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Diagnosis and prognosis of complex energy storage systems: tools development and feedback on four installed systems

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Abstract

Electrical Storage systems are used since many decades in stand-alone applications. Recently, their use in grid connected renewable energies installations increases not only the flexibility of these systems but also their complexity. The optimization of their operation in these systems is necessary for cost effectiveness and is a technical and scientific challenge. The research and development projects are increasing worldwide to tackle different aspects of these new solutions. This paper presents advanced analysis of some of these systems based on new approaches of data analytics. Four PV-Storage systems have been monitored for three years and an original diagnostic and prognostic tool is developed for the analysis of the performance and defaults of such systems.

In addition, the generic approach presented in this paper allowed to have a feedback on the performance of grid connected PV-storage systems with two different storage technologies: Li-ion and NaNiCl2. The efficiency analysis includes the performance of batteries and power conversion systems. So, the objective here is to compare the usage and the performance of electrical storage systems along time within each power plant and also between the monitoring power plants using experts' knowledge and data processing.

Keywords: Energy Storage Systems; Batteries; Diagnosis; Statistical analysis; Usage analysis; Performance indicators.

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1. Introduction

The quick growth in variable renewable energy, namely solar photovoltaic (PV) and wind, is catalyzing efforts to modernize the electricity system. At high levels of penetration, variable renewable energy increases the need of resources that contribute to system flexibility. This ensures that system stability is maintained by matching supply and demand of electricity. Battery storage is one of the options for enhancing system flexibility in these circumstances by managing electricity supply fluctuations. However, the implementation and the management of renewable energy plants have significant cost of investments. The operation is characterized by its complexity. The addition of energy storage systems allows better planning of production but these solutions are still costly.

In order to optimize production costs and increase plant availability and productivity, the renewable energy developers must be able to produce energy with enhanced equipment effectiveness. Therefore, new research axes must be introduced to improve the storage system performances. Thus, the data acquisition of such systems and data processing and analysis are relevant. This work is positioned between the issues related to the complexity of storage systems, and their operations, and the systems performance evaluation for diagnosis and prognosis.

Nomenclature

BESS	Battery Energy Storage System
DoD	Depth of discharge
Ec	Charged energy
Ed	Discharged energy
FMECA	Failure Modes, Effects and Criticality Analysis
IdC	Comparison Indicators
IdE	Status Indicators
IdH	Health Indicators
IdO	Operation Indicators
IdP	Performance Indicators
η_E	Energy efficiency
ρ_E	Energy losses
Pabs	Absolute Losses
Prelative	Relative Losses
Pc	Charge Power
Pd	Discharge Power
SoC	State of Charge of the battery
SoC_i	initial State of Charge for the calculation of the energy efficiency
SoC_f	final State of Charge for the calculation of the energy efficiency
SoH	State of Health of the battery related to the degradation per ageing

2. Objectives

The aim of this work is to present the results of a generic approach for the operation aiding of the energy storage systems and the global energy efficiency of PV-storage systems using the analysis of operation data. Our objective is to follow the time evolution of the key indicators in order to improve performances and availability of these complex systems. Different plants are addressed in order to make a comparative study as representative as possible. Also, several methods and tools are advised here. Firstly, this paper presents a literature review about diagnosis and prognosis methods. Then, an approach to develop these methods is proposed. Following the proposed methodology, the evolution of a performance analysis tool for renewable energy including storage systems is described in [1]. So, the originality of this work is the generic methodology, starting from actual operation data that integrates the variety of available information and arriving at the decision support tool to improve performances and availability of these

systems. Also, several methods and tools are recommended here.
After this brief introduction and the targeted objectives, the next sections are organized as follow:

- A literature review about battery in renewable energy systems is described in section 3.
- Section 4 presents the approach used to develop the diagnostic and prognostic tools for the complex PV- storage systems.
- Section 5 presents the tool description and examples of the indicators.
- Section 6 presents the key indicators evolution of four systems monitored and analyzed in this work and proposes to compare their uses and energy losses.
- Finally, section 7 ends the document with the main conclusions.

3. Literature review

The database of grid connected energy storage is referenced in [2]. The accumulated installed power is 193 GW within 1632 projects. Among these projects, 990 use electrochemical storage with accumulated power of about 3295MW. The applications of energy storage are divers like renewable capacity firming, electric energy time shift, frequency regulation, and voltage support. Some of energy storage projects were presented in [3]. However, the feedbacks on these systems are rarely presented in literature. One of them is a three years operation analysis which was presented in [4]. The authors presented a method for diagnostic of the storage from the real data operation analysis. The main goal for this study was to understand the usage of the BESS in order to be able to replicate it in the laboratory on single cells. Another study [5] focus on several days of operation of a storage system with electrical car. The study [6] presented a method for non-destructive diagnostic for estimation of the capacity loss of lithium-ion battery based on the OCV (open circuit voltage). An integrated modelling methodology which includes reduced-order models of a lithium-ion battery and a power electronic converter was introduced in [7], the model parameter extraction was only based on the test data of a 4.8 Ah lithium–polymer battery. The parameter extraction for modelling based on the operating data is more challenging because of the missing data and measurement uncertainty.

4. Approach

One of the key performance factors of complex systems is keeping them in normal operating conditions. To propose suitable operation support methods, a methodology to apprehend the real process must be proposed. For this, a literature review led us to an approach adapted to the storage systems. It is derived from the PHM field (Prognostics and Health Management). Also, a PHM approach aims to improve the reliability and the availability of complex systems during their life cycle. The proposed functional architecture is shown in Figure 1.
This approach seeks to improve the efficiency and availability of complex storage systems according to the following support functions:

- Data processing: this is a key step in the development of advanced approaches for systems analysis. In a first step, an acquisition of the monitoring data is performed automatically. Then, a data-processing structures the raw data and extracts the performance key indicators using statistical techniques. Five main families of indicators are proposed:
    - Operation Indicators IdO
    - Status Indicators IdE
    - Solicitation Indicators IdS
    - Performance Indicators IdP
    - Comparison Indicators IdC

- Diagnosis: this step aimed to localize the defective component and identify the nature of the failure according to an effect-cause approach. The techniques used are focused on diagnostic methods based on data processing. Other diagnostic methods also exist, knowledge-based methods (expert system, FMECA, etc.) and model-based methods (observer, etc.) [8]. We use here a monitoring function which computes a new family of indicators: diagnosis Indicators (*IdX*): these indicators are directly calculated from the actual battery measurements: current, state of charge, voltage, temperature, etc. The monitoring of these measurements and their limits is a tool for the identification of failures.
- Prognosis: the objective of a prognosis is to predict the future state of a system [9]. In our work, we aim to estimate a state of health indicators based on monitoring techniques and deviations analysis. As for the diagnosis, we use a monitoring function and we distinguish three prognostic approaches, model-based, data-driven and based on experience. We use here a monitoring function which computes a new family of indicators:
    - Health Indicators *IdH*: these indicators are calculated from the battery measurements: time, current, state of charge, voltage and temperature. The monitoring of these indicators allows to predict a performance deterioration of a battery system.
- Operation aiding: this last step of decision-making helps to optimize the overall operation of the system. Depending on the indicators calculated by the diagnostic / prognostic tools, an action plan is triggered. This action plan may correspond to a maintenance intervention on the storage system.

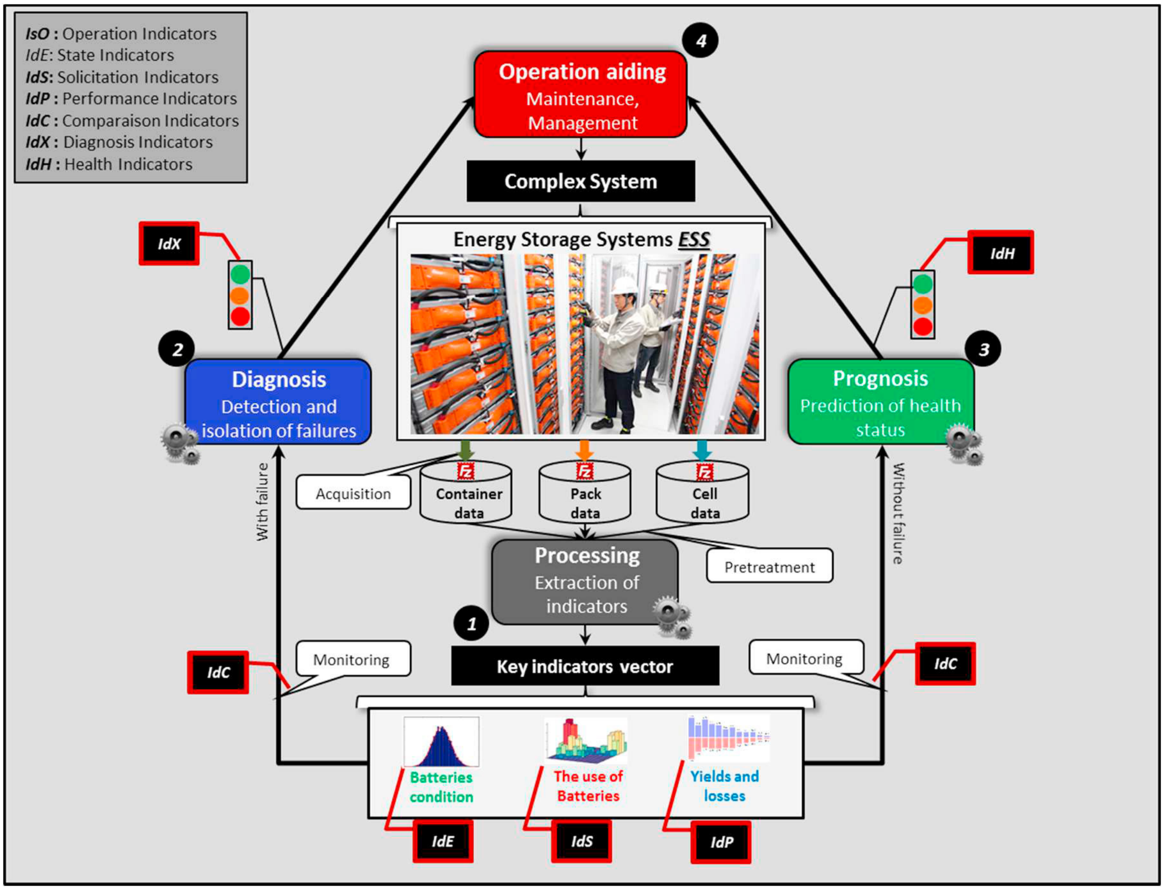
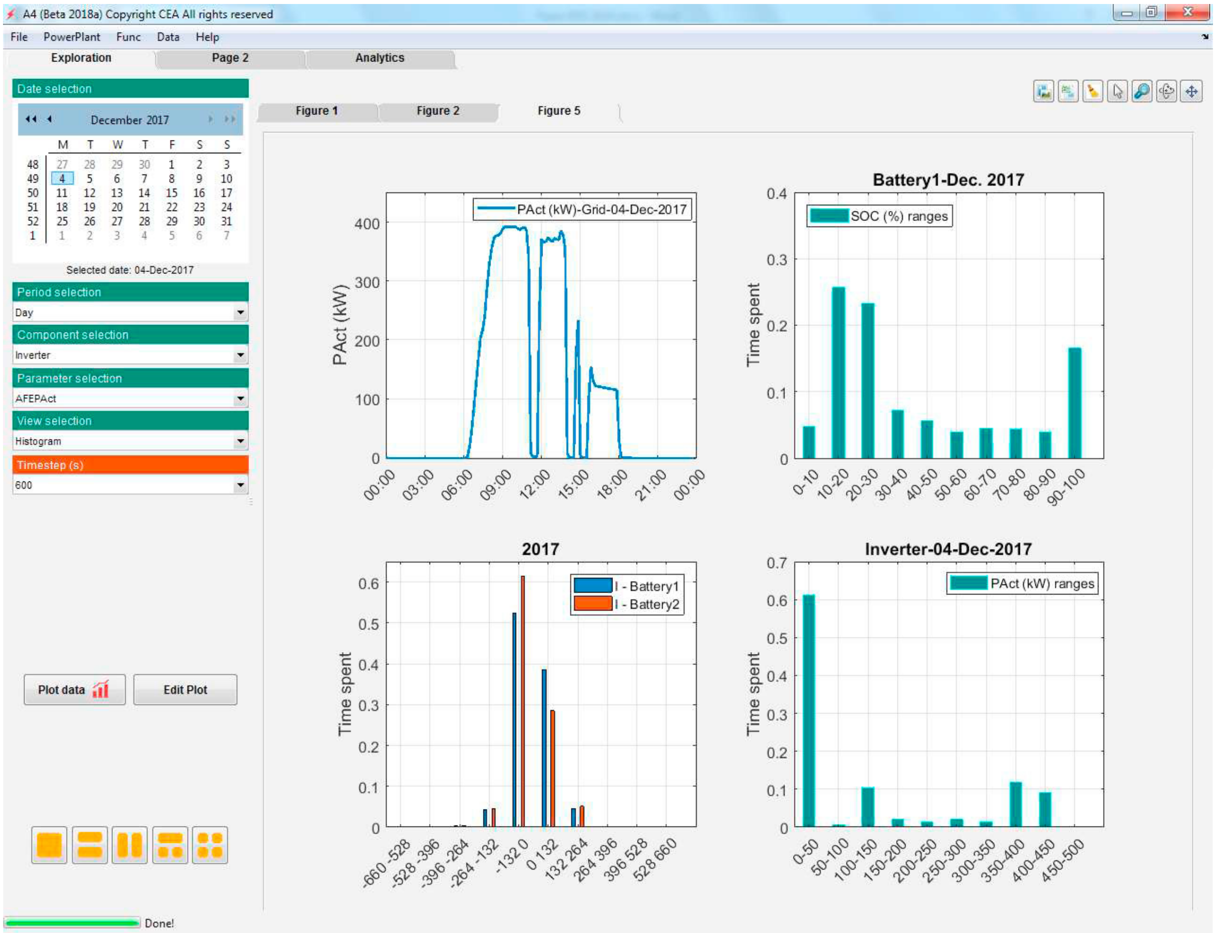


Figure 1. Architecture for diagnosis / prognosis

The study presented here focuses on the first support-function of the approach described above. It is based on research on photovoltaic (PV) application associated with energy storage systems (ESS).

5. Advanced data analysis tool "A4"

A study was conducted on operational systems, it led us to develop the advanced data analysis tool "A4". It is resulting from the application of the architecture described above. This involves the development of the first support function in particular: data acquisition, pre-processing and processing. So, this analysis tool allowed to extract performance indicators by transforming the raw data into pertinent information. This tool has been developed using the object-oriented programming and the GUI (Graphical User Interface) in Matlab©. It was first developed for storage systems and then extended to the other components of Grid Connected Renewable Energy with Electrical Storage Systems (ESS). The interface is generic and useful for several power plants. The list of components is automatically adapted according to the power plant electrical architecture. The parameter selection is automatically adaptable to the type of the selected component. A calendar allows to select the date on which the analysis should be done. Period selection allows to select the period of the analysis: day, week, month or year. A full capture of this tool is given in Figure 2.



A4 (Beta 2018a) Copyright CEA All rights reserved

Selected date: 04-Dec-2017

Period selection: Day

Component selection: Inverter

Parameter selection: AFEPAct

View selection: Histogram

Timestep (s): 600

Done!

Figure 2. Advanced Data Analysis Tool

The functionalities of the “A4” interface dedicated to the performance analysis and the usage of storage systems and renewable energy power plants are:

- State of Charge verification for one battery
- Time series visualization of all measurements for one component.
- Time series visualization of one variable for all batteries.
- Status indicator for SoC, T, etc.
- Multi-variables status indicator for SoC, Voltage and Temperature, etc.
- Solicitations indicator with histograms
- Heat maps of one parameter allowing to see the density of the parameter in each range
- Time-Comparison Indicator for one component.
- Modules-Comparison Indicator for all batteries.
- Performance indicators (efficiency) for one or all components of one type
- Operation indicator of one or all batteries
- Cumulated energy of one or all components of one type

We illustrate here some categories of results:

5.1. Operation indicators

Here, a monthly comparison of the operation of one battery. The use of the system is accumulated by the number of hours and the number of days.

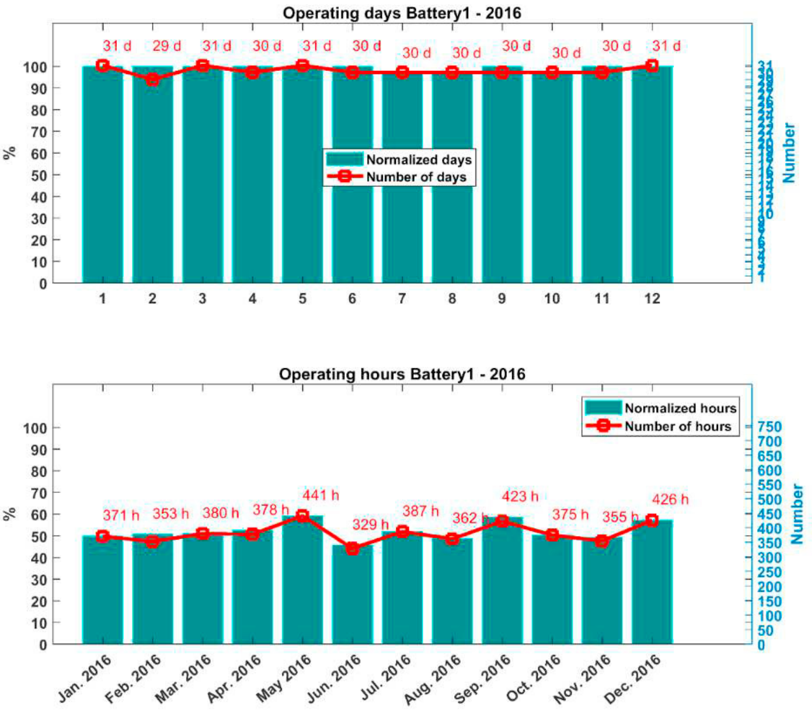


Figure 3. Battery Operation for the full year 2016

5.2. Status Indicator: heat map of the SOC

Figure 4 shows the distribution of the state of charge within one month as a heat map. The tool processes this kind of graphs on the selected variable corresponding to a selected component of the power plant and for the selected date and period. With a click on the heat map, the time evolutions of the selected parameter during the selected day is plotted and also during three similar days. This figure shows that the SOC range is similar except for day 5 with longer period between 90 and 100%.

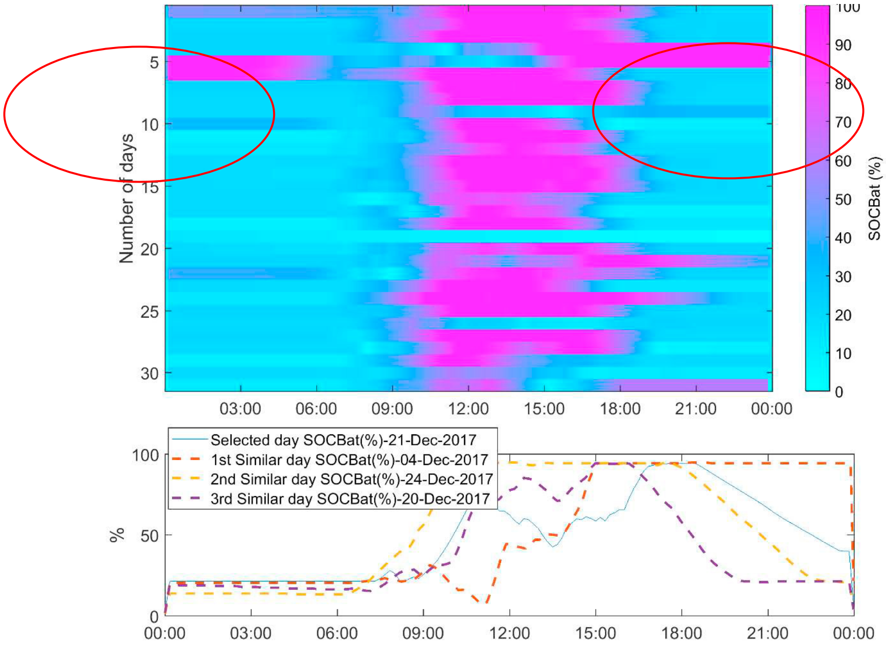


Figure 4. Heat map for State of Charge for one month

5.3. Solicitation indicators

Figure 5, Power Solicitation Indicator: shows the charge and discharge power solicitation for an energy storage system for a full annual operation period.

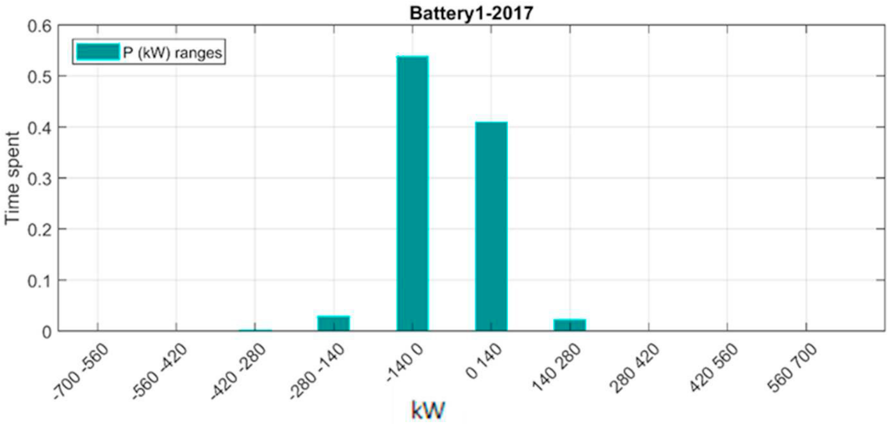


Figure 5. Time spent for Power solicitation

5.4. Comparison indicators over time

Figure 6, Comparison Indicator for the storage systems state of charge SOC, we use a dynamic approach that takes the temporal evolution into account. Thus, comparison indicators are generated automatically by the analysis tool. The idea is to make comparisons over time and between components (compare for the same system an indicator for several days, weeks, months or years). Or compare for the same period, the indicators between different systems.

The red columns indicate that the time spent in this state is higher than twice standard deviation relative to the mean of the distribution.

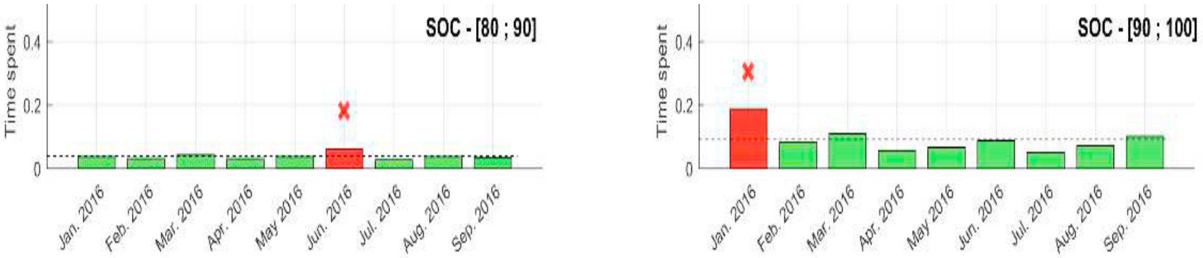


Figure 6. Comparison Indicator for the storage systems SOC

5.5. Performance indicators

For optimal planning of a PV-Storage plant, the monitoring of efficiencies is necessary in order to diagnose the gaps between what has actually been produced and what can be produced. Thus, we calculate energy efficiencies and losses. These indicators are functions of the state of charge and of the power, they are defined as follows.

$$\eta_E(SoC_i, SoC_f, P_d, P_c) = \frac{E_d}{E_c}$$

$$\rho_E(SoC_i, SoC_f, P_d, P_c) = E_c - E_d$$

$$: E_c = \int_{SoC_i}^{SoC_f} P_c \, dt \quad et \quad E_d = \int_{SoC_i}^{SoC_f} P_d \, dt$$

The round-trip efficiency is calculated for equal variation of state of charge for the charge and discharge of the battery (the term depth of discharge DoD is often used). It is important that after discharge and charge operation (or charge and discharge operation) the end value of SOC is the same as the value at beginning of battery charging or discharging operation.

A daily value of the efficiency is calculated and then averaged for week, month or year period. Following, a graph showing the round-trip efficiency of one battery (Figure 7) and a graph showing the monthly efficiencies of two batteries from one power plant during year 2017 (Figure 8).

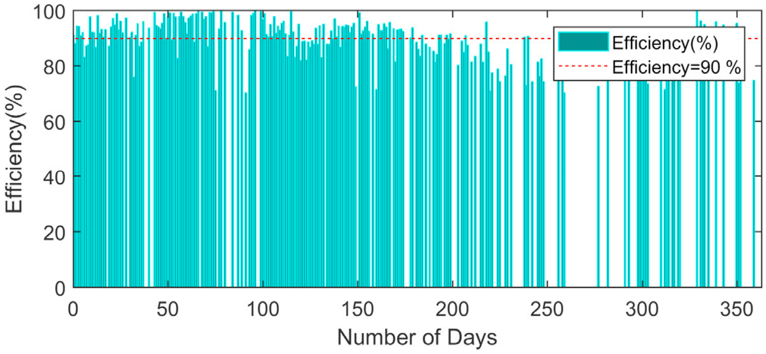


Figure 7.Round trip efficiency of one battery during one year

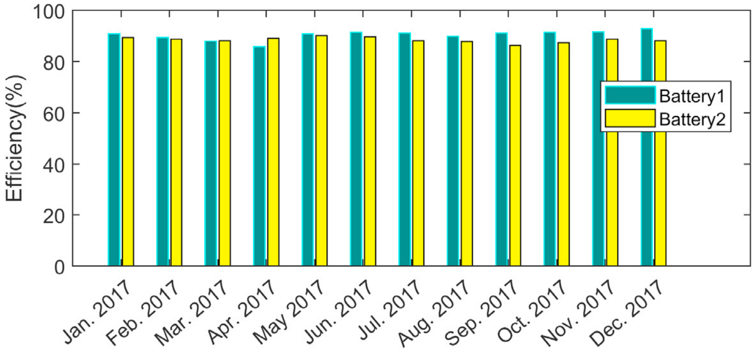


Figure 8.Annual performance indicators (round-trip efficiency of two ESS)

The energy efficiency is also calculated for other components of the power plant such as power conversion systems DC/DC and DC/AC and transformers (AC/AC). For power conversion systems, power efficiency is also calculated and displayed as a density. Fitted curves present the power efficiency evolution of the selected components. Figure 9, gives an example of the results of power efficiency for PV inverters part.

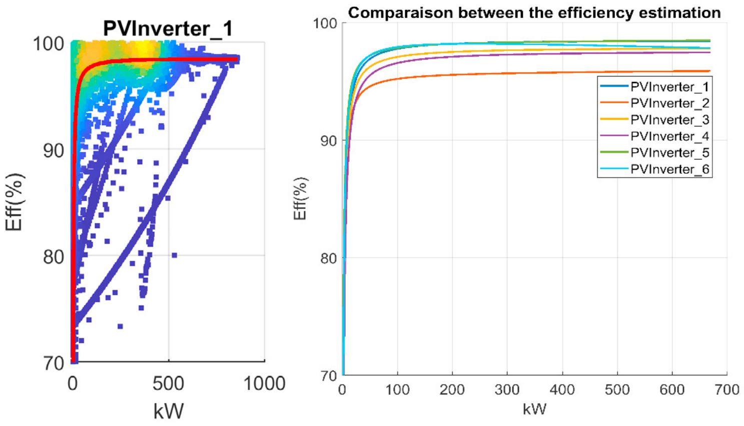


Figure 9. Power efficiency of PV inverters

6. Power plants performance comparison

In this part of the paper, operational energy plants are introduced. We present an example of plant architecture for illustration. Then, a focus on the batteries technologies and finally, the analysis results and the plants comparison.

6.1. Monitored power plants

Four power plants have been monitored during 2 to 3 years. Among these power plants, two are with ESS using Lithium-Ion batteries from LG-Chem and two are based on NaNiCl2 batteries.

- The ESS named Li-ion (L), NaNiCl2 (T) and Li-ion (S) are used for the regulation of the injected PV power to the grid with a trapeze profile as requested in the call for tender of the French Regulatory Commission of Energy in 2012.
- The ESS named NaNiCl2 (A) is used to increase the self-energy-production of the building on which the system is installed, to guarantee the production/ consumption profile on the power injection point and to contribute to the energy mix during peak consumption hours.

The characteristics of the PV and ESS are summarized in the following table:

Table 1. Studied power plants

Power Plant	PV Power (kWp)	Battery technology	Battery energy (kWh)	Operation since
Li-ion (L)	946	Li-ion	2 x 598	Jan. 2015
Li-ion (S)	4400	Li-ion	6 x 718	Oct. 2015
NaNiCl2(T)	4995	$NaNiCl_2$	9 x 704	Dec.2014
NaNiCl2(A)	100	$NaNiCl_2$	188	Sept. 2015

6.2. Example of power plant architecture

Following a schema of the Li-ion (L) power plant. It contains PV panels, Energy Storage System ESS, DC-DC choppers, DC-AC inverter and transformer connected to the grid [14]. In our work, all the components of the system are taken into account in the tool with the corresponding monitored parameters in order to compute efficiencies, cumulated energies, energy balance, etc.

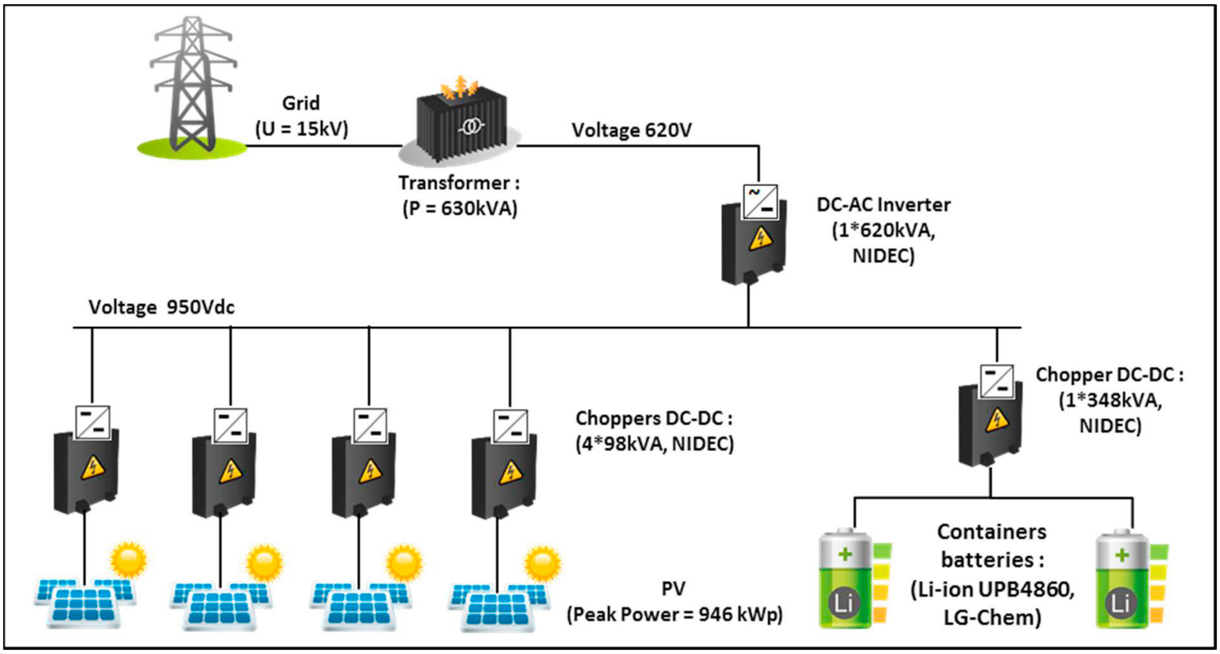


Figure 10. Electrical architecture for Li-ion (L) power plant

6.3. Brief description of used batteries technologies

Two batteries technologies are used in the monitored power plants. Following a description of the main features of each technology.

- Lithium-ion batteries

A brief description of the Li-ion batteries can be found in [10] and is given following: Lithium-ion (Li-ion) batteries operate through the movement of the lithium ions between the positive and negative electrodes. While charging, the lithium ions de-intercalate from the positive electrode and then intercalate into the negative electrode via the electrolyte; at the time, the negative electrode is in a lithium-enriching status. When the battery is discharged, the lithium ions move in the opposite direction. The positive electrode of the lithium-ion battery is composed of lithium based compounds, such as lithium iron phosphate (LiFePO4) and lithium nickel manganese oxide (NMC). The most extensively used negative electrode material of the lithium-ion battery is graphite.

- NaNiCl2 batteries

NaNiCl2 batteries called also ZEBRA batteries and their degradation are described in the publications [11] and [12]. It has been widely investigated as a promising energy storage device for renewable energy applications as well as smart grid applications. NaNiCl2 battery is typically operated in the temperature range between 250 and 340°C in order to achieve adequate battery performance by improving the ionic conductivity of the solid electrolyte and secondary liquid electrolyte. The electrochemical reaction of a NaNiCl2 battery during discharging is described as follows: $2Na + NiCl_2 \rightarrow 2NaCl + Ni$.

6.4. Results and discussion

The data from each system was processed in order to get useful indicators. Then these indicators were compared within each power plant and between the power plants. Three indicators are compared here: i) the operation indicators in terms of operating hours number; ii) the energy efficiency mainly of the batteries and iii) the energy balance with the losses and injected energy. Note that, all the computing results are done using 2016 data.

- *Comparison within each power plant*

Within each power plant, the comparison was done between the components of the same type with results similar to the figure 8 and the minimum, maximum and average values are given. The summary of the results of the power plants Li-ion (L), Li-ion (S) and NaNiCl2 (T) is given in table 2. The NaNiCl2 (A) has only one battery container so this kind of comparison is not relevant.
For the calculation of the operating hours, it should be noticed here that the values are filtered for current absolute value higher than 2 A.

Table2. Comparison between batteries from the same power plant, data 2016

Power Plant	Batteries Operation (h)	Batteries Efficiencies (%)	Batteries Energies (MWh)	MWh(ESS)/MWp (PV)
Li-ion (L)	Min=4579 Max=4525 Average=4552	Min=92 Max=92 Average=92	Min=185.39 Max=219.80 Average=202.59	Min=196 Max=232 Average=214
Li-ion (S)	Min=2473 Max=3614 Average=3243	Min=91 Max=92 Average=91	Min=144.25 Max=210.91 Average=189.07	Min=33 Max=48 Average=43
NaNiCl2 (T)	Min=4471 Max=5108 Average=4821	Min=78 Max=82 Average=79	Min=79.45 Max=97.88 Average=86.06	Min=16 Max=20 Average=17

- *Comparison between power plants*

The percent is calculated relatively to the daylight number of hours during the year 2016 for each location. For this, the calculator in the website [13] is used. The calculator inputs are the longitude and latitude of each location used to compute a table and the name of the location used only for legend. The calculator output is a table of the daylight duration per day for the months of the chosen year. Thus the numbers of daylight hours in 2016 are 4431 for Li-ion (L), 4436 for NaNiCl2 (T), 4467 for Li-ion (S) and 4440 for NaNiCl2 (A). The graph below shows the number operating hours of each of these ESS during one year.

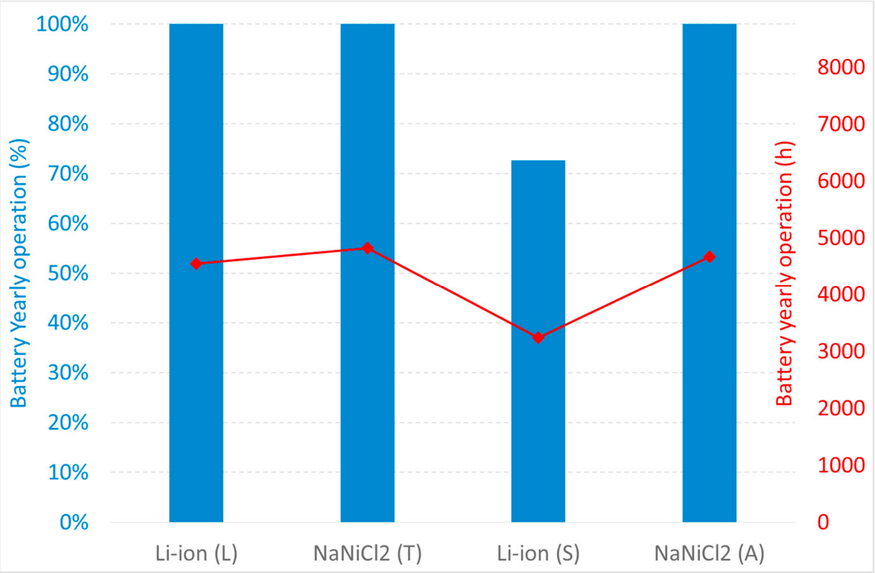


Figure 11. Battery yearly operation for 4 monitored ESS

This graph shows that the lowest operation is for Li-ion (S) ESS~73% and 3243 h. This is mainly due to the stop of the monitoring during a lot of periods. For the other ESS, the operation is near 100% relatively to the daylight duration with an average operation of 4381 h per year.

Regarding the efficiency of the batteries, it depends especially on the battery technology. It is 10% lower for NaNiCl2 batteries (79%) compared to lithium ion batteries (91%). This is due to the need of heating for NaNiCl2 batteries. The results for the four ESS are displayed in the Figure 12.

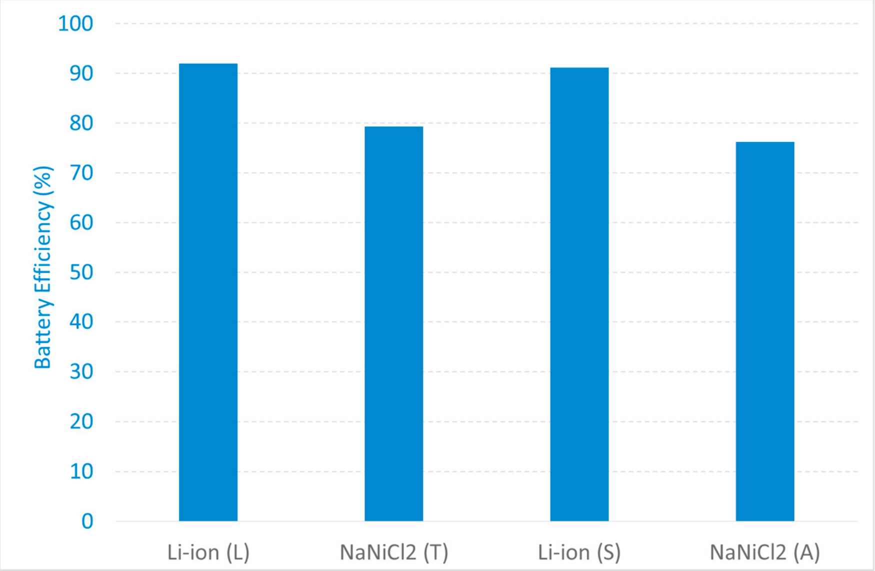


Figure 12. Yearly round-trip efficiency for 4 ESS

The yearly discharged energy is presented in Figure 13. It depends on the ESS size and on the efficiency of the battery. The discharged energy of the ESS NaNiCl2 (A) is very low compared to the other power plants. It is due to the ESS size. The Li-ion (S) ESS energy is higher than the NaNiCl2 (T) ESS, the biggest one. This is due to the higher efficiency of Li-ion ESS. In order to better compare battery use, the discharged energy during one year is reported to the PV peak power. Doing that, we find that Li-ion (S) has lower ratio than Li-ion (L) even if they have the same battery chemistry and the same SOC range. The NaNiCl2 (T) has lower energy ratio than NaNiCl2 (A). This is due to different size and utilization.

The differences are complex to explain and related to many parameters of system: size, utilization, efficiency, EMS algorithm, etc.

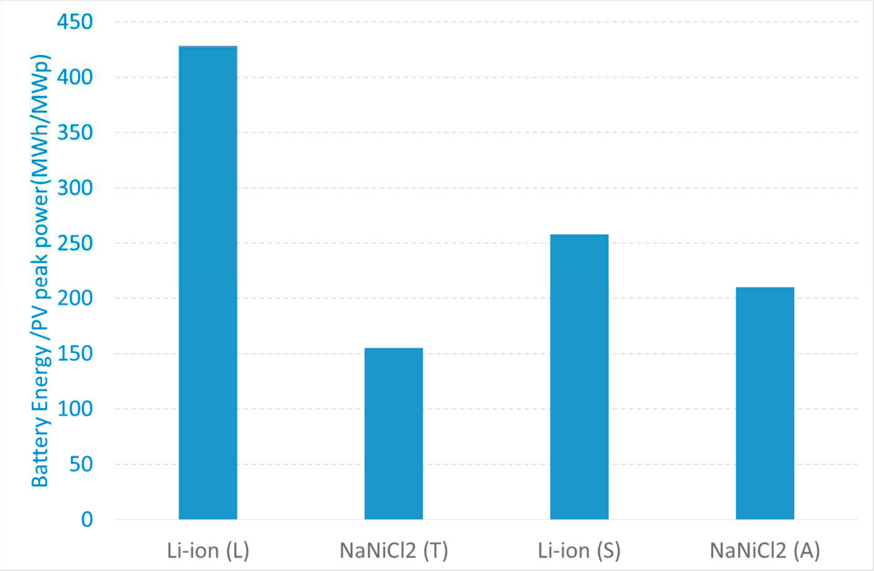


Figure 13.Yearly discharged energy for 4 ESS

The analysis of the output energy and efficiency of each component of the systems allows us to calculate the energy balance and losses at each stage. This calculation is done according to the following steps:

- *Average efficiency* for each component type, A4 output
- Cumulated output energy for each component type E_{cum}, A4 output
- Absolute loss of each component type:

$$Pabs = 100\% - Average\ efficiency$$

- Relative loss for each component type:

$$Prelative = \frac{(100\% + Pabs) * E_{cum}}{100\%} * \frac{1}{Total\ energy} * Pabs$$

- Deduced net injected energy:

$$Deduced\ energy = \frac{(100\% - \sum Prelative)}{100\%} * Total\ Input\ Energy$$

Note that the deduced net injected energy can be compared to the injected energy calculated by the integration of the injected power to the grid. Also, the *total input energy* in the case of the studied systems is the produced energy from the PV.

The graph below gives the energy balance of two power plants:

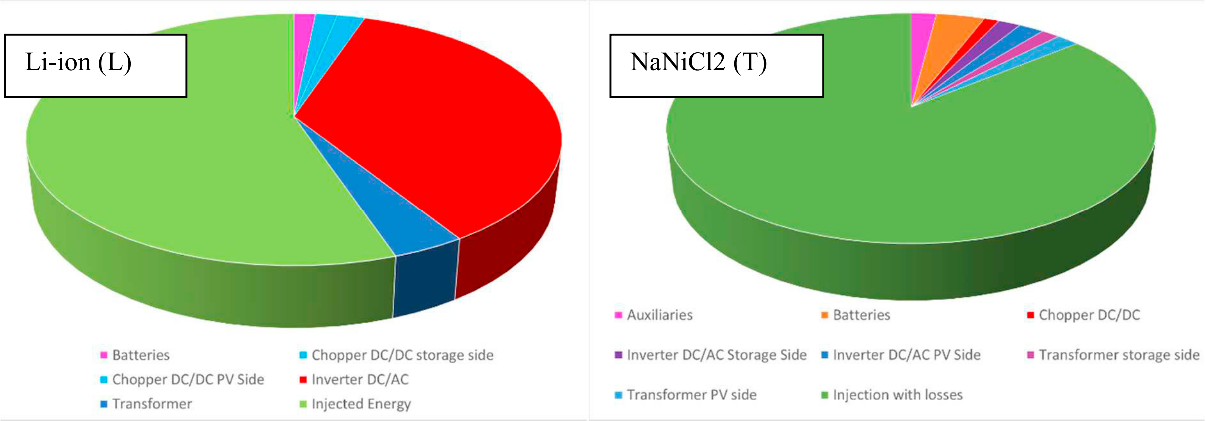


Figure 14. Energy balance of Li-ion (L) and NaNiCl2 (T) power plants

According to the Figure 14, we can notice that:

- The injected energy is 56% for the Li-ion (L) power plant and 85% for the NaNiCl2 (T) power plant.
- The main losses are in the DC/AC inverter stage for Li-ion (L) power plant. The inputs of this inverter are the outputs of all DC/DC choppers. To explain this we have calculated the power efficiency of this inverter. The highest densities are for Eff~40% and Eff~60%. The power input is 2 times higher compared to the power output. More investigations are still needed for this inverter.

7. Conclusion

This work is carried out in the field of performance analysis of energy storage systems, especially in terms of the prediction of possible degradation. The presentation of the context highlighted the complexity of these systems.

The aim of this work is to propose a generic approach for the operation aiding. The objective is to follow the time evolution of the diagnostic and prognostic indicators in order to improve performances and availability. Therefore, a bottom-up methodology is proposed. The main results are as follow:

- ⇨ Analysis of key indicators for battery faults: transform raw data into useful and relevant information.
- ⇨ Diagnosis of the root causes of recorded faults: localize the defective component and identify the kind of the failure.
- ⇨ Prognosis of the future state of health of the system and the risk of occurrence of one or more failure modes.

To support the proposed approach, an Advanced Data Analysis Tool “A4” was developed and tested with operating data. The *Matlab* Graphical User Interface and object oriented Matlab programming are used. This proposed tool is generic and was extended to the other systems (PV, power converters, transformers, etc.).

Future works will focus on the tool extension in order to use the indicators calculation in decision-making. Taking the results of performance analysis into account, recommendations on the use of the storage systems and power conversion systems will be defined. So, predictive maintenance activities can be scheduled in order to improve PV-storage power plants availability and reliability.

Finally, the A4 tool will be used as official software for Data Analysis in TILOS Horizon 2020 European Project (http://www.tiloshorizon.eu). TILOS project aims at powering the island solely from wind and solar energy, utilizing an intelligent hybrid grid with the addition of a battery system and demand side management aspects. This will eventually constitute a prototype for smart micro-grids that facilitate increased participation of renewable energy sources under the optimum exploitation of energy storage and demand side management assets. This innovative project will thus drastically reduce the islands' dependence on power generated from expensive imported fossil fuels and avoid, at the same time, troublesome black outs

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