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Comparative Study of Energy Storage Systems between Photovoltaic Solar Battery and Flywheel of Inertia

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Abstract In this article, we presented a comparative study of energy storage systems between an electromechanical system called flywheel of inertia and solar batteries photovoltaic (PV).

In order to reduce the costs of electrochemical storage generally of lead in PV plants, we propose in this article to replace these batteries by an inertial energy storage system (ISSE).Indeed, it will be necessary to plan the replacement of these batteries without also counting their maintenance cost, whereas the flywheels of inertia have a very high life cycle and can withstand very high ambient temperatures. This study allows decision makers to have the appropriate technico-economic choice of energy storage system.

Indeed, in this work, following a proposed model for calculating the cost of energy storage of the kWh, we have shown that a PV plan without batteries coupled to an inertia flywheel optimizes the size of the field photovoltaic and reduce the operating time of the generator set.

Keywords Storage, electrochemical, battery, energy, photovoltaic, flywheel, inertia, plan

1. Introduction

In Africa, the problem of access to electricity is a detrimental factor in economic and social growth. This problem is rather felt in rural areas where the electrical network is almost non-existent or very remote. While, these areas have enormous potential for renewable energy [1].The promotion of renewable energies through the development of decentralized hybrid (solar / (GS)) power plants with energy storage then becomes the ideal solution to eradicate this scourge [2].A hybrid plant is consisted mainly of two or more sources of energy because of the intermittence of these renewable energies.Although very interesting from a technico-economic and environmental point of view, the operation of a hybrid power plant requires the use of an adequate energy storage device to compensate for the phase shift between daytime production and consumption at any moment.Electrochemical storage by lead-acid batteries is currently the most widespread and accounts for 20 to 30% of the investment cost of these photovoltaic solar power plants with very limited life cycles [3].

These batteries are still very sensitive to the very high ambient temperature of tropical countries and need to be replaced after a few years of operation, resulting in an additional investment on the cost of the project. To overcome this challenge caused by the weakest link (battery) of the PV system, this paper proposes to study a storage technique in order to make a technico-economic and environmental analysis between energy storage systems.

The storage technique envisaged is the use of the inertial system of electromechanical energy storage more commonly known as the flywheel of inertia. This proposed storage technology is still little known but could meet the technico-economic expectations of the development of the decentralized hybrid power plant sector, especially for tropical countries where the average ambient temperatures are very high and the environmental factor has to be taken into account. The paper proposes a comparative study of energy storage by flywheel (electromechanical system) and that of electrochemical lead-based storage in a photovoltaic power plant allowing technical, economic and environmental decision-making.

2. Concept and Discussions

2.1. Electrochemical Storage

2.1.1. Electrochemical Storage for Photovoltaic Power Plants

Most solar photovoltaic PV / generator set solar power plants have special batteries (plantary lead alloy batteries) that store energy generated by the power source in anticipation of periods when there is no sun. These batteries are designed to restore a stable current for long periods while maintaining their recharging abilities, and this on a large number of occasions (cycles).These are referred to as plantary or deep discharge batteries.

The diagram which follows represents the synoptic of a model of a hybrid photovoltaic plant with a device for storing electrochemical energy with lead.

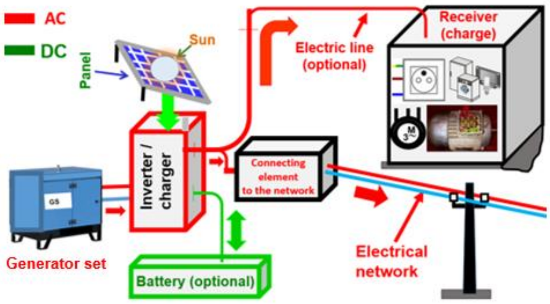

Figure 1: Synoptic of a hybrid photovoltaic plant with electrochemical storage

For the various interconnected elements of figure 1, the solar batteries represent the weakest link in terms of the lifetime of the chain of the components of these photovoltaic solar power plants.

2.1.2. General information on lead solar batteries

The lead battery has positive and negative electrodes composed of dissimilar alloys immersed in an electrolyte (acid).The assembly is encapsulated in a sealed tray or fitted with a filler cap and a vent. The oxidation-reduction reactions that govern the operation of a battery are reversible, as long as it has not been fully discharged or overloaded for a long time. Prolonged operation in either state would result in permanent battery destruction. This cycle of reversible chemical transformations is summarized by the following simplified and detailed double equations [1]:

$$PbO_2 + Pb + 2H_2SO4 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O \quad (1)$$

This equation (1) can also be expressed in the following equation (2):

$$\underset{\text{positive}}{PbO_2} + \underset{\text{negative}}{Pb} + \underset{\text{electrolyte}}{2H_2SO4} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} \underset{\text{negative}}{PbSO_4} + \underset{\text{electrolyte}}{2H_2O} + \underset{\text{positive}}{PbSO_4} \quad (2)$$

These equations are accompanied by the elements constituting the accumulators of figure 2.

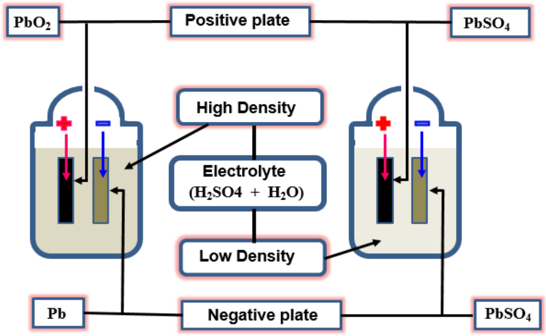

Figure 2: Components of an accumulator

The discharge of the lead accumulator consumes the solids of the electrodes and the H^+ ions of the electrolyte (the concentration of acid decreases, the pH increases). There is formation of lead sulphate $PbSO_4$ on the electrodes. The charge of the lead accumulator forms the solids of the electrodes and the H^+ ions of the electrolyte (the acid concentration increases, the pH decreases). The lead sulphate $PbSO_4$ disappears of the electrodes. Due to its low electrical conductivity, the $PbSO_4$ formed on the electrodes decreases the capacity of the battery by contacting the reactions on the terminals of the battery. This is due to prolonged or too deep discharge of the battery and / or gasification of the electrolyte. This phenomenon of sulphation is accentuated as the temperature increases.

In view of all these phenomena which are the basis of the failures of batteries, it is necessary to find alternatives. Cause for which, in this article, an electromechanical solution based on flywheel of inertia is proposed as storage solution.

2.1.3. Effect of temperature on lead solar batteries

Temperature plays a negative role on the lifetime of lead-acid batteries. When the temperature increases by 10 ° C, the velocity of the electrochemical reactions doubles, which decreases by a factor of 2 its lifetime. This state of rapid aging is accelerated by the corrosion of the terminals of the battery. If the battery is used in an environment where the ambient temperature is high, the amount of heat produced during intensive degassing may exceed the amount of heat that escapes from the battery. The temperature of the battery then rises, and this further accelerates the speed of the exothermic chemical reactions. This phenomenon is called thermal runaway of the battery. The battery will be destroyed.

In this article, to study the negative impact of temperature on batteries, the study concerns the solar power plant of Ndiolofène Village in the south of Senegal with a power of 10 kWc whose total electrochemical energy storage capacity is 48 kWh / day. The recording data of the inverter made it possible to plot in Excel the figure 3.We have highlighted the rapid deterioration in the state of health (storage capacity) of lead-acid batteries installed in the PV / GS solar hybrid plant depending on the temperature of use and the local containing them.

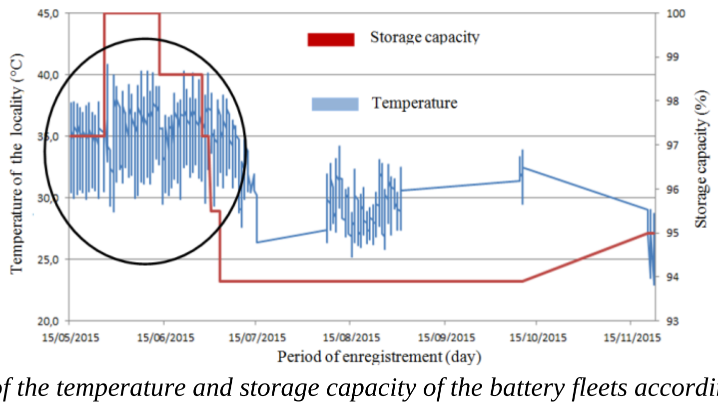

Figure 3: Profile of the temperature and storage capacity of the battery fleets according to the period of enregistrement

Since the nominal capacity of lead-acid batteries is given at 20 ° C by the manufacturers, analysis of the plant's inverter recording data enabled us to show the effect of the increase in temperature on its actual use capacity of the energy stored in the lead batteries.

Between 20 and 25 °C, the capacity of use of the energy stored in the batteries to decrease by 5%;

- Between 25 and 30 ° C, this decreases the usable capacity to evolve up to 8% ;
- If the temperature is very high> 30 ° C, as shown in the figure, the state of health of the battery park deteriorates considerably in less than a month between June and July. It coincides with the period of the great heat of the locality;
- If the batteries are put to rest for some time after being used at high temperature, the state of health becomes constant or even improved. This is the period when the power plant has suffered some downtime due to technical failures of the electrical distribution cabinet.

The health of a battery should not be confused with its lifetime. The state of health characterizes the current usable capacity of the batteries in relation to its nominal capacity. Generally, for PV / GS hybrid power plants, if the health of the batteries degrades on the effect of temperature, it will be necessary to extend the operating time of the GS to cover the night demand.

However, consumption patterns have shown that night-time energy demand in the sub-Saharan rural environment is very low (see figure 4), so that the GS is likely to operate at low regime [2]. This would increase the fuel consumption of the generator set. And with the absence of a relay GS, it will be necessary to relieve the receivers of the PV system so as not to further degrade the batteries by exceeding their authorized discharge threshold. These shortcomings make electrochemical storage problematic from the point of view of continuity of electrical supply and environmental.

Therefore, in order to overcome the weaknesses of electrochemical storage, in this paper we propose a more intelligent storage system (flywheel of inertia) and less expensive and that respects the environment. To do this, it is necessary to have the profile of the energy demand of the village.

The census of all electrical equipment, following the electrical power balance, allowed us to plot the energy demand profile of the village Ndiolofène in Excel in figure 4.

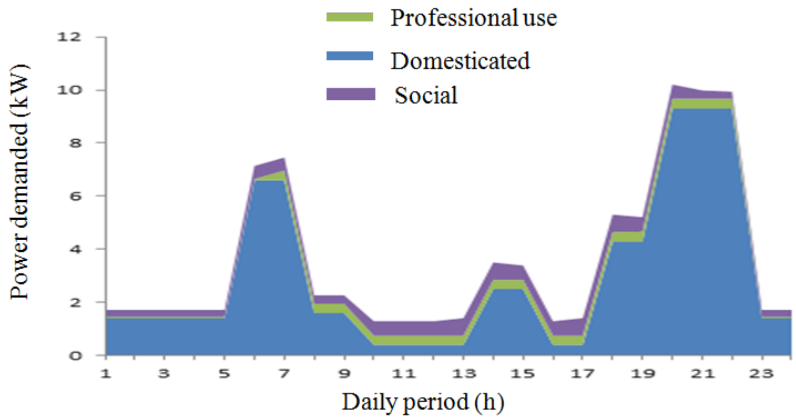

Figure 4: Profile of the energy demand of the village of Ndiolofène

This figure shows that, whatever the category of the user, energy demand varies for 24 hours.

It remains very low especially between 10 am and 1 pm. Peaks are noted between 7 pm and 11 pm and for all categories. This shows that the storage systems proposed in this article must undergo heavy constraints between 5 am and 8 am and especially between 7 pm and 11 pm.

2.2. Inertial storage

2.2.1. Theory on the inertial storage system of energy (ISSE)

a. Principle of operation of a ISSE

Long used, on distinguishes two categories of inertial system of energy storage. The ISSE with fast flywheel whose materials used are in composites and the ISSE by slow flying made up of metallic materials [2]. The ISSE principle is based on electromechanical or kinetic storage technology. In this article, kinetic energy is the energy possessed by the flywheel (rotating mass) because of its rotation. Figure 5 below shows the 6 main components of an inertial storage system.

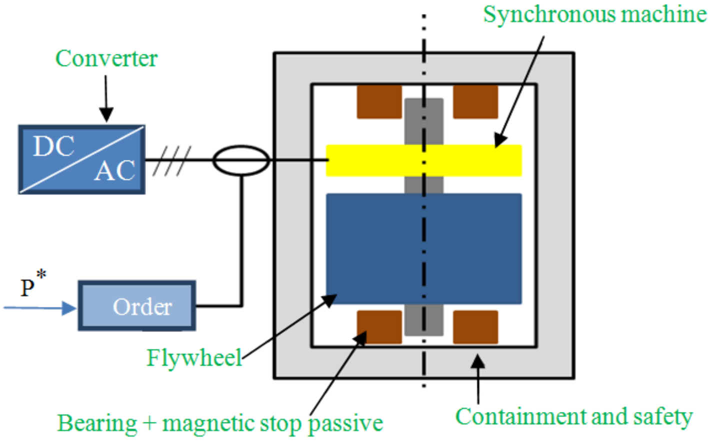

Figure 5: Inertial Storage system of energy (ISSE)

The main element of the system is the flywheel serving as energy storage. During the storage phase, the surplus of the PV or GS energy is converted into mechanical energy by the synchronous machine (motor), which in turn is stored as kinetic energy at the flywheel (flywheel acceleration phase). It is followed by the discharge phase where the kinetic energy stored on the flywheel is then transformed as an electrical energy by the synchronous machine (alternator) (braking phase). The flywheel is guided in rotation by the palaces (ball bearings) and a passive magnetic stop that supports the weight of the steering wheel. The system is placed in a containment and safety creating a vacuum around the steering wheel to remove the friction in contact with air. The system is also equipped with an electronic power and control converter which define the operating regime (load / discharge) of the flywheel thus imposing the direction of transfer of energy to the synchronous machine [4, 5, 6, 7].

b. Studies of the physical characteristics of the flywheel

The physical characteristics of the flywheel play an important role in the design of an inertial storage system. The table below gives the various mechanical characteristics of the flywheels according to the materials used [6, 7].

Table 1: Mechanical characteristics of flywheels

Materials	Kevlar	Aluminum alloy	Carbon fiber	High-strength steel	Reinforced concrete of fiber	Single concrete
Density (kg/m^3)	1 800	2 700	1 500	7 800	2 400	2 400
Breaking resistant (MPa)	4 800	594	1 264.91	1 300 2 100	130 250	50
Specific resistance (Nm/kg)	2.66	0.22	0.84	0.26 0.16	0.05 0.10	0.02

Once the field of high frequencies of rotation is approached, the risk of explosion of the ISSE becomes a most constraining phenomenon due to the centrifugal force which limits the amount of energy to be stored. This phenomenon can be caused by exceeding the linear peripheral velocity of the material used. This material must then have a very high breaking strength and a very low density in order to be able to withstand these constraints.

By taking into account these considerations, according to the table the Kevlar has mechanical properties much more interesting than that of simple concrete. However, because of its high cost, other materials can be considered for the flywheel such as synthetic fiber reinforced concrete. The latter is relatively cheaper and accessible, the storage properties of which (related to density) are relatively interesting.

2.2.2. Dimensioning of a inertial flywheel

The dimensioning of a storage flywheel must take into account two main factors:

- the speed of rotation;

- the energy capacity to be stored.

During the acceleration phase of the flywheel, the stored kinetic energy (Ec) is given by the following expression:

$$E_C = \frac{1}{2} J\Omega_{max}^{2} = \frac{1}{2} \iiint V^2 . dm \quad (3)$$

With, Ω_{max} = maximum rotational speed of the electrical machine;
V = peripheral speed of the flywheel;
J = moment of inertia of the flywheel which depends on its geometric form.
It measures resistance which opposes a torque tending to turn the object.
The maximum speed of rotation applied to the machine is defined by the constraint σ exerted on the periphery of the steering wheel. This constraint represents the cohesive forces in the solid which allow the material to withstand solicitations [4]. It is defined by the following general expression:

$$\sigma_{max} = \rho . \Omega_{max}^2 . R^2 \quad (4)$$

This stress σ is produced by its rotation and is maximum in the region of its outer radius R. In this expression, the nature of the material and its geometrical shape are not taken into consideration. This maximum constraint can be expressed taking into consideration this time the physical parameters of the material. The latter define the coefficient of velocity (k) and is proportional to this constraint [7].

$$\sigma_{max} = \frac{\rho . \Omega_{max}^2 . R^2}{k^2} \quad (5)$$

The coefficient k depends only on the Poisson coefficient of the material and on its geometric shape [4]. Equations (3) and (4) show that this constraint increases with increasing velocity V and it is fundamental to define its maximum peripheral velocity. This speed can be deduced from this relation:

$$V_{max} = k\sqrt{\frac{\sigma_{max}}{\rho}} \quad (6)$$

With, V_{max} = maximum peripheral speed of the flywheel; ρ = density of the material; σ_{max} = maximum constraint of the material.
Since the cohesive forces and the Poisson coefficient are specific to the material chosen, equation (6) shows that in order to have a high peripheral velocity it will be necessary to choose a material whose density is as low as possible. The expression of the kinetic energy of the steering wheel can be rewritten by introducing equations (5) and (6):

$$E_c = \frac{1}{2} \alpha M k^2 \frac{\sigma_{max}}{\rho} \quad (7)$$

This equation (7) shows that it is possible to store more kinetic energy by playing on the density of the material chosen and on its speed of rotation. With a lightweight material the flywheel can be rotated at very high peripheral speeds around 1000 km / h[8]. This technology offers several advantages and would be less expensive than the previous ISSE because concrete is about 10 times cheaper than steel. One could also store more energy and restore it in a longer period. This therefore justifies the interest of choosing a light material such as reinforced concrete of fiber [9, 10].

2.2.3. Choice of the electrical machine of the electromechanical storage system

The flywheel is coupled to a reversible electric synchronous electromechanical energy conversion machine. It is called an alternator (transforms mechanical energy into electrical energy) if it operates as a generator and provides an alternating current. In regime motor (transforms electrical energy into mechanical energy), its frequency of rotation is imposed by the frequency of the alternating current supplying its armature.
The electrical machine must be capable of delivering two power ranges between the base speed and the maximum speed as shown in figure 6. The machine must also deliver a correct AC voltage [11].

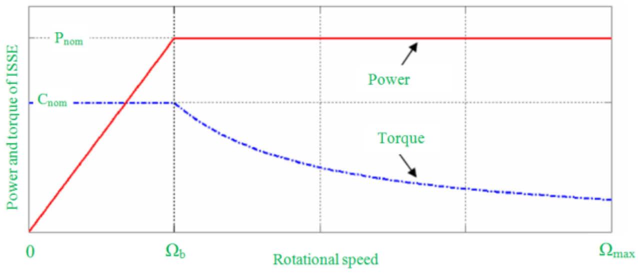

Figure 6: Variation of power and torque of ISSE electrical machines as a function of rotational speed (angular)

Between 0 and base speed (Ω_b), the power supplied by the machine is increasing and its torque is maximum and constant. Its power is maximum when the machine reaches Ω_b. This configuration makes it possible to respond to the typical demands of decentralized hybrid power plants over a very long period. Between Ω_b and Ω_{max}, the power of the machine is constant and its torque decreases. This phase makes it possible to do the smoothing of the network with a very short discharge time ranging from the second to a few minutes.

2.2.4. Connecting an inertial storage system to a photovoltaic power plant

The configuration of the connection model will depend on the nature of the load and must allow the maximum transfer of energy produced. In this work, the electrochemical storage system (batteries) is replaced by an electromechanical storage system (flywheel) with a buried wheel to minimize the risk of an accident in the event of its bursting.

The proposed connection model is given in the block diagram below:

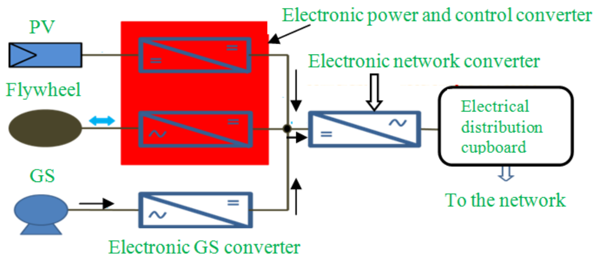

Figure 7: Synoptic diagram of the PV / GS power plant connected to a flywheel

This diagram shows a PV plant connected to a flywheel and a generator set of supplement to serve the network via a distribution cabinet. Its operating principle is similar to that of a power station connected to an electrochemical storage system. The electronic power and control converter of the steering wheel is used to store the surplus energy produced by the solar panels and the GS. This converter is composed of a voltage booster and an inverter DC/AC. That of the generator makes it possible to straighten the tension delivered by this one in order to be able to recharge the steering wheel and to cover the peak of the energy demand. The power converter transforms energy from power sources to supply the distribution network.

However, the steering and control unit of the power electronics replaces in this diagram the lead-acid batteries. The arrows indicate the direction of energy transfer.

With the application of Excel, we simulated the production and consumption profile model of the proposed hybrid power plant (see figure 7). The case study still focuses on the village of Ndiolofene. Photovoltaic power has been adjusted for to cover all energy demand.

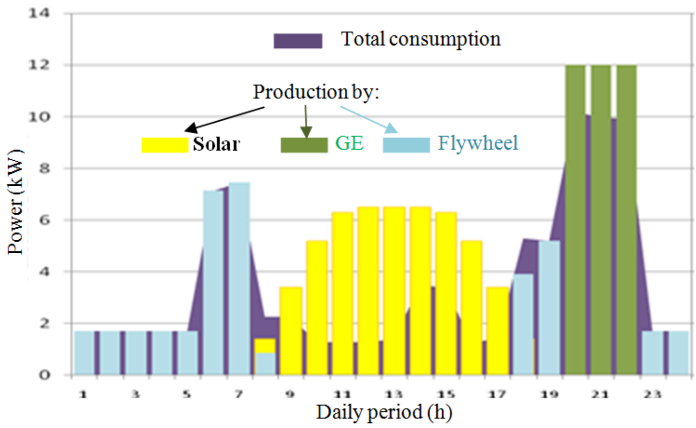

Figure 7: Production / consumption profile with inertial flywheel

During the day (from 7:30 am to 5 pm), the photovoltaic production feeds the loads and the evening (from 6 pm to 7:30 am) the steering wheel restores the energy that it had stored. At any time, the surplus of the photovoltaic production and / or of the diesel generator is stored in the steering wheel. The peak of the night demand (from 8 pm to 11 pm) is provided by the generator. The energy stored in the steering wheel can be restored in its entirety.

This configuration proposed in this work, makes it possible to optimize the cost of the photovoltaic field and to reduce the gas oil consumption of the group.

2.3. Comparative study of inertial and electrochemical lead-based storage systems

The technological evolution of storage systems must meet the expectations of sustainable development, namely the technical, economic and environmental needs to be integrated into the electricity network [12]. Each storage technology has its own specificities in terms of size, power delivered, cost, cycling, lifetime, etc.... In this part of the article, emphasis is placed on the technico-economic and environmental comparison between the use of an inertia flywheel and lead-acid batteries in a hybrid photovoltaic plant for an application of stationary type and isolated network. Thus, the specificities of comparison in our case are the investment and storage costs, the lifetime and the environmental aspect of the system to be chosen [13, 14].

Lead batteries have a cycle number ranging from 1200 to 8000 cycles depending on the discharge depth. But this number of cycles also depends on the temperature because an increase of 10 ° C would decrease by half its lifetime. For example, for a hybrid plant equipped with a 131 kWh pellet storage device with an average discharge depth of 53.31% and an operating temperature of > 40 ° C, its service life is reduced to approximately 1,250 cycles. This means that the batteries must be renewed every 41 months, more than 7 times for a 25-year project. And they have an energy efficiency of 75%.

The flywheels have a number of cycles> 10,000, whatever their depth of discharge. In addition, a steering wheel can operate under tropical temperature conditions because the steering wheel is confined in an empty enclosure. Under the same conditions as the previous one, the use of a single flywheel will cover the duration of the project. The inertial flywheel with fiber reinforced concrete and fretted has an energy efficiency of 90%. Its energy efficiency is higher than that of a lead-acid battery [15].

The safety or operational aspect is also a very important technological criterion because any storage device presents risks of explosion. The chemical reactions of the batteries produced during the electrolysis release oxyhydrogen gas (a mixture of oxygen and hydrogen in molar proportion) which has a certain concentration (> 4%) and which makes this gas explosive especially if the temperature is too high. Lead batteries pose a serious environmental problem, especially for their recycling. Abandoned after use, they can pollute the land for more than a century. Research has shown that human exposure to lead can cause harmful diseases such as lead poisoning especially in children and pregnant women. This exposure may be due to the presence of lead dust in the atmosphere as a result of an explosion or improper use of the batteries [16]. For inertial systems also the rotation speed must be controlled to prevent the flywheel from bursting.

Comparative cost analysis of storage systems is very important because it affects the total cost of the project. This comparison can be made on the investment cost of the storage system or on the cost of stored energy reported over the life of a decentralized hybrid power plant project. Initial investment on an electrochemical storage system is less costly than on a flywheel due to the technological maturity of the lead batteries. However, if this investment is reduced to 25 years and the cost of renewal and recycling is added, lead-acid batteries become more expensive because they will have to be changed periodically [17]. Not to mention the cost of maintenance which is not insignificant.

To determine the storage cost per kWh of the system, we propose a model for calculating the cost of electricity in a battery (or steering wheel). This method of calculation takes into account the total cost of the batteries C, the lifetime (N_C) which varies according to the discharge depth (DDP) and the storage capacity (Q_N), thereby deducing the energy capacity in kWh (Q_{tot}). This cost is given by the following expression [18]:

$$C = \frac{P_{batt}}{2a} = \frac{P_{batt}}{N_c \times DDP \times Q_N} \qquad (8)$$

The equation shows that for the same storage capacity and discharge rate, the inertial system gives a better storage cost than the lead batteries. This means that when the storage technology chosen has a very high cycle number, the cost of storage kWh is the lowest. In addition, it should be noted that increasing the temperature by 5 ° C would increase the cost of storage kWh by 19%.

3. Conclusion

Through this paper, we have presented two storage technologies, namely the photovoltaic lead batteries and the electromechanical system (flywheel) to make a comparative study allowing a technico-economic decision-making in the choice of the use of the storage system in decentralized hybrid power stations. We have shown that the comparison of storage systems for stationary and isolated network applications depends largely on three parameters, which are the lifetime of the system and the cost of investment as well as the cost of storage kWh.

This study revealed that to store more kinetic energy it will be necessary to choose a material whose density is low and that its resistance to rupture is important. In other words, with a light material, it will be possible to store more energy and to restore it in a longer period. In order to better carry out this comparative study between the two energy storage systems, a model for calculating the cost of kWh of energy storage has been proposed. From this study, the cost of storage also depends on the local temperature.

The proposed calculation model also optimizes the size of the photovoltaic field and reduces the operating time of the generator set while showing that any energy storage device presents environmental hazards.

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