Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Research Article

INFLUENCE OF TEMPERATURE ON THE PERFORMANCE OF A COMMERCIAL SOLAR BATTERY USED IN NIAMEY, NIGER

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Received: 04 July 2023 / Accepted: 07 August 2023 / Published: 08 August 2023

ABSTRACT

This work aimed to assess the influence of temperature on the performance parameters of a commercial solar battery used in the city of Niamey in Niger. After an investigation, a sealed lead acid battery (VRLA-AGM, 12 V-80 Ah) was subjected to various tests. Based on the meteorological data of one year from the city of Niamey, experiments were carried out at different temperatures (17 °C, 30 °C and 42 °C). The experimental results showed that the battery capacity, discharge time, charge time and gassing rate are relatively large at high temperature (42 °C). However, the battery internal resistance is relatively high at low temperature (17 °C). Relatively better performance was obtained at the temperature of 30 °C.

Keywords: Lead-acid solar battery, inventory, temperature, performance, Niamey.

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doi: http://dx.doi.org/10.4314/jfas.1331

1. INTRODUCTION

1.1. Photovoltaic solar energy and lead acid battery

Photovoltaic solar energy is one of the most promising alternative energy sources for driving an energy transition and ensuring sustainable development, particularly in developing countries with high sunshine potential such as Niger. However, the intermittency of the sun considerably limits the use of this renewable energy source on a permanent basis. To overcome this insufficiency, the use of energy storage device is necessary. The storage system is a crucial element of the photovoltaic installation both from an economic and a technical point of view. The storage system most commonly used is the accumulator battery, particularly the lead-acid one, because of its relatively low cost, its wide availability and its advanced technology which allows the recycling of lead [1-5]. There are two lead-acid battery technologies: the open battery with liquid electrolyte and the sealed battery with immobilized electrolyte. The sealed battery (Valve Regulated Lead Acid: VRLA), with electrolyte absorbed on a glass matrix (AGM) or gel electrolyte (GEL), is the most used because it does not require maintenance. The lead-acid accumulator consists of a negative lead (Pb) electrode and a positive lead oxide (PbO_2) electrode immersed in an aqueous solution of sulfuric acid (H_2SO_4) and a separator between the two electrodes. The operation of the battery is based on chemical oxidation-reduction reactions, the main reactions are given by the following equations [6]:

$$PbO_2(s) + Pb_{(s)} + 2H^+_{(aq)} + 2HSO_4^-{}_{(aq)} \underset{\textbf{Charge}}{\overset{\textbf{Discharge}}{\rightleftharpoons}} 2PbSO_{4(s)} + 2H_2O_{(l)} \quad (1)$$

In overload: $H_2O_{(l)} \rightarrow \frac{1}{2}\ O_{2(g)} + H_{2(g)}$ (2)

However, these batteries have a limited lifetime and/or undergo premature aging phenomena caused by several factors including temperature.

1.2 Effect of temperature on lead acid batteries

Among all of the environmental factors, the temperature is the one that influences the most the behavior of the battery in terms of charging and discharging. The explanation lies in temperature-dependent electrochemical reactions (Arrhenius' law) [7].

Numerous studies have been reported on the influence of temperature on lead-acid batteries. D. Pavlov experimentally evaluated thermal phenomena during chemical and electrochemical processes of the oxygen cycle in VRLA batteries [8]. Bhatt studied experimentally the effect of temperature on the performance of a VRLA battery and proposed an optimum operating temperature range in which the battery gives better performance under the climatic conditions of India [9]. Oliveri *et al.* have experimentally determined the effects of temperature on the lifespan as well as on the capacity of the High-Performance Lead-Acid Batteries Enabled by Pb and PbO_2 Nanostructured Electrodes [10].

Niger, a Sahelian country, has an average sunshine of 8 hours per day and extreme temperatures depending on the two seasons: cold and hot [11]. This state of affairs reveals, on the one hand, a significant potential for the exploitation of solar energy in Niger at competitive costs [12] and on the other hand the need to assess the effect of temperature on the performance of commercial solar batteries in Niger. The objective of this work is observe experimentally some physicochemical performance parameters of the most widely used commercial solar battery technology in households in Niamey under different temperatures that characterize the climate of Niger in order to determine a range of temperature for optimum operation. A direct interview survey was conducted among suppliers and users of commercial solar batteries in Niamey to identify the technology most used in households. The following performance parameters were evaluated: discharge time, charge time, capacity, gassing rate and internal resistance. The various experiments were designed with reference to the performance tests in IS – 15549: 2005 [13].

2. EXPERIMENTAL METHODS

2.1. Study area and survey

Niamey city, the capital of Niger has five (5) municipal districts, Figure 1. It is the largest urban agglomeration in Niger. It concentrates most of the political, administrative powers and economic activities of the country [14]. However, the city of Niamey is poorly served by electricity. Thus, to deal with irregularities in the electricity supply, the residents of Niamey have for several years been using photovoltaic solar energy coupled with batteries [15]. Hence the choice of the city of Niamey to carry out this study. Thus, a survey was conducted among suppliers and users of solar batteries in some neighborhoods of the five communal districts of the city of Niamey. Solar street lighting and solar emergency power for telephone companies were not included in the survey. An inventory of types of commercial solar batteries used in households was carried out and the battery technology most used in Niamey was identified

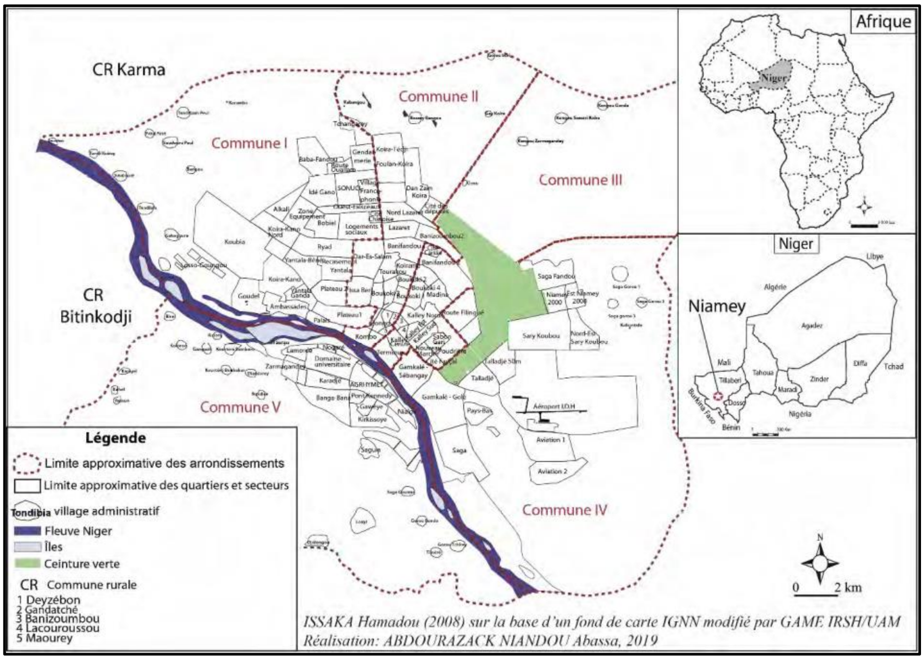

Fig.1. Location of the city of Niamey [15]

2.2. Choice of study battery

The choice was made following the survey that was conducted in the five municipal districts of the city of Niamey with around a hundred people selling or using commercial solar batteries in the identified sites. Thus, a commercial solar battery with nominal characteristics of 12 V-80 Ah (VRLA-AGM), purchased on the market, was chosen as the object of study.

2.3. Choice of test temperatures

There are many performance parameters affected by temperature. In this work the parameters evaluated are the battery capacity, the charge and discharge time, the internal resistance and the gassing rate. A temperature record covering one year was obtained at the African School of Meteorology and Civil Aviation (EAMAC) in Niamey. From this reading, two temperatures were identified corresponding to the average extreme temperatures of the two seasons: an average minimum temperature of 17 °C (cold season) and an average maximum temperature of 42 °C (hot season). Then an average was established to determine the third study temperature: an average temperature of the two extremes 30 °C.

2.4. Experimentation

The influence of temperature on physicochemical performance parameters such as discharge time, charge time, capacity, internal resistance and gassing rate was evaluated during the experiment. A sealed lead-acid technology commercial battery with 12 V-80 Ah characteristics was used for the various tests. All experiments were designed with reference to acceptance testing in IS-15549:2005 as described in [9]. Figure 2. and Figure 3 respectively show the diagram of the experimental device and the experimental set up.

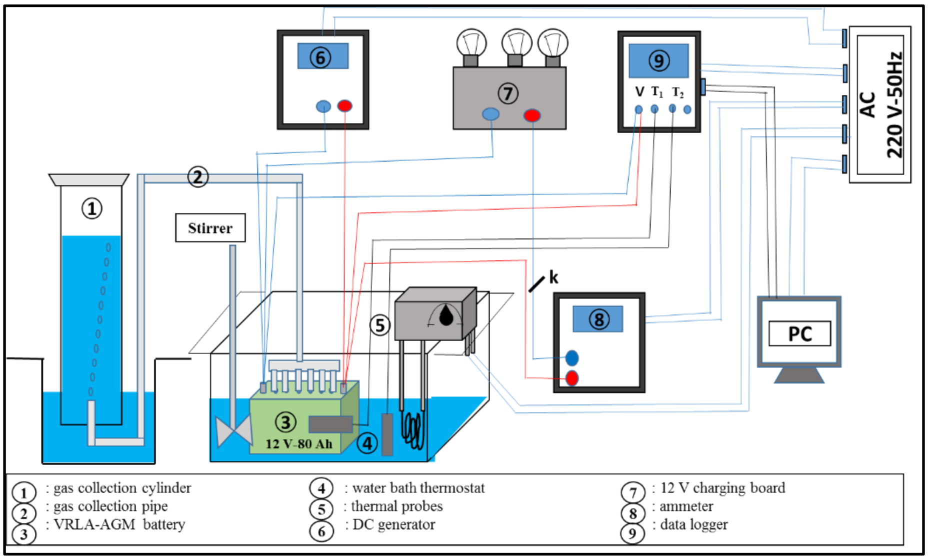

Fig.2. Diagram of the experimental setup

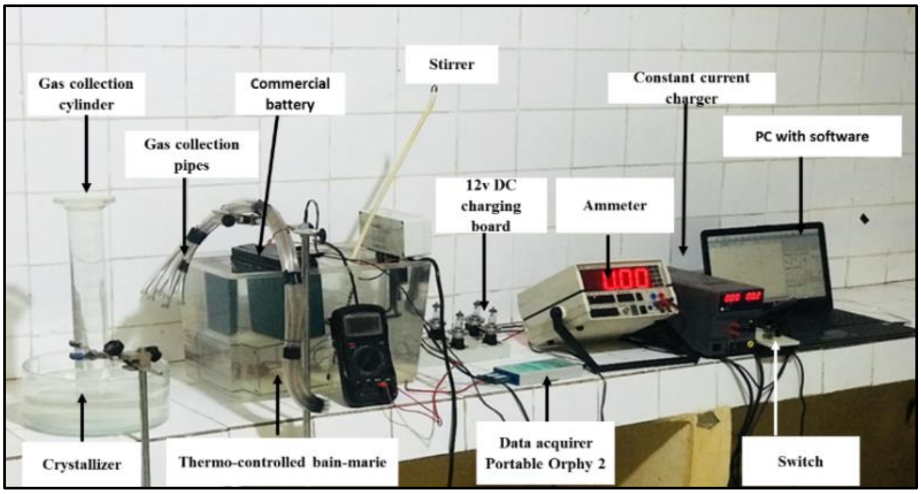

Fig.3. Experimental setup for charge and discharge test, capacity and gassing rate

For each test, the battery was placed in the water bath for at least 2 hours until its temperature equaled the test temperature. The discharge test and the capacity test were carried out under the same conditions with the battery fully charged (14.5 V). Then it was discharged with a current of 8.62 A, or around a rate of $1C_{10}$. The data were recorded at one-minute intervals up to the predefined minimum voltage value of 9.6 V. The battery capacity was calculated as follow:

$$Q = t \times I \quad (3)$$

With Q: capacity in Ah, **t:** discharge time in hours and I: discharge current in A. The charging test was carried out with a constant current charger so the limiting capacity is 3.51 A. The data were recorded each 10-minute interval until the battery voltage reaches the preset maximum value of 14.5 V. The experimental setup of the discharge test is the same as that of the load test except that at the discharge the generator is replaced by a charging board with a discharge current of 8.62 A or about $1C_{10}$. The internal resistance of a battery is the overall equivalent resistance in the battery.

Gassing occurs during overcharging of a battery. So, there are gassing vents provided above the battery for this purpose. The battery was overcharged with a low current of 1 A to prevent thermal runaway. Data was recorded at each one-minute interval up to a preset voltage of 14.5 V. Gas evolved was measured by collection over water:

$$V_{\text{gas evolved}} = V_{\text{water displaced}} \quad (4)$$

The resistance test was carried out in a circuit comprising the battery, a resistance (R) of 100 Ω, an ammeter and a switch which are placed in series, Figure 4. The open circuit voltage of the battery corresponding to the electromotive force (E) was measured. Then, after closing the circuit and stabilizing the voltage (at least 1 minute), the circuit current (I) and the voltage across the resistor (U) were measured. The internal resistance (r) was calculated by Pouillet's relation:

$$r = (E/I)-R \quad (5)$$

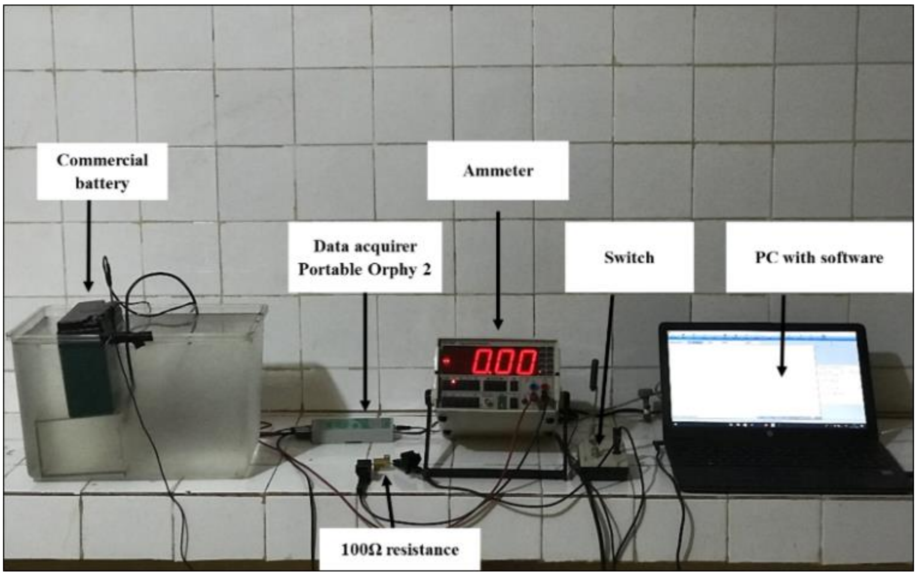

Fig.4. Experimental setup for battery internal resistance measurement test

3. RESULTS AND DISCUSSION

3.1. Inventory of commercial solar battery types used in Niamey, Niger

All five municipal districts of Niamey were involved in the survey, Table 1. These results of the survey shown a marked presence of battery suppliers in the markets located towards the center of Niamey; with the exception of a few neighborhoods on the outskirts where the coverage of the electricity network is not effective. Contrary to suppliers, users are more present in outlying districts with poor electricity network coverage, Table 1. The batteries listed during the investigation are of various origins and various technologies. The sealed lead-acid technology (98%), VRLA-AGM type (78%), Chinese origin (81%) is the most widely used in households in Niamey (Figure 5, Figure 6 and Figure 7). This would be due to the accessibility and availability of the ranges of varied powers of Chinese batteries which are within reach of all budgets like the VRLA-AGM type study battery with a capacity of 12 V-80 Ah, Figure 8.

Table 1. Number of suppliers and users of solar batteries on surveyed sites

Designation	Sites surveyed	Suppliers	Users
Number	**25**	**38**	**128**

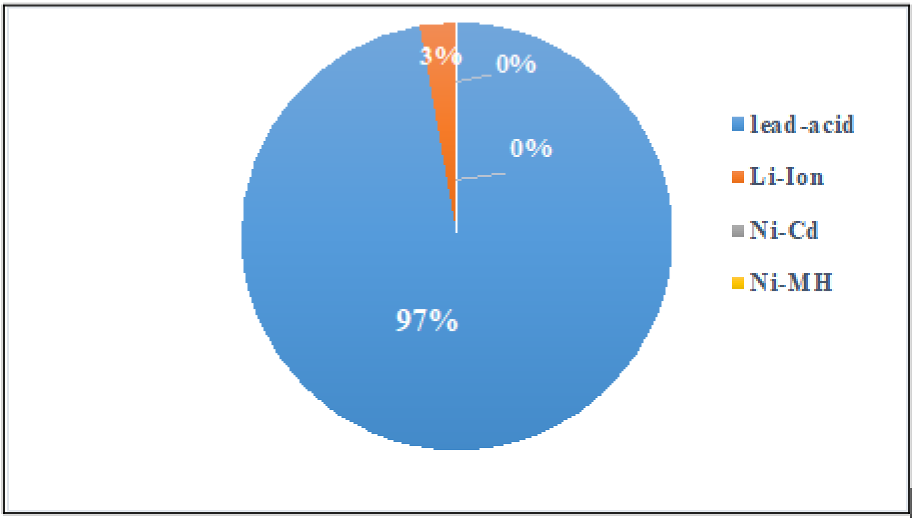

Fig.5. Types of solar batteries used in surveyed households in Niamey

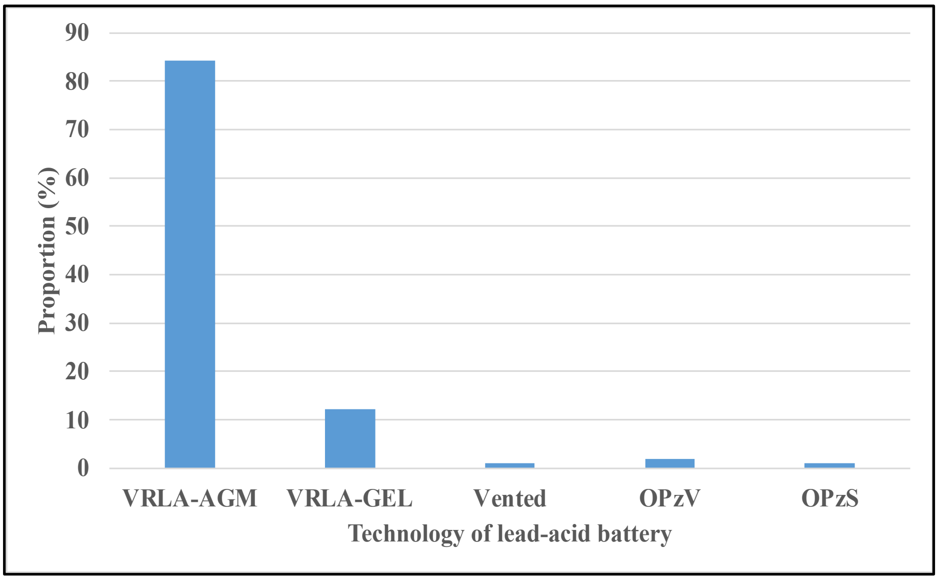

Fig.6. Different lead-acid commercial solar battery technologies encountered during the survey in Niamey

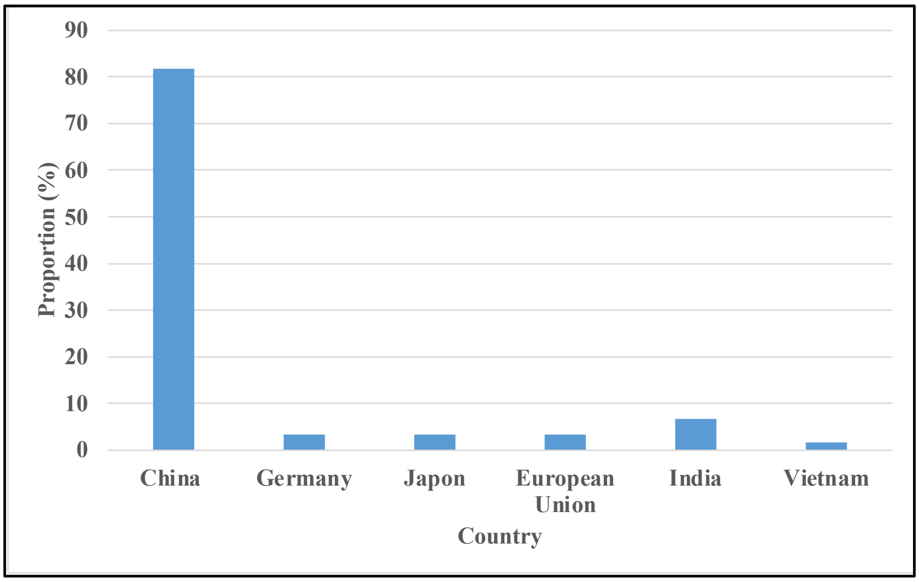

Fig.7. Country of origin of the commercial solar batteries encountered during the survey in Niamey

Fig.8. The commercial VRLA-AGM lead-acid technology solar battery studied

3.2. Average temperature values in Niamey according to the months of a year

Two temperatures have been identified corresponding to the averages of Niamey's two extreme temperature seasons: 17 °C (minimum temperature, January) and 42 °C (maximum temperature, April), Figure 9. Then an average was established to determine the third study temperature: 30 °C (average temperature) [11].

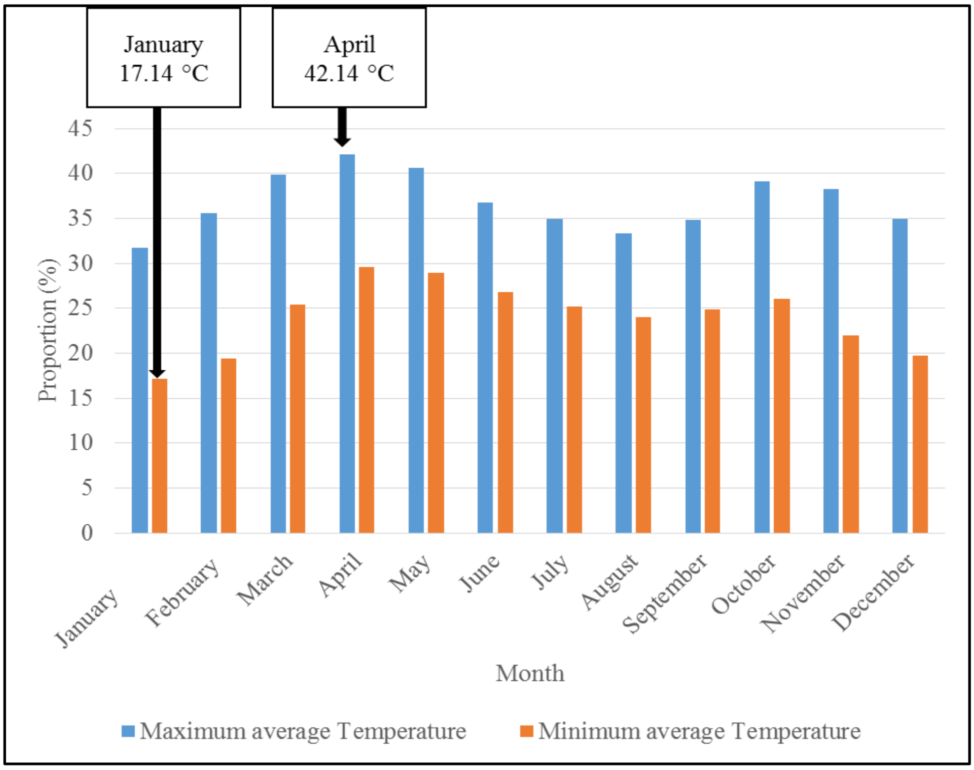

Fig.9. Monthly variation in average maximum and minimum temperatures in Niamey for the year 2016

3.3. Results of tests

3.3.1. Discharge test

It was observed that the duration of the discharge varies with the ambient temperature (**Fig. 10.**). The highest discharge time (57 minutes) was obtained at 42 °C with a discharge current of 8.62 A around $1C_{10}$ and the lowest discharge time (41 minutes) was obtained at 17 °C with the same current, Table 2.

The voltage drop varies with the ambient temperature, Figure 10. In fact, the voltage V at the terminals of a generator is given by the formula:

$$V = E - \Delta V \qquad (6)$$

With: E: electromotive force and ΔV: overvoltage linked to the internal resistance. This overvoltage depends on an overvoltage linked to the speed of the reactions ΔVa, an overvoltage linked to the ohmic conductivity ΔVr and an overvoltage linked to the diffusion of ions in the electrolyte ΔVc [16]:

$$\Delta V = \Delta Va + \Delta Vr + \Delta Vc \qquad (7)$$

At low temperature, the overvoltage (ΔV) would be high due to the low speed of the reactions, the low electronic conductivity and a high viscosity which would reduce the mobility of the ions in the electrolyte. This led to a rapid drop in voltage. On the other hand at high temperature, the speed of the reactions, the conductivity and the mobility of the ions would be better, hence a low overvoltage; which led to a more uniform and slower voltage drop at high temperature.

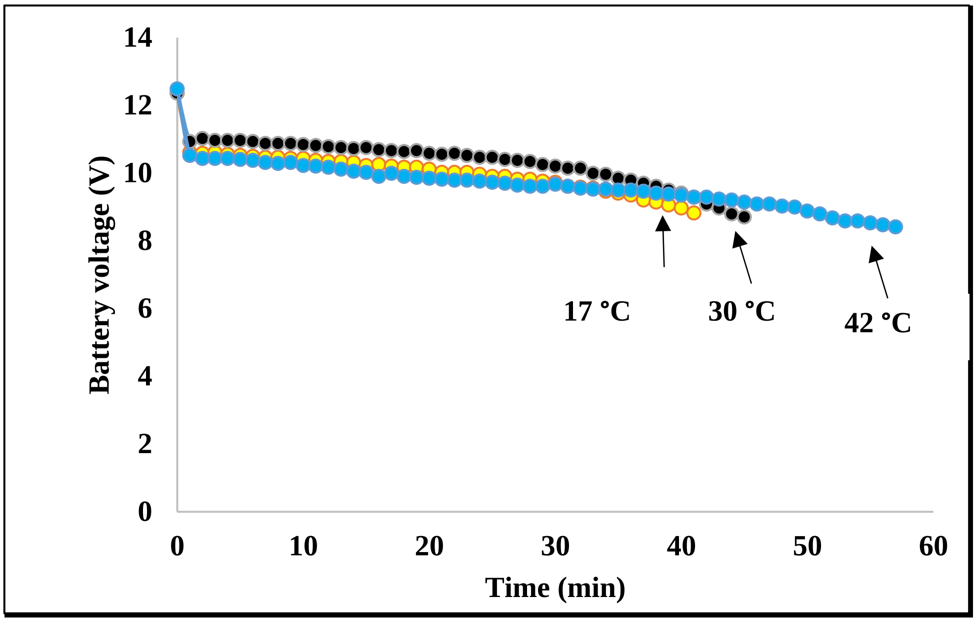

Fig.10. Commercial battery discharge time comparison for capacity test at 17 °C, 30 °C and 42 °C

Table 2. The discharge time of the 12 V, 80 Ah commercial battery at 17 °C, 30 °C and 42 °C

Temperature (°C)	**17**	**30**	**42**
Discharge time (min)	41	45	57

3.3.2. Capacity test

The capacity of the battery is given according to the ambient temperature of the water bath, Table 3. In this work, the battery was discharged with the same current of 8.62 A. Therefore, the variation in capacity would be related to the variation in ambient temperature. The highest battery capacity (8.19 Ah) was observed at a temperature of 42 °C while the lowest value (5.69 Ah) was observed at 17 °C, Figure 1. This would be explained by the fact that the rate of reactions and the mobility of ions would be low at low temperature, which would lead to a low capacity and vice versa [9].

Moreover, it has been shown that the higher the rate of discharge, the greater the difference between the available capacity and the total capacity. This would explain the low capacities obtained well below the nominal capacity (Peuker's law) [16].

However, by using this law of Peuker under conditions of 25 °C to estimate the real capacity of the battery, the result obtained is well below the nominal capacity, i.e. approximately 12 Ah for 80 Ah announced. This raises the question of the reliability of the nominal characteristics announced on the commercial batteries used in Niamey.

Table 3. Commercial battery capacity 12 V, 80 Ah at 17 °C, 30 °C and 42 °C

Temperature (°C)	17	30	42
Capacity (Ah)	5.69	6.46	8.19

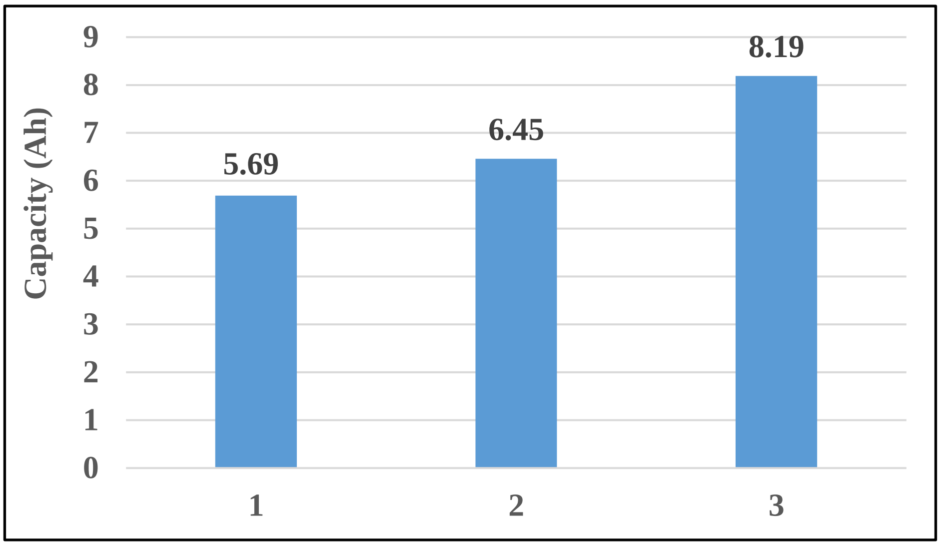

Fig.11. Comparison of commercial battery capacity at 17 °C, 30 °C and 42 °C

3.3.3. Charge test

Battery charge time was found to vary with ambient temperature, Table 4. The preset maximum charging voltage (14.5 V) was reached fastest (52 min) at the temperature of 17 °C while the highest charging time (2 h 14 min) was obtained at 42 °C, Figure 12.

Since the charging current was constant (3.56 A) during all charging tests. Thus, the variation of the charging time was related to the ambient temperature. Indeed, with the drop in temperature, the viscosity of the electrolyte would increase, which would reduce the ionic mobility and limit the chemical reactions at the interfaces of the electrodes. Moreover, at low temperature, the internal resistance of the battery would increase and the speed of the reactions would be low [9]. The long charging time at high temperature would be explained on the one hand by the low resistance within the electrolyte, hence a good ionic conductivity, and on the other hand by the improvement in the speed of the reactions. This allows deeper cycling of the active ingredient. Prolonged use of the battery in high temperature conditions could cause corrosion of the electrodes.

Table 4. 12 V, 80 Ah commercial battery charging times at 17 °C, 30 °C and 42 °C

Temperature (°C)	17	30	42
Charging time (minute)	52	103	134

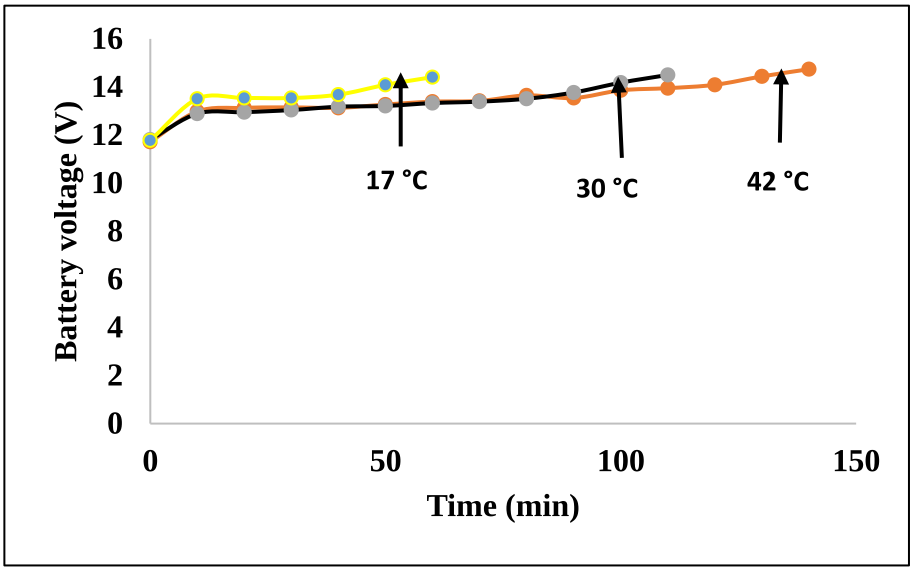

Fig.12. Comparison of commercial battery charging process at 17 °C, 30 °C and 42 °C

3.3.4. Resistance test

It was observed that the battery resistance decreased as the ambient temperature increased. The highest internal resistance was observed at a temperature of 17 °C and the lowest at a temperature of 42 °C, Table 5. Bhatt also observed in this work that the internal resistance of the battery increases when the temperature drops [9]. The decrease of the internal resistance of the battery with the increase in temperature would be explained by the fact that the viscosity of the electrolyte would be low at high temperature, which improves the mobility of the ions and the rate of chemical reaction at the electrodes consequently a low internal resistance. The high viscosity of the electrolyte would oppose the transfer of charge between the electrodes which would lead to a high internal resistance [9].

Table 5. Internal resistance of commercial battery 12 V, 80 Ah at 17 °C, 30°C and 42 °C

Temperature (°C)	**17**	**30**	**42**
Internal resistance (Ω)	**5.75**	**5.16**	**5**

3.3.5. Gassing test

It was observed that the minimum amount of gas released from the battery during the gassing test was at 17 °C and the maximum amount of gas released from the battery was at 42 °C, Table 6. This result is similar to that of Bhatt who obtained 1.4 mL at 10 °C and 29 mL at 45 °C with a VRLA-AGM battery of 12 V-7 Ah [9].

The gas release rate increased with increasing temperature. The high gassing rate at high temperature would be mainly explained by two reasons. On the one hand, the chemical reaction rate is faster between the positive electrode and the negative electrode at a higher temperature, which increases the rate of gassing in the event of an overload [17]. On the other hand, by the fact that when the charging current and the temperature increase, the efficiency of the oxygen recombination cycle decreases [8].

Table 6. Volume of gas released from the commercial battery during the gassing test

Temperature (°C)	17	30	42
Gas volume (mL)	12	16.07	36.36

4. CONCLUSION

A survey conducted in the Niamey region among sellers and users of commercial solar batteries permits to establish an inventory of the types of commercial solar batteries used in households. The lead-acid battery (98 %), particularly the VRLA-AGM technology (78 %) is the most used in households in Niamey. The effect of the ambient temperature of the city of Niamey on the performance of a commercial solar battery of lead-acid technology of the VRLA-AGM type (12 V, 80 Ah) was studied. Performance parameters such as discharge time, capacity, charge time, gassing rate and internal resistance were tested at different temperatures (17 °C, 30 °C and 42 °C) characteristic of the Nigerien climate. Discharge time, charge time, battery capacity and gassing rate increase with temperature and vice versa. The internal resistance is high at low temperature and decreases at high temperature. The capacity and the discharge time are better at high temperature (45 °C); but prolonged operation at high temperature leads to deep cycling which can lead to deterioration of the electrodes, which is responsible for reducing the life of the battery. On the other hand, prolonged use at high temperature can cause the AGM separator to dry out (high gassing rate), which is also responsible for reducing battery life. This means that the high temperature of the VRLA-AGM battery is beneficial for a short time but becomes disadvantageous when used for a long time. Such a high temperature for a long time reduces battery life. In addition, at low temperature (17 °C) the internal resistance of the battery is high, which leads to a slowdown in chemical reactions and poor electrical performance. Therefore a low temperature is not as beneficial to the battery. Finally, for better performance of this commercial solar battery used in Niamey, it should not operate at high temperatures (42 °C) nor at low temperatures (17 °C) but in a temperature range from 25 °C at 30 °C.

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