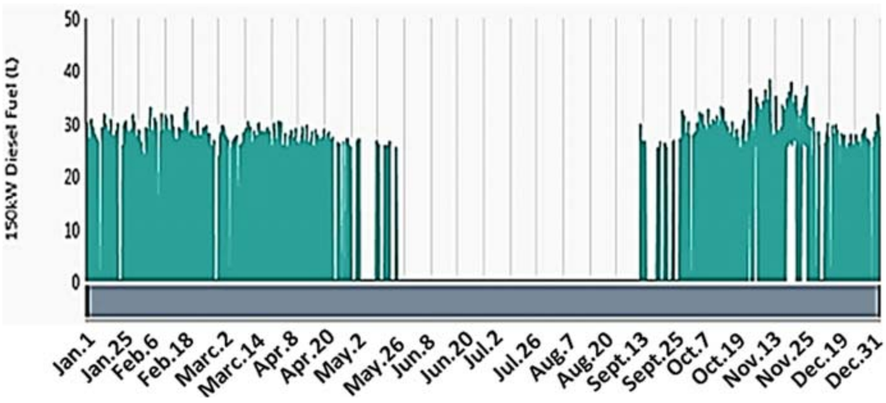


Fig. 6 150 W Diesel fuel profile

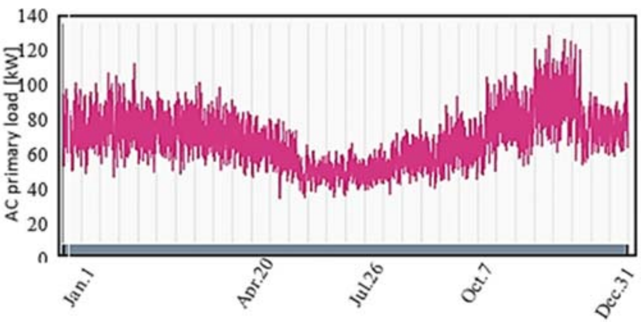


Fig. 7 AC primary load profile

The grid demand charge is calculated using (2):

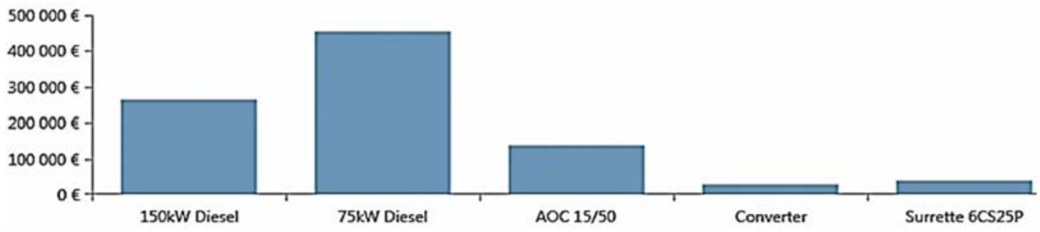
$$C_{grid,demand} = \sum_{i}^{rates} \sum_{j}^{12} P_{grid,peak,i,j} \cdot C_{demand,i} \quad (2)$$

where $P_{grid,peak,i,j}$ = the peak hourly grid demand in month j during the time that rate i applies [kWh]; $C_{demand,i}$ = the grid demand rate for rate i [$/kW/month]. In Fig. 7, we present the AC primary load profile.

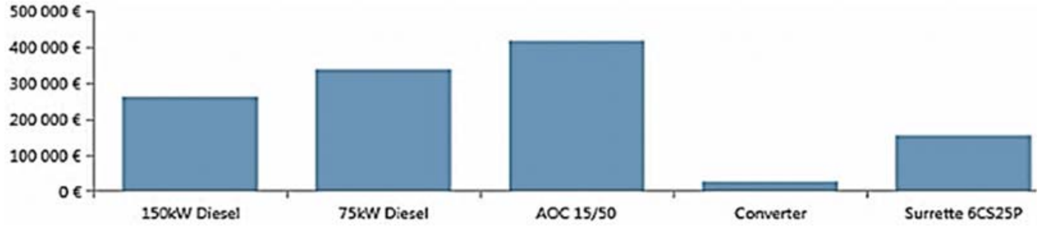
A. Financial Balance Sheet

After developing the model, we then made an effort to evaluate the cost summary based on Net Present by component with BESS normal operational operation inside the BESS deterioration. This illustration is seen in Figs. 8 (a) and (b).

Following the degradation and subsequent failure of the equipment and ultimately for the entire system under investigation, and according to the management strategy adopted, we find that the system must be oversized after the degradation which also includes the failure of the BESS, which requires additional costs in terms of equipment. Therefore, the system must be expanded depending on the chosen management plan.

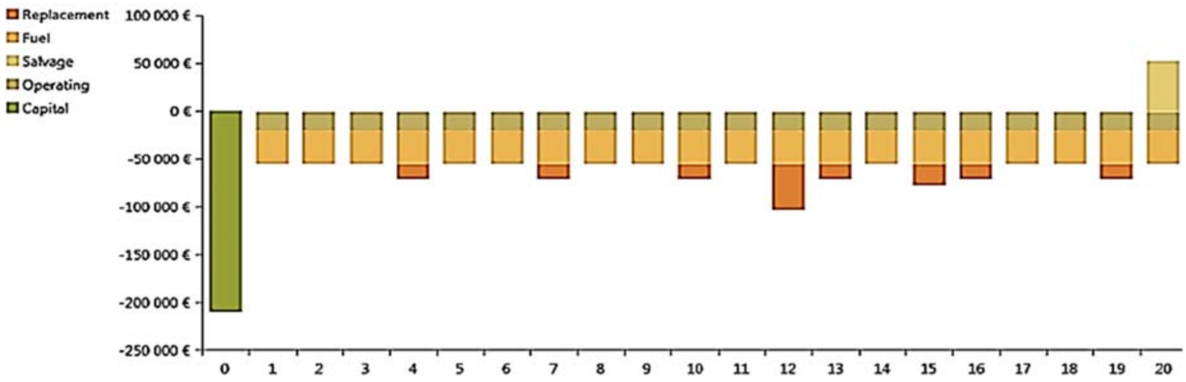


(a) Normal operating

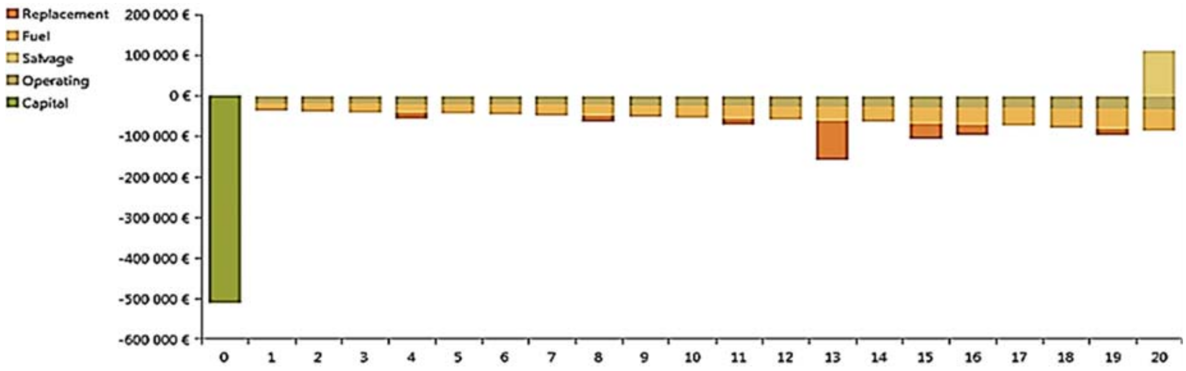


(b) BESS degradation

Fig. 8 Cost summary- Net present by component



(a) Normal operating



(b) BESS degradation

Fig. 9 Cash flow by cost type

The component's net present cost is calculated by subtracting the present value of all the costs related to installing and maintaining the component over the duration of the project from the present value of all the income it produces over the same time period (also known as life-cycle cost).

Other evaluations that are based on net present by cost type, annualized per component, show the same logic of progression.

Fig. 9 displays the cash flow's evolution by cost type over the 20-year lifetime. The expense that, if it occurred consistently throughout the project, would provide a net present cost equal to the actual cash flow sequence associated with that component.

The entire capital that came in or left throughout the course of each year is shown by a bar on the graph.

Each year's cumulative cash inflows and outflows are visually represented by bars on the graph. The initial system cost, both before and after optimization, is depicted by the first bar on Fig. 9.

Positive values signify expenditures such as fuel costs or equipment replacement expenses, while negative values represent cash outflows. When documenting costs or revenues for projects with positive or negative figures, it's crucial to account for the corresponding cash inflows or outflows. To emphasize, the first bar on the graph (Fig. 9) denotes the system's initial cost, which is also displayed post-optimization.

Each element in the system is represented by a distinct color. Fines and fixed system expenses are included as "Other" costs in the diagram. "Other" expenses consist of fines and system-fixed fees.

A nominal cash flow is the actual income less the projected expenses for a certain year. It is calculated as expected revenue minus anticipated costs for a certain year. Discounted cash flows are nominal cash flows that have been carried forward to year zero. It is determined by multiplying nominal cash flows by a discount rate.

A stacked bar is used to illustrate each cash flow, with each color denoting one of the five expense categories (capital, replacement, salvage, O&M, and fuel). The salvage value is evident as a positive value at the end of the project's lifespan. The O&M cost type pays for grid sales for grid-connected systems that fuel the grid with power.

- Comparing Economics Analysis

This case includes an economic comparison of the selected base case and the winning system with the lowest net current cost. The result will seem different depending on whether the basic case is the winning system or if there are no viable alternatives.

The winning plan will be the one with the lowest net present cost. There may be instances when the system with the lowest initial capital cost—the base case system—also turns out to be the winning system.

Table I includes a list of the two systems that we wish to financially compare. In Fig. 10 are superposed the evolution of the cumulative cash flow of both the base case and the current studied system, over the whole lifetime, during the normal operation mode.

TABLE I
THE TWO COMPARED SYSTEMS

Base system		Diesel	Diesel	BESS	Converter		75,0	150	24	25,0	807096€	99900€
Current system	WT	Diesel	Diesel	BESS	Converter	1	75,0	150	24	25,0	922278€	209900€

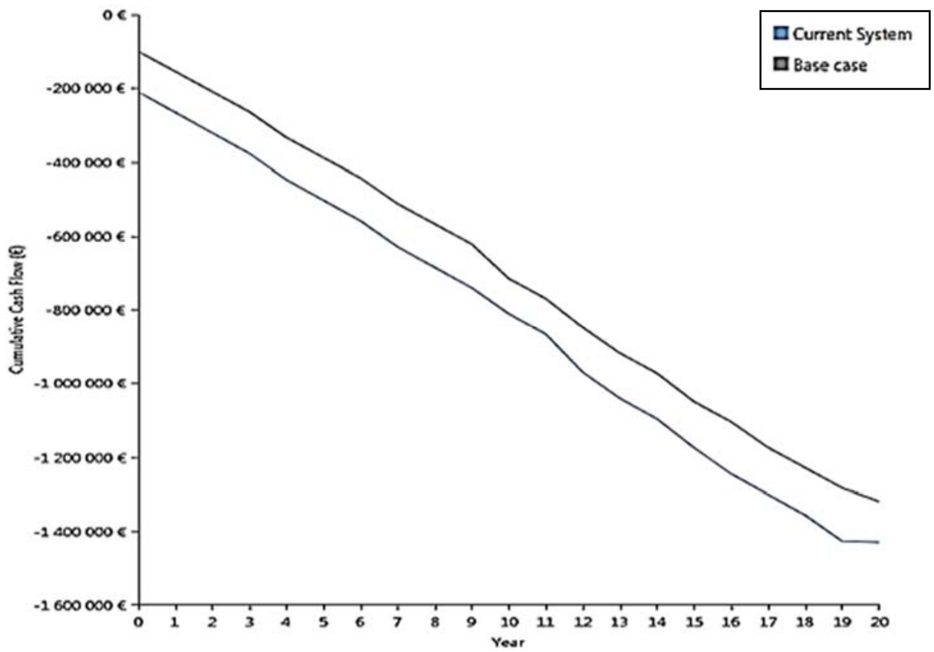


Fig. 10 Annually cumulative cash flow evolution in a normal operation mode

TABLE II
ECONOMIC BASE CASE SYSTEM CHARACTERISTICS

Metric	Value
Present worth (€)	-115181
Annual worth (€/yr)	-9946
Return on investment (%)	-5.0
Internal rate return (yr)	n/a
Simple payback (yr)	n/a
Discounted payback (yr)	n/a

Table II represents the base case system cost characteristics. In the same logic, both Figs. 11 and 12 represent separately the total annual cash flow of the current and base case systems, respectively, during the nominal operation mode.

B. Battery's Affected Technical Characteristics

The storage energy cost reflects the typical cost that the system has experienced whereas purposely charging the storage bank. The "cost of cycle charging" refers to the extra cost spent by the system particularly for charging the storage.

The amount of energy that is presently stored in the battery is shown on Figs. 14 (a) and (b) as a percentage of its full capacity.

The DMap displays the time of day on one axis and the day of the year on the other. Each time step of the year is represented by a rectangle that is colored in line with the data value for that hour. When compared to a simple time series plot, this presenting structure typically makes it simpler to discern daily and seasonal trends.

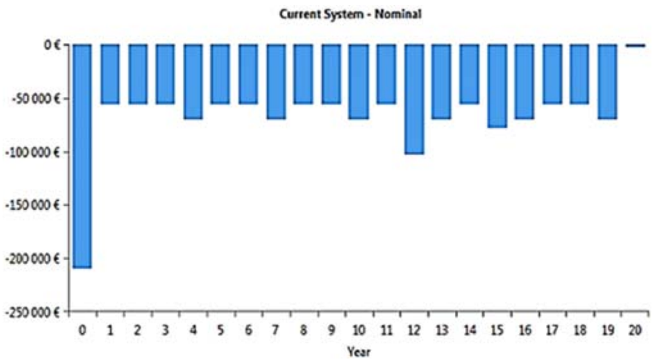


Fig. 11 Total annual cash flow current system

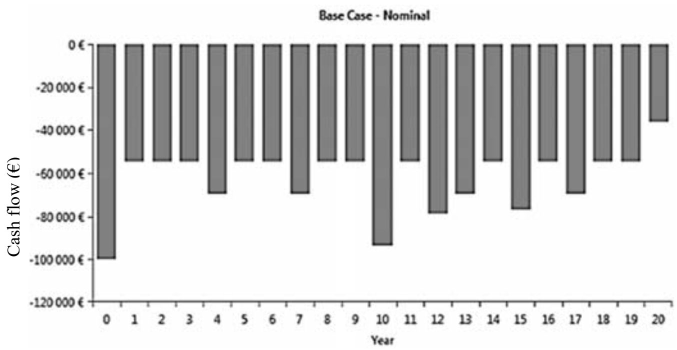


Fig. 12 Total annual cash flow base case

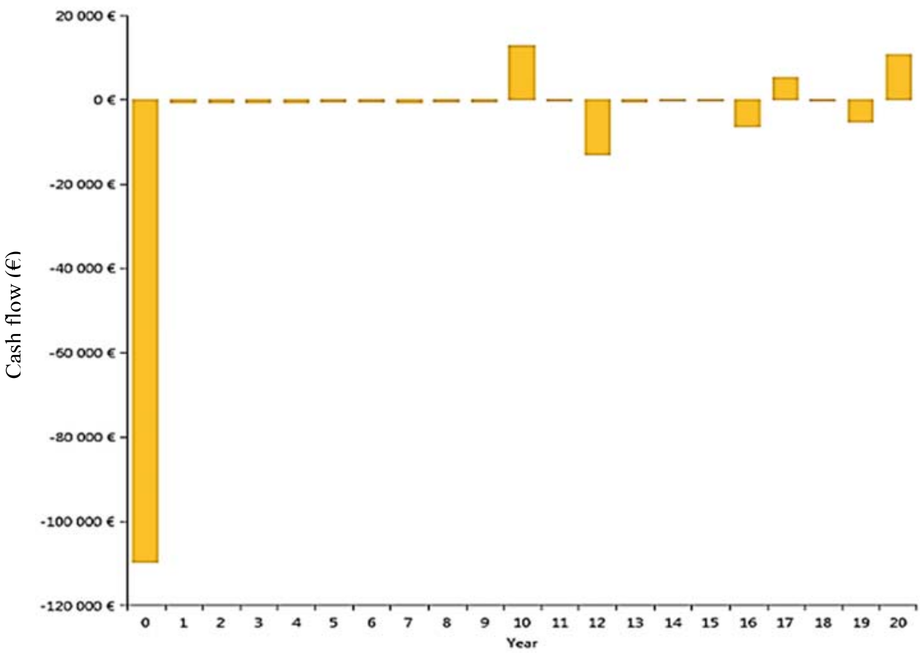
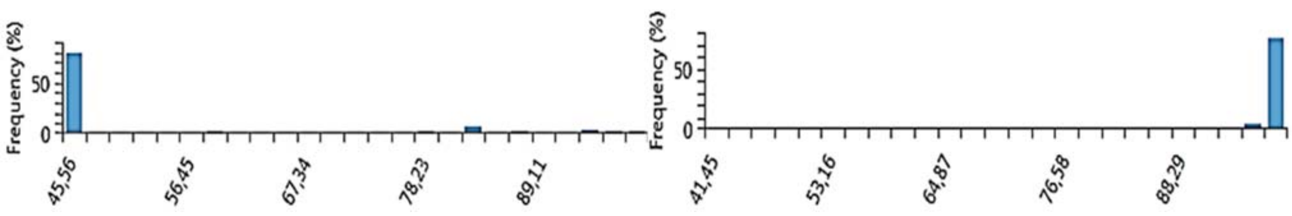


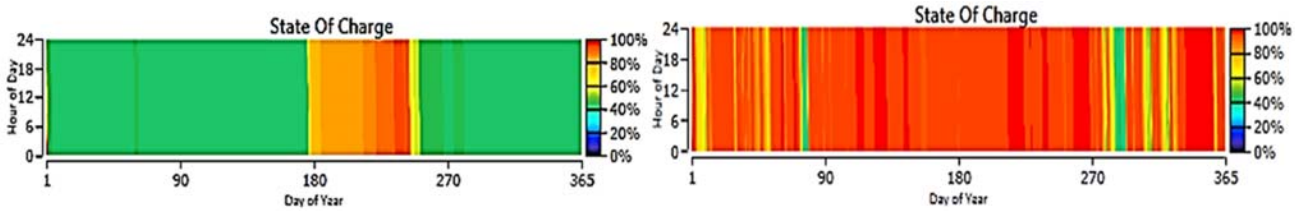
Fig. 13 Annually total cumulative cash flow evolution in a discounted operation mode



(a) (b)

Fig. 14 SOC frequency: (a) Before degradation; (b) After degradation

Fig. 16 illustrates the hourly profile of the maximum charge/ discharge power hourly profile in both cases (a) before BESS degradation, then after its degradation on (b).



(a) (b)

Fig. 15 DMap SOC

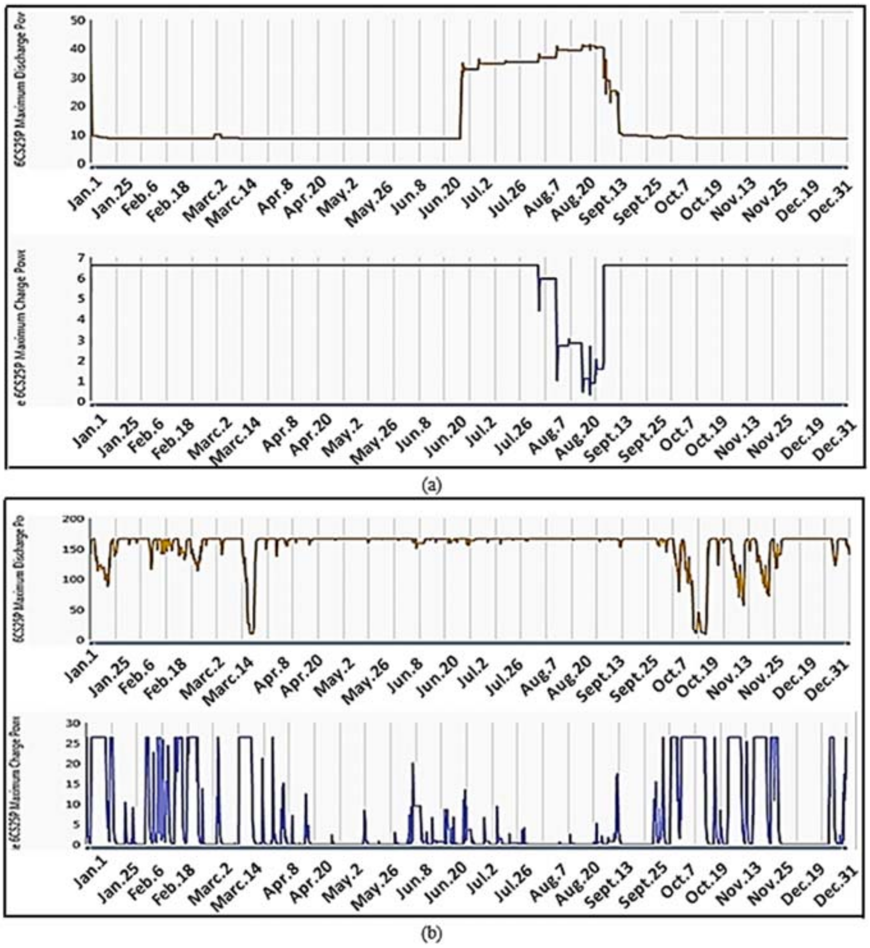


Fig. 16. Hourly maximum charge/discharge power

The battery's maximum charge and discharge power varies from one one-time step to the next depending on the battery's present level of charge and recent history of charge and discharge. The maximum charge rate variable limits the speed at which the system may charge the storage bank. When it is empty, the capacity of the storage component is precisely proportional to that cap.

There are three limitations on the storage bank's maximum charging power. The first constraint results from the kinetic storage concept. The second limitation relates to the maximum charge rate of the storage component replacement. The component is changed out when one of the two degradation variables crosses this line. Fig. 17 demonstrates the impact of time on battery autonomy. The third one is about the storage component's maximum charge current.

The proportion of capacity deterioration that triggers the component has to be changed. The component is changed out when one of the two degradation variables crosses a certain threshold.

The autonomy is steadily decreasing year on year because of its degradation which worsens with time. Fig. 18 presents the hourly SOC superposed to the DC operating capacity profiles.

The maximum DC electrical load that the system can manage at any one moment is represented by the maximum load lifting capacity of the lift equipment for a particular load zone. Both dispatchable power sources (generators, the grid, and storage banks) and renewable power sources provide the operating capacity (wind, solar, and hydro). It is expected that the Storage

Component has to be changed after a certain number of energy cycles through the storage, regardless of the depth of the individual charge-discharge cycles. This lifetime storage throughput is a key factor used to calculate the cost of the storage bank's life and wear.

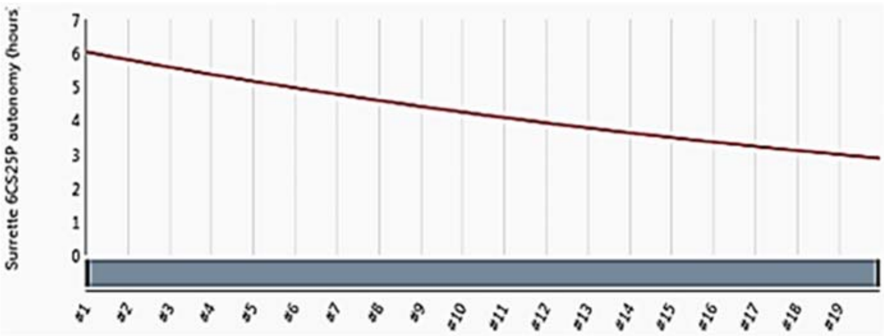
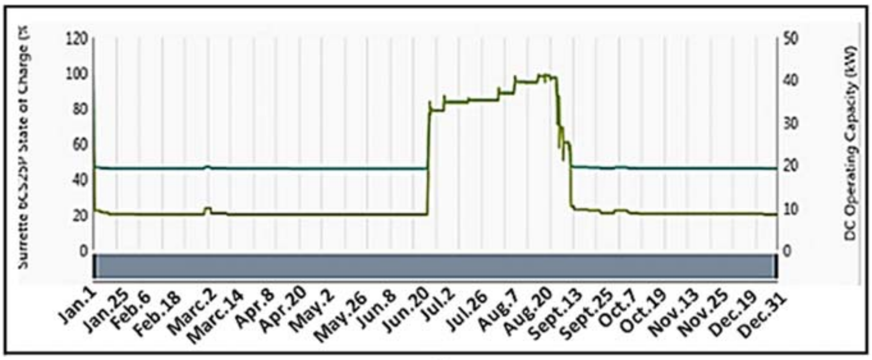
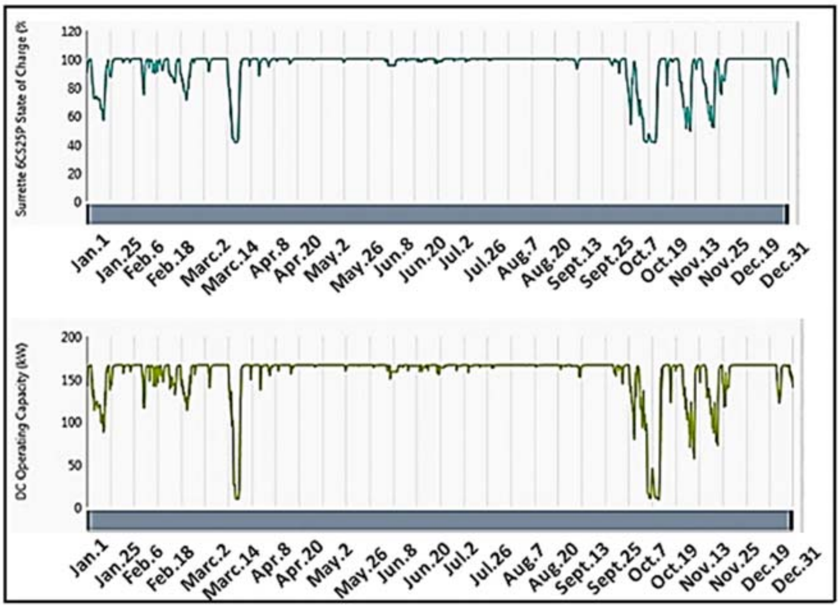


Fig. 17 Evolution of the battery autonomy over lifetime



(a)



(b)

Fig. 18 Hourly SOC superposed to the DC operating capacity profiles

Throughput and depletion evolution over lifetime are shown respectively in Figs. 19 and 20.

Depletion is the difference in the storage SOC at the beginning and end of the year. It fluctuates degrading over the year. We illustrate the AC operating capacity evolution via Fig. 21 in the two introduced operation modes. We present the annual energy losses due to storage inefficiency during lifetime in Fig. 22.

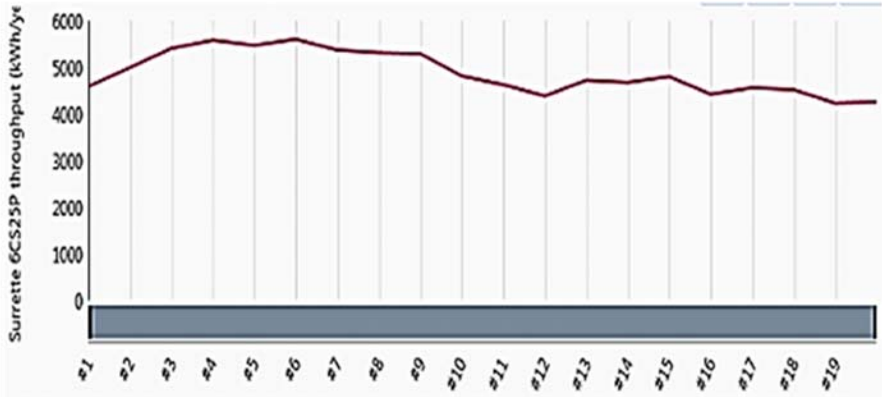


Fig. 19 Battery throughput over system lifetime

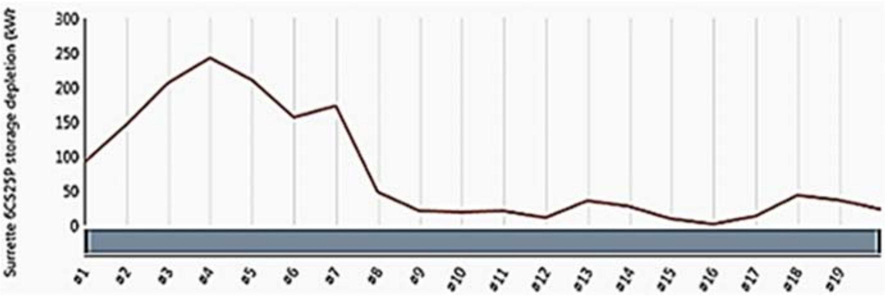


Fig. 20 Battery depletion evolution over system lifetime

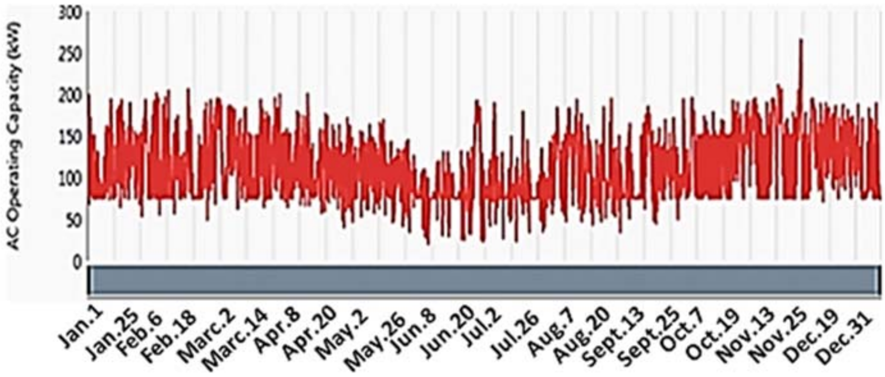


Fig. 21 Hourly AC operating capacity evolution

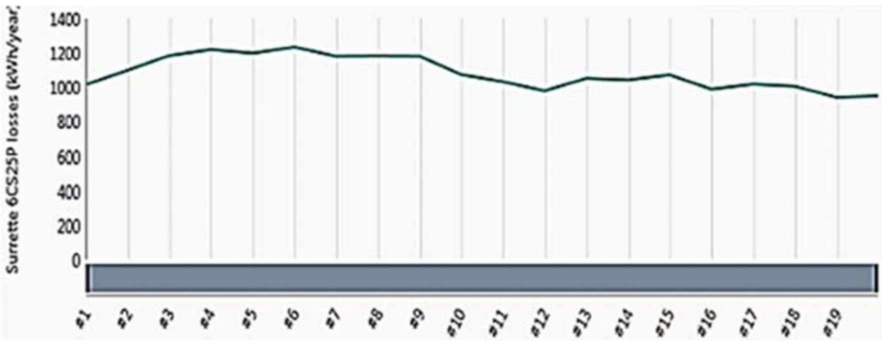


Fig. 22 Battery losses during lifetime

V. Conclusion

This examination investigated the influence on the general features of the battery and the economic feasibility of employing ESS based on advanced storage batteries to generate wind power was carried out for the Algerian energy market. The lifespan of the BESS has a big impact on how profitable an investment is assessed. The battery's performance deterioration owing to usage, age, and temperature history, as well as the values of degradation due to time, temperature, and degradation-cycling value, all contribute to the battery's requirement for replacement.

The total equivalent complete cycle for the battery was calculated using the Rainflow counting algorithm technique. The impact of current magnitude on the temperature-dependent aging rate curve at different SOCs have been examined.

The resulted Levelized Cost of Energy (LCOE) has as consequence that Algeria will be able to depend less on fossil fuels, which have severe environmental impacts, variable costs, and more on solar and wind generating facilities to ensure its electrical needs.

To maintain battery performance, it is necessary to undertake frequent lead-acid battery charging to prevent capacity loss due to sulphation during storage or completely drain nickel-cadmium batteries to prevent capacity loss owing to the "memory effect" (formation of unreactive lead sulphate in the battery plates). Batteries may be constructed to prevent deterioration whereas in storage by adopting reserve designs, in which one component—typically the electrolyte—is left out during production and added shortly before use.

An examination of the literature revealed that grid behavior has long been recognized to have a major impact on lead-acid battery performance [9].

There may be some uncertainty when comparing the conclusions of different researchers, which may be explained by the complexity of the system being studied and the diversity of the materials source.

According to different authors who have investigated the behavior of positive plates or alloy samples, PbCaSn grids are less corrodible than antimonial grids [9]; yet, some data also show that PbCaSn alloys are more vulnerable to anodic attack arcs [9]-[12]. The effects of polarization, acid concentration, alloy composition, notably with respect to calcium [12], tin [13], and antimony [10], have been the subject of several investigations [9], [8], [12], [13].

Batteries need maintenance in order to operate at their best; for instance, complete nickel discharge. Therefore, using accelerated lifespan experiments in the lab to create a lifetime model is extremely desired. The remaining useful lifetime (RUL) is the period of time that a system has before its performance reaches an undesirable level [12].

A storage state estimator is absolutely necessary in order to precisely estimate the storage performance and existing circumstances, including stored energy, aging, and probable failures, as well as to establish the battery's genuine exploitability throughout both its first and second life applications.

To analyze the dependability of various experimental methodologies, our findings were taken into consideration together with experimental data from industry experiments. From these perspectives, we will investigate the impact of current on the temperature aging rate function at different SOCs in future.

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