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COMPARISON BETWEEN LEAD-ACID AND LI-ION ACCUMULATORS IN STAND-ALONE PHOTOVOLTAIC SYSTEM USING THE GROSS ENERGY REQUIREMENT CRITERIA

Y. Thiaux, L. Schmerber, J. Seigneurbieux, B. Multon, H. Ben Ahmed
SATIE, ENS CACHAN Bretagne
CNRS, UEB
Campus de Ker-Lann, F-35170 BRUZ (France)
www.satie.ens-cachan.fr
Phone number: +33 (0)2 99 05 93 31, e-mail: yael.thiaux@bretagne.ens-cachan.fr

ABSTRACT: The high economic (and energetic) cost of storage accumulator system is still limiting the proliferation of SAPV system. Presently, due to its technical maturity and its low economical investment cost, the storage system universally used in SAPV market, is the lead-acid technology**.** Nevertheless, the advantages offered by the Lithium-ion technology in terms of better charging/discharging efficiencies and ageing make lithium-ion accumulators more and more envisioned in such applications. In this paper, sizing optimisations of SAPV systems have been lead for each accumulator technology considered. The photovoltaic system has been simulated hour by hour on the whole cycle life duration. Experimental outcomes, lead in order to establish a complete energetic model for Li-ion accumulators, are presented in this paper. Results have been compared using the Gross Energy Requirement (GER) criteria of the whole SAPV system. Results show that Li-ion technology allows us to reduce the energy cost of SAPV systems notably when considering a simulation duration corresponding to the expected life time of PV panels.
Keywords: SAPV system, Lithium-Ion, Lead-Acid, Gross Energy Requirement, Life cycle analysis

1 INTRODUCTION

According to a recent study, more than three billion of people could have recourse to off-grid photovoltaic system by the year 2030 **[1]**. The storage element, generally electrochemical, represents a significant amount of the total life cycle energy cost of Stand-Alone Photovoltaic (SAPV) systems. A diagram of SAPV system is represented Figure 1. Presently, due to its technical maturity and its low economical investment cost, the storage system universally used in SAPV market, is the lead-acid technology **[2]**. However, relatively low charge/discharge efficiencies and a fast ageing of lead-acid accumulators suggest that Lithium-Ion storage technology could be envisaged in SAPV applications **[3]**. This technology, developed by SONY since 1991 for mobile devices because of the high energetic density of such technology, owns several advantages which could impose itself in SAPV system market in a near future. On top of higher energetic and power density, the Li-ion technology possesses better ageing features and improved energy efficiency in comparison with Lead-acid technology. These two features argue in favour of using Li-ion technology in SAPV system. This paper focuses on the comparison of these two technologies considering the life cycle energetic cost of SAPV system because we believe that this criterion is better than the classic economic one on the long-term. We will first describe the modelling of each element of the SAPV system and more particularly the accumulator one which has been deduced from experimental tests on a 45Ah capacity for 8h discharge (C_8), 48V rated accumulator. Then, the criteria employed to analyse the performances of the SAPV system will be explained. Afterward, the simulation algorithm and the optimization implementation using an evolutionary genetic algorithm will be presented. More detailed information SAPV system sizing using these criteria can be found in **[4]**. Finally, sizing optimizations results allowing us to compare both storage technologies will be discussed.

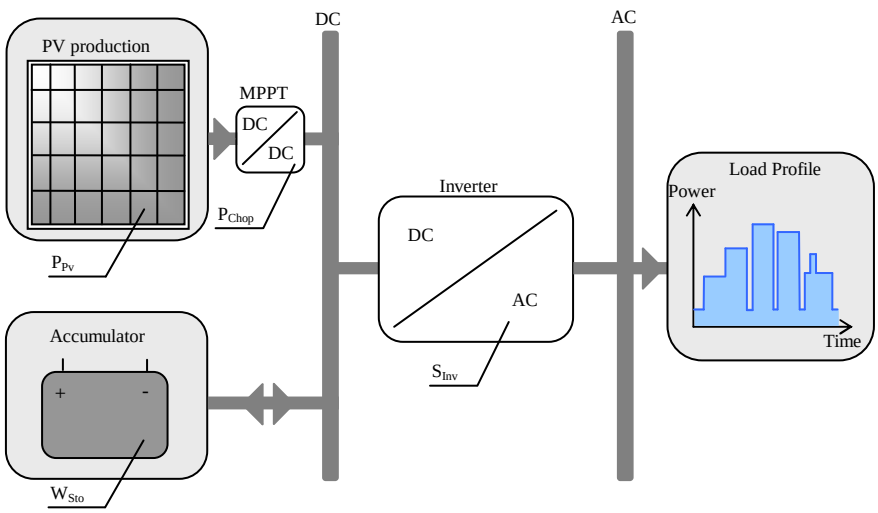


Figure 1: SAPV system

2 SAPV SYSTEM MODELLING

So as to simulate all the energy flows into the SAPV system, its different elements must be modelled. The numerical values of the different modelling parameters are quoted Table I.

2.1 Consumer

The load profile used in the simulation corresponds to the electric consumption of a four person's household where electricity is reserved to its specific uses (no electric water and house heating). The electric consumption measures have been performed hour by hour during one year. This profile is then duplicated in order to obtain the wanted simulation duration. The electric needs of this household are about 5.5MWh per year. The annual load profile is represented Figure 2.

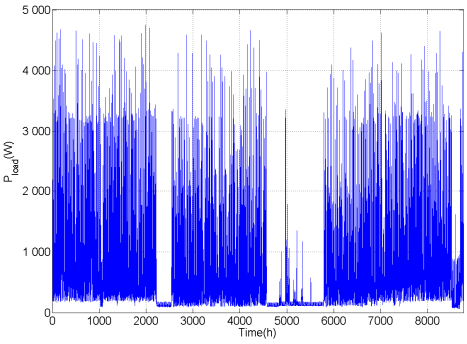


Figure 2: Annual load profile used in the simulations

The maximal power value asked by the consumer reaches 4.7 kW. The daily energy consumption evolves according to the presence of the consumer and the period of the year: the mean value corresponds to 16 kWh, the maximum value reaches 32 kWh and the minimum value only 3 kWh per day.

2.2 Photovoltaic panels

A polynomial model has been used to assess the maximum power which can be produced by the PV generators **[5]**. This one depends strongly on the meteorological conditions. This is why hourly temperature and solar radiation measurement performed between 1992 and 2002 (Rennes France data) have been used in order to calculate the maximum PV production at each time step:

$$P_{PV_{prod}} = P_{PV_0}.(1 + P_{PV1}.(T_j - T_{j_{ref}})).(P_{PV1} + E_s) \quad (1)$$

The producible PV production has been normalized for a 1 kW_p PV production. The average yearly PV production corresponds to an average of 1.35 kWh per Watt peak of PV panel installed. The daily PV production varies from a minimum of 0.3 Wh/W_p to a maximum of 7.4 Wh/W_p. Thus, the producible PV profile has been deduced from this model from rated power of PV generator.

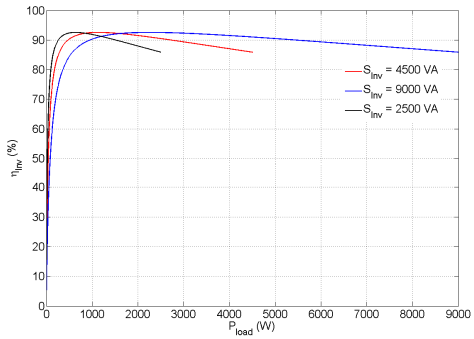
2.3 Converters

Usually, the manufacturers describe the efficiency of their converters by using the European efficiency which corresponds to a linear combination of the converter efficiency at different percentage of his nominal power **[6]**. In this paper, in order to quantify precisely the efficiencies of the converters, the losses have been modelled by a second order polynomial equation (taking into account the no load losses), deduced from measures realized on a 4.5 kVA inverter and a 1 kW DC/DC converter.

$$P_{loss_{Inv}}(t) = P_{Inv_0} + P_{Inv_1}.P_{load}(t) + P_{Inv_2}.P_{load}(t) \quad (2)$$

$$P_{loss_{Chop}}(t) = P_{Chop_0} + P_{Chop_1}.P_{PV}(t) + P_{Chop_2}.P_{PV}(t) \quad (3)$$

These modelling have been normalized by neglecting scale effect in order to be used with different converters sizing. So the global improvement of the energetic efficiency due to the converter rated power increase is not taking into account. Figure3 represents the evolution of the efficiency for both converters.



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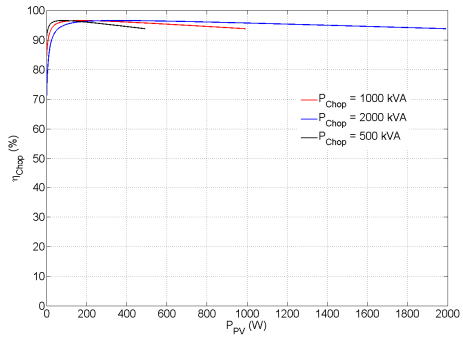


(b)

Figure 3: Inverter efficiency (a) and DC/DC converter efficiency (b) for many rated power values

2.3 Accumulator

The accumulator electric model is depicted on Figure 4.

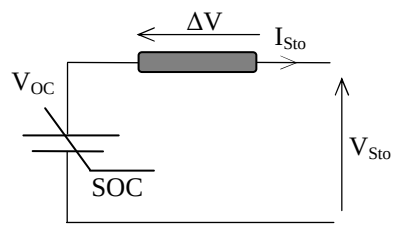


Figure 4: Accumulator electric model

It is used for both lead-acid and Li-ion technologies. It is rest on only two non linear elements, a voltage source which represents the open circuit voltage of one element, depending on the SOC of this one and an element

representing the drop of voltage due to the circulation of current throw the electrolyte and both electrodes. The modeling of the lead-acid accumulator has ever been described in previous papers (**[5], [7]**) therefore we will only focus on the Li-ion accumulator modeling.
The accumulator voltage can be expressed as follows:

$$V_{Sto}(t) = n_{element}.[V_{OC}(t) - \Delta V(t)] \quad (4)$$

The Li-ion accumulator used for the experimental test is a 45 A.h rated capacity, 48V rated voltage accumulator manufactured by SAFT initially for telecommunication applications and now envisaged in stand-alone applications (INTENSI*U*M3). It is composed of 14 serial VL45E elements. A picture of this accumulator is showed Figure 5.

Figure 5: INTENSI*U*M3 accumulator

Figure 6 represents the evolution of the OCV of the element according to the state of charge. This test has been realized by charging the accumulator by 5% SOC step at constant current. After each partial recharge, the accumulator is let in idle state for one day in order to make the electrolyte concentration homogeneous.

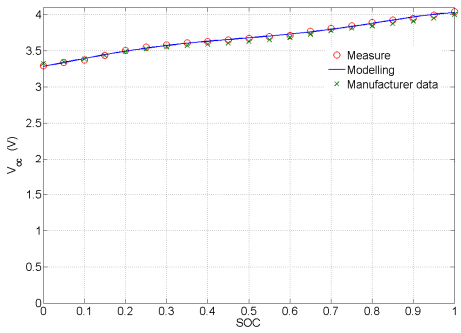
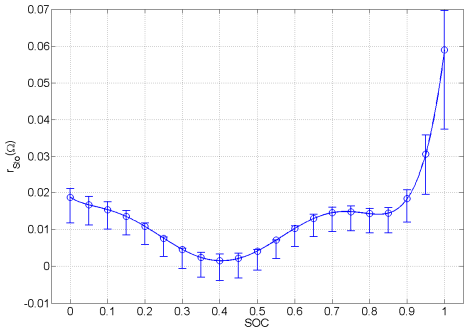


Figure 6: Open circuit voltage versus SOC for only one element

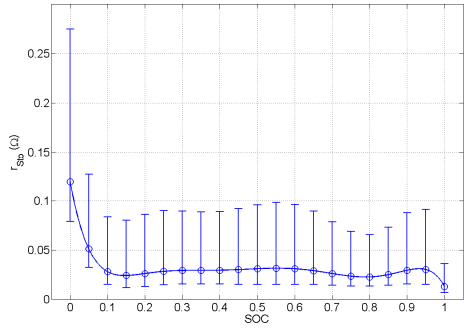
As shown by Figure 6, the open circuit voltage does not evolve linearly with the SOC of the element. Nevertheless, this function is bijective. This is why the open circuit voltage evolution according to the SOC has been modelled by a fifth order polynomial function:

$$V_{OC} = K_{OCV_1} + K_{OCV_2}.SOC(t) + K_{OCV_3}.SOC^2(t) + K_{OCV_4}.SOC^3(t) + K_{OCV_5}.SOC^4(t) + K_{OCV_6}.SOC^5(t) \quad (5)$$

Then several charges and discharges at constant current have been performed, the drop of voltage of the electrolyte and both electrodes has been deduced from the open circuit voltage measurement. The ratio of this voltage drop by the constant current of each test allowed us to determine the equivalent internal resistance of the accumulator both in charging and discharging mode. The different charges and discharges have been realized at different rates between C_5 and C_{45}. The mean value of the internal resistance vs. SOC is plotted on Figure 7.



(a)



(b)

Figure7: Measured values (with errors) of internal resistance in charging (a) and discharging mode (b) for module 45 Ah – 48 V

A seven order polynomial function has been chosen to model the internal resistance:
-Charging mode:

$$r_{Sto} = r_{c_1} + r_{c_2}.SOC(t) + r_{c_3}.SOC^2(t) + r_{c_4}.SOC^3(t) + r_{c_5}.SOC^4(t) + r_{c_6}.SOC^5(t) + r_{c_7}.SOC^6(t) + r_{c_8}.SOC^7(t) \quad (6)$$

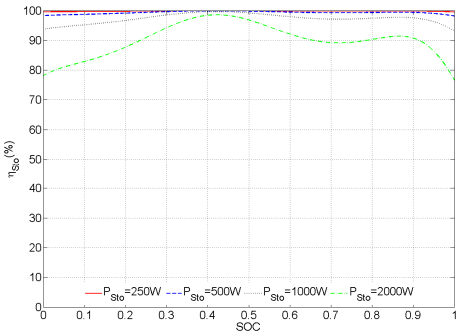
-Discharging mode:

$$r_{Sto} = r_{d_1} + r_{d_2}.SOC(t) + r_{d_3}.SOC^2(t) + r_{d_4}.SOC^3(t) + r_{d_5}.SOC^4(t) + r_{d_6}.SOC^5(t) + r_{d_7}.SOC^6(t) + r_{d_8}.SOC^7(t) \quad (7)$$

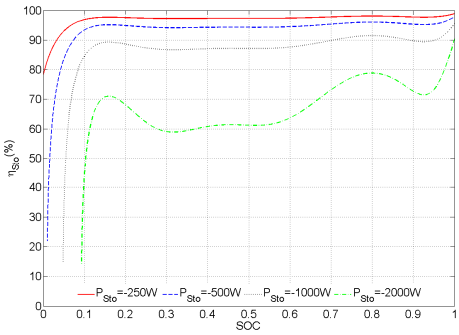
The losses due to this internal resistance can thus be determined, the Joule efficiency calculated (Figure 8).

$$\eta_{Sto} = \frac{P_{Sto} - r_{Sto}.I_{Sto}}{P_{Sto}} \quad (8)$$

At given SOC, the more the accumulator power, the lower the efficiency. Moreover, the efficiency is deteriorating at low SOC in discharge mode and in high SOC in charge mode. At last, at fixed power, the charge efficiency is generally better than the discharge efficiency.



(a)



(b)

Figure 8: Joule efficiency considering charging (a) and discharging (b) mode for the module.

In practice, the whole electric energy supplied to the accumulator is not converted into chemical energy. It is common to use a chemical efficiency named coulombic efficiency to quantify these losses. In charge, it represents the ratio of the electric charges which can be accepted by the accumulator on the maximum capacity of this one.

$$\eta_{Coul} = \frac{\int I_{Sto}(t).dt}{C_{Max}} \tag{9}$$

Figure 9 represents the evolution of the coulombic efficiency according to the charge or discharge current.

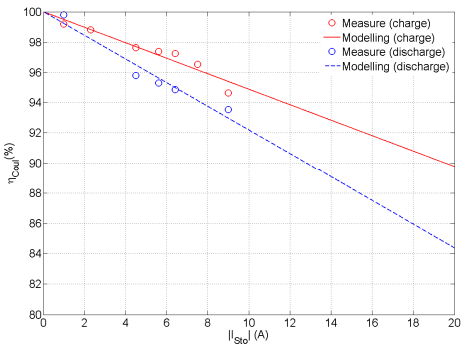


Figure 9: Coulombic efficiency considering charging and discharging mode (45 Ah module)

The capacity has been modelled by a linear equation:
-Charging mode:

$$C = C_{Ch_0} + C_{Ch_1}.I_{Sto} \tag{10}$$

-Discharging mode:

$$C = C_{Disch_0} + C_{Disch_1}.|I_{Sto}| \tag{11}$$

The coulombic efficiency can be expressed as follows:
-Charging mode:

$$\eta_{Coul} = \frac{C}{C_{Ch_0}} \tag{12}$$

-Discharging mode:

$$\eta_{Coul} = \frac{C}{C_{Disch_0}} \tag{13}$$

The SOC evolution will be calculated with the following equation:

$$SOC(t+\Delta t) = SOC(t) + \eta_{Coul}.\frac{I_{Sto}(t).\Delta t}{C} \tag{14}$$

In order to assess the GER of the whole SAPV system, the ageing of the accumulator must be taken into account. This ageing is commonly presented by the manufacturers as number of cycles at a predefined depth of discharge before the end of life of the accumulator. Usually, the accumulator must be replaced when a 20% mitigation of the accumulator capacity is noted. Figure 10 presents the ageing curves for Lead-acid and Li-ion technologies, data have been found in **[8]** and **[9].** The ageing curves correspond to VL45E Li-ion accumulators and deep discharge lead plates accumulators for lead-acid technology. For each technology, the exchangeable energy per Wh of accumulator capacity can be assessed by the following equation **[5]**:

$$W_{ex} = 2.DOD.N_{cycles} \tag{15}$$

As shown by figure 10, for Lead-acid technology, we assume that the product of the number of cycle by the depth of discharge is constant (this product evolves between 2000 and 3000 Wh/Wh of capacity).

$$N_{cycles}.DOD = k_{Sto} \tag{16}$$

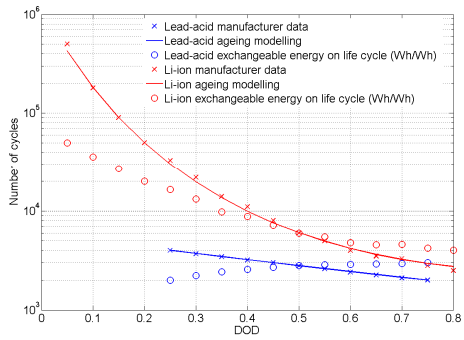


Figure 10: Ageing comparison between Lead-acid (deep discharge, lead plates) and Li-ion technology (VL45E)

Thus, the total exchangeable energy under is life can be estimated as follows:

$$W_{Life} = 2.k_{Sto}.W_{Sto} \tag{17}$$

Then, the number of accumulator replacement can be found:

$$n_{Sto} = \frac{\sum_{t=0}^{t_{sim}} |P_{Sto}(t)|.\Delta t}{W_{Life}} \tag{18}$$

On the other hand, considering Li-ion accumulators, the exchangeable energy per Wh of accumulator capacity evolves greatly with the DOD considered (50000 Wh/Wh for DOD=0.05 to 4000 Wh/Wh for DOD=0.8). In practise, the SOC evolution cycles are often partial ones. For this technology, we will use a method based on the Miner rule used in strength of materials **[10]**. This method counts each partial SOC cycle and assess the ageing caused by this one. We assume that the ageing caused by each partial cycle is due to the range of SOC fluctuations (ΔDOD) and not by the mean SOC value of the cycle. For this, the ageing curve must be modelled:

$$N_{cycles} = \exp\left(\frac{1}{n_{Sto_1} + n_{Sto_2}.\Delta DOD + n_{Sto_3}.\Delta DOD^2}\right) \quad (19)$$

The number of accumulator replacement caused by N partial cycles is then calculated as follows:

$$n_{Sto} = \sum_{i=1}^{N} \frac{1}{N_{cycles}(\Delta DOD_i)} \quad (20)$$

In order to assess precisely the energy cost of the storage system, the ageing caused by the cycling of the accumulator will be add to the initial investment cost.

$$LLP = \frac{\sum_{t=0}^{t_{sim}} P_{unmet}(t).\Delta t}{\sum_{t=0}^{t_{sim}} P_{load}(t).\Delta t} \quad (22)$$

When the SAPV system is downsized, this situation can occur. Indeed, if the consumer is asking energy to the accumulator while this one is empty, the system can not supply the whole electric demand. In order to compare in a coherent way lead-acid and Li-ion accumulators, SAPV system sizing results will be compared at equivalent LLP.

3 SAPV SYSTEM PERFORMANCE CRITERIA USED

3.1 GER criteria

This paper is focusing on the optimal sizing of SAPV system. Usually, this sizing is done in order to minimize an economic cost of the system over is whole life cycle. However, the investment cost depends strongly on the place where is located the system and on the financial incentive of the country. So as to avoid this drawback, we chose the Gross Energy Requirement to assess the optimal sizing of such s system. It represents the total energetic cost of the system over his entire life from the raw materials extraction to the recycling of the different element. The GER of the sub-systems are mentioned Table II. These costs are the results of precise life cycle analysis (**[11]**, **[12]** and **[13]**).

Table II: GER of the different sub-systems

Sub-system	**Elementary GER**
PV panels (Si-polycrystalline)	$GER^*_{Pv} \approx 9\ kWh/W_p$
Accumulator	Lead-acid: $GER^*_{Sto} \approx 360\ kWh/kWh$
	Li-ion: $GER^*_{Sto} \approx 520\ kWh/kWh$
Inverter	$GER^*_{Inv} \approx 0.3\ kWh/VA$
DC/DC converter	$GER^*_{Hach} \approx 0.3\ kWh/W$

The investment energy cost of Li-ion accumulator is higher than lead-acid one. Once the different GER are known, the total GER of the SAPV system can be evaluated:

$$\begin{aligned} GER_{Total} &= P_{Pv} \cdot GER^*_{Pv} + W_{Sto} \cdot GER^*_{Sto} \cdot (1 + n_{Sto}) \\ &+ S_{Inv} \cdot GER^*_{Inv} \cdot n_{Inv} + P_{Hach} \cdot GER^*_{Hach} \cdot n_{Hach} \end{aligned} \quad (21)$$

We consider a life cycle of 30 years for the PV panels **[1]**. According to **[14]**, the life duration of the converters can be supposed equal to 10 years. At last, the aforementioned methods allow us to assess the number of replacement of the accumulator whatever the technology used.

3.2 Loss of Load Probability

The so called Loss of Load Probability is commonly used to quantify the electric supply quality of the consumer (**[15], [16]**); it represents the ratio of the energy not supplied to the consumer while demanded on the total energy consumed by the consumer:

4 SIMULATION OF SAPV SYSTEM

Table III: Simulation parameters

Parameter	Value
SOC_{min}	0.3
SOC_{max}	0.9
Δt	1h
t_{sim}	10, 20 or 30 years

The SAPV system will be simulated hour by hour. At each time step, the algorithm represented on figure 10 will be followed. First, the power demanded by the consumer and the photovoltaic production are evaluated. Then, the losses into the converters corresponding to the aforementioned powers are assessed. The power requested to the accumulator can be calculated, the operating point of the accumulator can be assessed with a predefined tolerance and the next SOC estimated. According to the value of this SOC, several possibilities can occur. If the next SOC is contained between the minimum and maximum SOC values, the entire PV production can be produced and the consumer demand is totally supplied. On the other hand, if the next SOC is lower than the minimum SOC tolerated by the accumulator, the solar resource is produced but the entire consumer demand can not be supplied. The accumulator power is again calculated in order to assess a new SOC value. At last, in case of SOC value too important, the electric demand of the consumer is supplied but a part of the photovoltaic production is not used. The PV production must be reassessed so as to obtain a next SOC corresponding to the maximal value tolerated. It is important to note that there is no recharge strategy for the accumulator in order to limit the losses as suggested in **[7]**; these one is always recharged with the whole available power. The algorithm of the simulation is described on Figure 11, the main simulation parameters are quoted Table III.

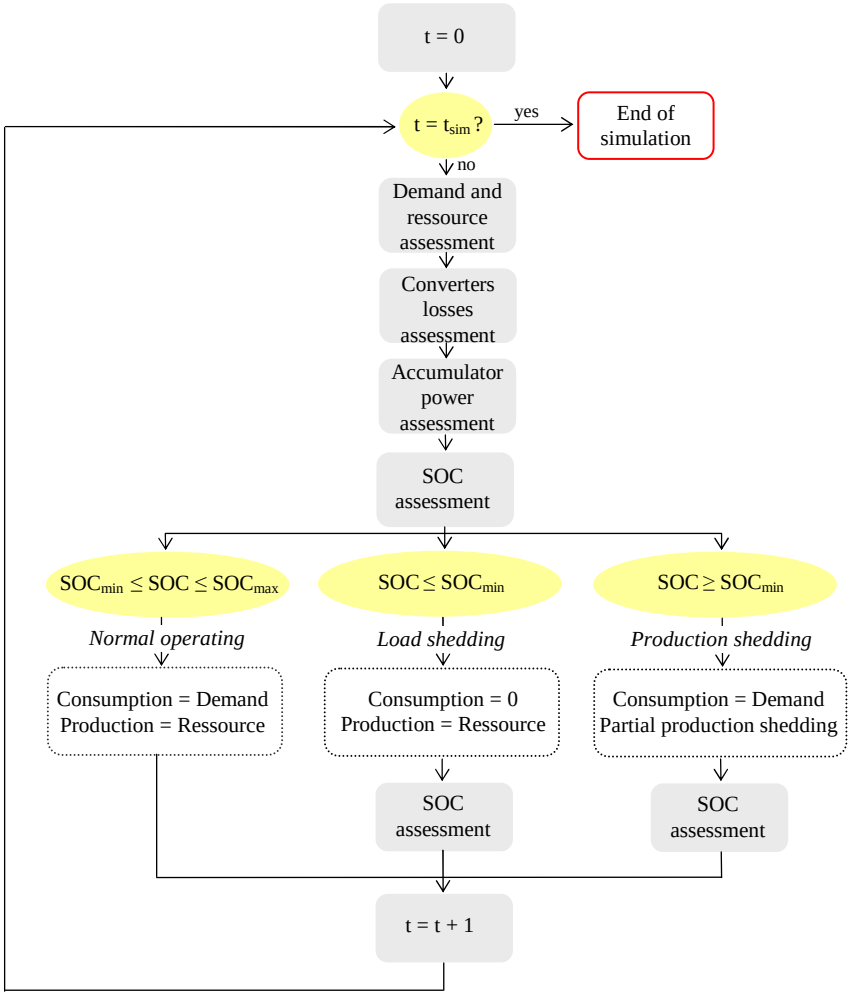


Figure11: Simulation algorithm

5 SAPV SYSTEM SIZING OPTIMISATION

The algorithm used in the optimizations is a genetic algorithm, based on the Darwin evolution theory, known as the Nondominated Sorting Genetic Algorithm II (NSGA-II) **[17]**. It is rest on a global approach by sweeping the entire optimization field in order to find the global optimums. The algorithm first creates an initial population by choosing individuals in the variable optimization field according to a specified distribution. Then, each individuals of the population is evaluated by calculating the objectives and the constraints in order to establish a ranking of this population. The next step is the selection of the best individuals. Afterwards the two main stages take place; this is these stages which give the genetic characteristic to the optimization. Each couple of chosen individuals is crossed in order to give birth to two others individuals. Next each individual can endure a mutation of his genes. The randomness of these two stages, represented Figure 12, allows avoiding the local optimums. Finally, the resultant population is again evaluated, then ranked and the best individuals are chosen to create the new generation. This cycle is replicated until obtain a predefined number of generations. The main features of the lead optimizations are quoted Table IV.

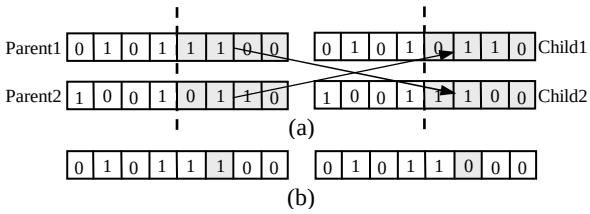


Figure 12: Crossing (a) and mutation (b)

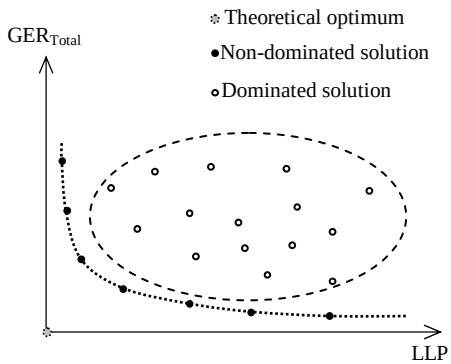


Figure 13: Bi-objective optimal solutions (Pareto front)

If the two objectives of the optimisation and the different parameters are well chosen, the individuals of the last

generation represent each a compromise solution between the 2 objectives. Figure 13 shows the non-dominated solutions of the last generation (representing a Pareto front) when both objectives have to be minimized. In this study, the two contradictory objectives will be the GER of the whole system and the LLP of the consumer. Four sizing parameters of the SAPV system were used as optimization parameters (P_{Pv}, W_{Sto}, S_{Inv} and P_{Chop}). The implementation of the sizing optimization is depicted on Figure 14.

Table IV: Genetic algorithm parameters used for the optimizations

Parameter	Value
Number of generations	100
Number of individuals	100
Crossing Probability	50%
Mutation Probability	2%

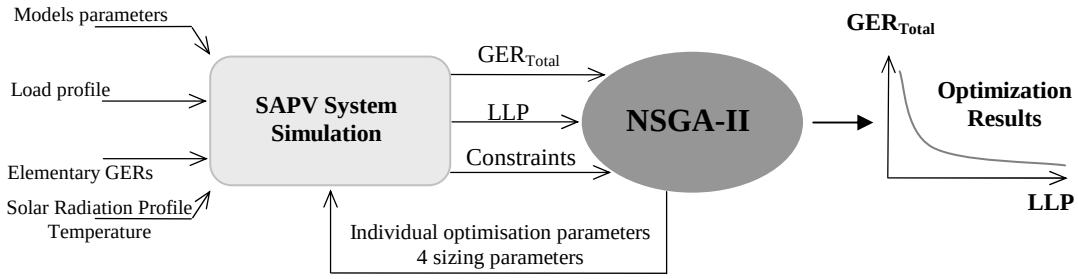


Figure 14: Optimisation algorithm implementation

6 RESULTS AND DISCUSSION

Sizing optimizations have been led for both storage technologies considering 10, 20 or 30 years for the life duration of the SAPV system. Optimization results are presented Figure 15.

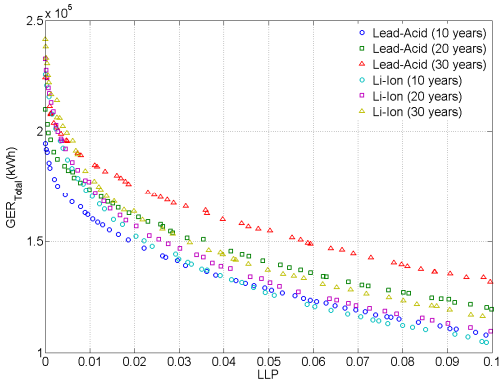


Figure 15: Sizing optimization results for both storage technologies for different lifetime of SAPV system

Considering fixed simulation duration, the optimal Pareto curves obtained for both technologies are crossing at a certain LLP. However, the results are quite close for lower LLP. On the contrary, the longer the simulation duration, the sooner the crossing and the higher the savings brought by Li-Ion technology. For example, considering 30 years simulation duration, results for both technologies are merged for LLP lower than 1% and Li-ion accumulators allows us to reduce the total GER of SAPV systems by 15 % when tolerating a LLP of 10%.

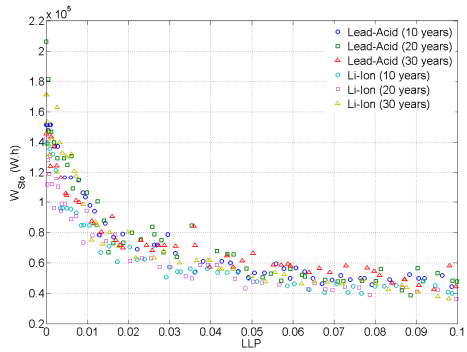


Figure 16: Storage capacity requirements for both technologies vs. LLP

The sizing of the storage capacity is plotted on Figure 16. The optimization algorithm has almost converged on the same values of storage capacity whatever the technology and the simulation duration. A storage capacity of about 100 kWh represents a good rough idea of the solutions found by the optimization algorithm. It corresponds to 6 times the mean electric consumption of the considered load profile. The number of accumulator replacement is represented on Figure 17. It turns out that the ageing of lead-acid accumulators is really more important than the Li-Ion one. For example, considering 30 years simulation duration, lead-acid accumulators must be replaced 2 or 3 times while Li-ion accumulators must not be replaced. It appears on figure 17 that the Li-ion accumulators do not have to be replaced whatever the life duration of the SAPV system considered. However, although the Li-Ion accumulators ageing must be reconsidered, this technology allows us to downsize SAPV systems by minimizing the number of accumulator replacement and by reducing the losses into the accumulator.

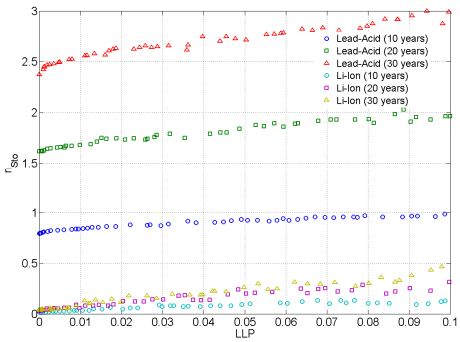


Figure 17: Number of accumulator replacement for both technologies

Besides, Li-Ion technology also allows the downsizing of the PV panels by minimizing losses into the accumulator.

7 CONCLUSION

This paper allowed us to compare lead-acid and Li-ion technologies within the framework of the life cycle sizing optimization of a stand-alone photovoltaic system. With regard to the Li-ion accumulator, we used an energetic model deduced from experimental measurement. These technologies have been compared by using the Gross Energy Requirement criterion of the whole system, which represents the total life cycle energetic cost of such systems. The behaviour of the SAPV system has been simulated by using energetic models experimentally validated for each sub-system. Then, genetic optimizations allowed us to find the optimal sizing for each storage technology considered. Due to lower energetic losses and higher expected life duration of Li-ion technology, the SAPV system GER can be greatly reduced. For this reason, Li-Ion technology could impose itself in SAPV system in a very near future and help to the proliferation of SAPV system.

Annex: Parameters of the SAPV system modeling

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
C_{Ch_0} (10)	49,72	K_{OCV_6} (5)	-4.9513	P_{Pv_0} (1)	0.98	r_{c_8} (6)	-0.959
C_{Ch1} (10)	-0,38	n_{Sto_1} (19)	0.0714	P_{Pv_1} (1)	-0.0029	r_{d_1} (7)	0.119
C_{Disch_0} (11)	46.45	n_{Sto_2} (19)	0.1175	P_{Pv_2} (1)	40.83	r_{d_2} (7)	-2.073
C_{Disch1} (11)	-0,23	n_{Sto_3} (19)	-0.0611	r_{c_1} (6)	0.0187	r_{d_3} (7)	17.412
k_{Sto} (16)	1400	P_{Chop_0} (3)	1.4	r_{c_2} (6)	-0.0658	r_{d_4} (7)	-73.294
K_{OCV_1} (5)	3.282	P_{Chop_1} (3)	4.1e-5	r_{c_3} (6)	0.7108	r_{d_5} (7)	170.792
K_{OCV2} (5)	1.038	P_{Chop_2} (3)	19.8e-3	r_{c_4} (6)	-5.2079	r_{d_6} (7)	-222.61
K_{OCV_3} (5)	1.218	P_{Inv_0} (2)	43.09	r_{c_5} (6)	14.771	r_{d_7} (7)	151.33
K_{OCV_4} (5)	-7.81	P_{Inv_1} (2)	3.34e-5	r_{c_6} (6)	-17.93	r_{d_8} (7)	-41.672
K_{OCV_5} (5)	11.25	P_{Inv_2} (2)	4.6e-3	r_{c_7} (6)	8.7279		

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