

**Development of test procedures for benchmarking components in
RES applications, in particular energy storage systems**

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**Evaluation of literature search and results of survey about
lifetime expectancy of components, in particular the
energy storage systems in existing RES applications**

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I. Summary

In this report the results of a literature survey on the lifetime expectancy and on operational experience concerning lifetimes and problems of components, in particular the batteries in PV-hybrid applications, are presented. First the general ageing mechanisms of lead acid batteries and the factors that affect ageing are reviewed. Then, the specific operating conditions of batteries in renewable energy applications are examined in respect to the factors that affect the ageing processes and battery lifetime. Next, lifetime characteristics of batteries and battery operating conditions RES systems are presented in view of terms that determine battery lifetime expectancy. Following, actually achieved lifetimes of batteries, in field or laboratory, as have been reported in various reports found in the literature, are summarised. Finally, problems and experiences regarding other PV components are presented.

II. Introduction

In almost all PV or hybrid stand-alone systems, a means of energy storage is required in order to balance the differences between power production and consumption. The most widespread means for the storage of electrical energy are batteries. Lead acid technology is the main technology used in RES systems, due to its maturity and low cost, and will be for the next years. Manufacturers design specific products to meet the requirements of the operation of batteries in small to large RES systems. It is often stated however that batteries in RES applications exhibit shorter lifetimes than those expected by manufacturers' data or those experienced in traditional applications.

In the framework of the 'Benchmarking' project, a literature survey was conducted on the lifetime expectancy and on operational experience concerning lifetimes and problems of batteries operating in RES applications. Parallel to this, information on problems and experience regarding other RES components was collected. An attempt for collection information also through contacts with RES operators and mailing of questionnaires was made, but with poor results. Therefore, published literature became the main source of information for this report. The report is also focused on PV systems as they are more widely used than wind or hydro in small to large stand-alone systems. Especially in small-scale stand-alone systems the basis is always solar electricity, while wind energy is considered as an auxiliary power source. Wind energy is targeted to large-scale applications, concerning direct connection to the grid. So operation of lead-acid batteries under solar conditions was mostly considered. Additionally to the recording of field experience, an inquiry of the factors that affect the ageing of batteries in RES applications was made, as found in the literature.

The results and the analysis presented in this report have been prepared by CRES (HE) for the EC founded project ENK6-CT2001-80576 entitled "Development of test procedures for benchmarking components in RES applications, in particular energy storage systems", with contribution of literature information and comments coming also from the other partners of the project.

III. Literature survey

III.1 LEAD ACID BATTERY AGEING

Two types of battery failures can be distinguished:

- Sudden or catastrophic failure, characterised by a sudden inability to recharge and deliver electrical energy
- Progressive deterioration in performance, characterised by a gradual decline in capacity.

Sudden failures can be caused by manufacturing faults and improper handling or can be the result of slow ageing processes. This failure mode occurs if there is an interruption of the current path, i.e. because of a corroded cell or intercell connector or a corroded terminal.

The main ageing processes that finally limit lead acid batteries lifetime are briefly reviewed.

III.1.1 Corrosion of positive grid

The metallic lead of the positive plate grid is oxidised slowly to lead oxide due to the potential of the positive plate. A lead dioxide layer is formed on the grid surface which penetrates slowly into the grid, combined with growth of volume [1]. Corrosion is a side effect that occurs continuously in lead-acid batteries and finally limits the useful life. The rate increases with increasing temperature and strongly depends on the positive electrode potential. It is minimal for cell voltages around 2.23V, and increases rapidly at cell voltages below 2.0V and above 2.4V. The rate of corrosion and the rate of grid growth are also influenced by manufacturing parameters such as alloy composition and casting conditions [2].

Corrosion leads to grid and plate expansion, and capacity loss due to loss of contact between the active material and the grid [3]. It also leads to increase of ohmic resistance, as a result of the reduction of the cross-section of the grid and of the smaller specific conductivity of the corrosion products than metallic lead. Very often battery life is limited by a failure which occurs when the grid due to its expanding in length comes into contact with the negative top-bar to create a short-circuit [2,4].

Positive grids in lead-acid batteries for long service-life are oversized to compensate for corrosion attack.

III.1.2 Irreversible sulphation

Irreversible sulphation is the formation of large lead sulphate crystals on the plates of a lead-acid battery.

When a battery is discharged fine crystals of lead sulphate which are reconverted during recharge are formed on both electrodes. The size of the crystals increases with increased time spent at low acid concentrations, occurring at low state of charge [5]. Large crystals reduce the true surface area and result in longer charging periods and lower efficiencies during recharging [5,6]. When a battery remains in low state of charge for a long period (weeks), the lead sulphate is transformed into large crystals that are not easily reconverted during recharge. The part of the active mass that is irreversibly sulphated results in loss of active material and loss of capacity.

Lead sulphate has approx. half the density of either lead or lead dioxide and its presence therefore leads to mechanical strain in the porous active materials on either the positive or negative electrode. As with almost all other ageing effects, some existing deterioration accelerates the ageing even more, so that this is a self accelerating process.

Sulphation is more frequently observed on the negative plates and is promoted by elevated temperatures. However, to remove sulphation during charging, higher temperatures can be beneficial because they cause a faster dissolution reaction. The negative electrode is usually oversized to the positive and the full recharge of the electrode may be difficult. The full recharge of the negative electrode of VRLA cell may be also hindered by the oxygen recombination cycle. Thus higher irreversible sulphation is frequently observed at the negative electrode.

Measures against sulphation are to have a surplus of electrolyte and a frequent full charge of the battery [5].

III.1.3 Degradation of positive active material (PAM)

During cyclic operation of batteries the conversion of lead and lead-dioxide to lead sulphate and the reverse is combined with changes in the structure of the active material and changes in volume. Such repeated transformations affect mostly the positive plate. They cause the positive active material to lose its initial structure and mechanical strength, lose contact between individual particles of active material, and reduce electrical performance, as parts of the active material become electrically isolated. Deep discharges at low rates, that utilize most of the active material, have a detrimental effect on the degradation or 'softening' of positive active material.

Especially at deep discharges and strong gas evolution part of the 'softened' active material may fall off the plate as fine particles. This process is called shedding and is a characteristic ageing feature in flooded flat plate batteries under cyclic operation. Accumulation of the shed material at the bottom of the cell increases the risk of electrical short circuits between positive and negative plates. Tubular designs of positive plates are less susceptible to this mode of failure. In VRLA batteries active material cannot fall off the electrode due to immobilized electrolyte.

Degradation finally results in capacity loss due to a decrease of available active material. Batteries using high antimony alloyed grids are more resistant to degradation of PAM.

The term premature capacity loss (PCL) is often used to generally address this mode of capacity deterioration, though initially PCL referred to the rapid walk-down of capacity during cycling of early non-antimonial batteries ('antimony-free effect').

Evidence from experimental studies indicates that apparent density is the critical determinant of positive plate conductivity and performance, and that minimization of the progressive expansion of positive material during cycling is beneficial in terms of cycle life [7,8].

Batteries with antimony grids and tubular plates are known to have superior cycling performance. This is consistent with the presumable influence of porous material density, as both Sb-grids and tubular design restrict the expansion of porous material.

Other minor degradation and failure modes of batteries involve the following:

III.1.4 Degradation of negative plate

Degradation of negative plates is usually related to degradation of the expanders that are used to maintain a high inner surface, caused by operation at elevated temperatures or by reverse charging during deep discharges [5].

In VRLA batteries also a type of corrosion of negative top-bar is often reported, mainly in floating applications [1,2].

III.1.5 Degradation of separator

When a battery remains in low SOC for a long time, a failure mode related to the separator known as 'leading-through' of separator is promoted. In dilute electrolyte, due to high solubility of lead sulphate, thin lead fibres (dendrites) can grow from the negative plate through the separator and finally cause short-circuits with the positive plate.

Degradation of separators can also occur under conditions of persistently high battery temperature [9].

III.1.6 Water loss/thermal runaway

In vented batteries, a substantial amount of water can be lost during operation, caused mainly by secondary reaction of gas evolution, which can lead to a low level of electrolyte. As there is the possibility of refilling, if regularly carried out, this is seldom a life-limiting factor.

In VRLA batteries only a small amount of water is lost through recombination inefficiencies, grid corrosion and water vapour loss through the container, but there is no possibility of refilling. As a result, under severe overcharge and environmental conditions, water loss can lead to drying-out and limit lifetime.

Progressive water loss may affect other ageing processes, for example the rate of corrosion as a result of the increased acid concentration [9]. In VRLA batteries it also increases the recombination efficiency which leads to higher battery operating temperatures and increases the risk of thermal runaway [2]. Thermal runaway is defined as the critical condition arising during constant voltage charge in which the current and the temperature of the battery produce a cumulative, mutually reinforcing effect which further increases them and can lead to the destruction of the battery.

The rate of each failure mechanism and which will finally dominate is greatly influenced by the operating conditions, but also by the specific design and manufacturing details of each battery type. For example, VRLA batteries, due to recombination reaction, experience higher floating currents and positive plate potentials that influence the rate of grid corrosion. Depending on alloy composition and casting conditions, this can lead to a tremendous growth of the grid, which will eventually limit lifetime. Regarding operating conditions, corrosion is the most critical parameter for batteries at float applications and at operation in high temperatures, while sulphation and degradation of active material are mainly related to cyclic operation of batteries.

III.2. OPERATING CONDITIONS OF BATTERY IN RES APPLICATIONS

Batteries in RES systems often operate on a daily cyclic basis, which results in active mass degradation, and therefore batteries with good cycling performance are required for such applications. In applications where a long period of autonomy is required and there is a large seasonal variation of load or generation, batteries are sometime kept in more or less floating operation for months.

Operating conditions of batteries in RES applications, however, feature some characteristics that are not usually met in other applications. In conventional applications after a discharge there is always energy available to recharge the battery. In most cases there is also time to fully recharge the battery, despite the long time required to charge the last Ahs of capacity (5% to 10%) with a constant voltage charge. Under these conditions the charge regime can be optimally controlled.

In RES applications batteries are operating on a daily cyclic duty, with various daily cycle depths depending on the system design and type. The cycling is irregular, and usually there is a deep long cycle during the winter season. The battery state of charge is affected by the input energy which is generated by solar irradiation, and which is a stochastic parameter. The battery can operate in an undercharged condition for a long time, without full recharge. Even in hybrid systems, full recharge of the battery by a diesel generator does not occur frequently, as it is not efficient to operate the diesel for the long time and small currents required for the full recharge of a lead acid battery under constant voltage. The operating currents are low, usually on average around 0.2I₁₀. As a result of all this, batteries experience some special conditions that result in shorter lifetimes.

III.2.1 Operation at partial state of charge

A main characteristic of battery operation in RES systems is operation at partial state of charge (SOC). The battery is subject to cycles of discharge and partial charge at intermediate SOC. Due to the limited energy and time available it never reaches full SOC and gassing voltage for a long time. This mode of operation leads to stratification of the electrolyte, to the formation of large lead sulphate crystals which are difficult to recharge and to the development of differences between single cells.

III.2.1.1 Stratification

Battery cycling at partial state of charge leads to stratification of the electrolyte. The electrolyte at the bottom of the battery has a higher acid concentration than the electrolyte at the top. A too low upper voltage limit at charge can lead to this situation too. The concentration differences are growing from cycle to cycle, especially in tall cells. After a few weeks of operation at partial state of charge, differences in specific gravity in the range of 0.1 g/cm^3 can develop between the electrolyte reservoir above the plates and below the plates [5,10,11,12]. The problem of stratification is mainly related to flooded batteries. In VRLA type the problem is reduced (but with no ability to recover).

Stratification is a serious problem. It causes uneven current distribution and stresses the lower parts of the plates, which experience higher active mass utilisation. By simulations it has been calculated that stratification in conjunction with small currents leads to undercharging of the lower parts of plates, with differences in 'local' SOC up to 30% [12]. This means that the lower part of the electrode is cycled at a lower SOC without full charge for extended periods, with increased risk of suffering from sulphation.

If no additional special equipment is used (acid circulation system), stratification in flooded batteries is prevented or recovered by overcharging. The gas evolution forms bubbles that mix the electrolyte and make the concentration uniform in the cell. Recovery requires extended heavy gassing of the battery at voltages at or above 2.4 V/cell for hours. Overcharge, however, should be applied for a limited time and in infrequent intervals to avoid excessive water losses and corrosion.

It is noted also that if the problem of stratification is eliminated, operation at partial state of charge for some time can be beneficial in terms of battery lifetime and efficiency due to the reduced overcharge that the battery receives [10].

III.2.1.2 Irreversible sulphation

During partial cycling, the size distribution of crystallites changes to fewer and larger lead sulphate crystals. This leads to mechanical stress, and more importantly to longer charging times as the dissolution rate of lead sulphate crystals is the limiting factor at the end of charging. Sulphated batteries still have lead sulphate material left

even after the charge has been terminated. This is due to the fact that the end-of-charge criteria used in chargers are not sensitive to detecting sulphation.

III.2.1.3 Single cell differences

Another consequence of the fact that usually there is no time and energy available for the full recharge of the battery is that differences between single cells develop over time. Each cell has its own individual characteristics, resulting in differences in SOC and uneven sharing of total terminal voltage among cells during operation. If there is no equalisation process, these differences grow from cycle to cycle, causing deep discharge of the weakest cell and overcharge of the other cells. Especially in high voltage battery banks, which are often met in PV-hybrid applications, there is an increased probability for a single cell failure. After a single cell failure the whole battery bank does not operate properly, as the battery charger voltage limits are wrongly shared among cells.

Restoring of single cells to an equal state of charge can be achieved also by overcharge if no additional special equipment is used. Usually, after a charge of the battery at a constant potential (usually 2.35 - 2.45V/cell for fast recharging) an equalisation step of charging at a slightly higher voltage (2.5 - 2.6V/cell) with a small current is applied, to allow all cells in the battery string to reach full SOC. The equalisation step also should be limited to short durations and only applied in infrequent intervals.

III.2.2 Operation at low SOC

As the battery SOC in PV-hybrid applications is affected by solar irradiation, for periods of low sunshine, the battery can remain in low SOC for a long time. Caused by the low currents the SOC can be very low (deep discharge), if no proper end-of-discharge criteria either by SOC or voltage is defined.

This situation gives rise to related failure mechanisms of sulphation and 'leading through' of separators, which are further accelerated in stratified cells.

The accumulated sulphation is not easily removed, due to inadequate charging related to solar irradiation. Analysis of battery plates after operation in PV applications has shown that sulphation of both plates is the most common problem [13].

III.2.3 Operation at wide temperature variations

Batteries in RES applications are often exposed to wide temperature variations. Temperature affects the rate of the chemical reactions. The rate of corrosion and gassing is approximately doubled for each 7 to 10 K rise of temperature. If the battery is expected to operate in a wide temperature range, a temperature compensation of the upper voltage limit should be applied (-3 to -6 mV/K per cell), to reduce rate of

gas evolution and corrosion at high temperatures and to facilitate charge at lower temperatures.

III.2.4 Battery abuse

RES systems also are often installed at sites not easily accessible causing an extension of the maintenance intervals, or they are installed for users with no technical knowledge. Excessive water consumption in these cases can lead to a too low level of electrolyte. It has often been experienced that the user intervenes to the installed system, by for example bypassing the charge controller and connecting extra loads to the batteries.

III.2.5 Solar charging

Battery performance is largely influenced by the operation of the charge controller. A charge controller is an electronic circuit which monitors the charge in and out of the battery and, based on a set of voltage thresholds, regulates current flow in order to limit overcharge and overdischarge. It is obvious from the above that the operation of the charge controller is critical and that advanced techniques are required to compensate all factors affecting battery life. A too low value of a single upper voltage limit will give rise to sulphation and stratification while a too high value will give rise to excessive corrosion and water loss.

Field experience has shown that in PV applications a battery is charged inadequately without reaching full SOC even in periods of high sunshine [14,15,16,17]. This leads to a gradual decline of the 'useful' capacity to the user and operation of the battery at lower 'true' SOC. Initially this is not a true capacity loss, as full capacity can be recovered by an extra charging, but it affects the ageing mechanisms and long-term performance if these extra charging events are not performed frequently.

This incomplete recharge and decline of capacity can be partially explained by the limited available charging time (few sunshine hours per day) which is not sufficient for restoring the battery to a high SOC. Under constant voltage charge the current decreases as SOC approaches 100%, and, conventionally, a full charge is considered achieved when the current does not show any appreciable change for a couple of hours. This requires several hours, and is also hindered by the presence of any sulphation on battery plates. So in many PV applications full charge of a battery is not easy to be achieved.

The decline of capacity may be contributed also to stratification and sulphation caused by a partial recharge.

Moreover, the type of the solar charge-controller and the voltage thresholds used influence the decline of capacity and play an important role in the efficient charge of the battery. Two basic methods are used for regulating the current during the charging procedure in PV chargers, interrupting or ON-OFF charging and constant voltage charging.

ON-OFF controllers are simpler and cheaper, so they are frequently used worldwide in small applications. This type of controller either allows full array current to the battery or switches current off when an upper threshold, called the voltage regulation (VR), has been reached. When the terminal voltage falls below a threshold of voltage reconnect value the controller switches to the ON mode to charge the battery. As a result, after reaching VR value, the controller actually cycles between ON and OFF mode at a low frequency. This mode of operation has been found to lead to substantial decline of useful capacity. The reason for such behaviour indicates that during operation of continuous ON-OFF cycling of the charge controller, solar energy is not efficiently utilised and valuable amounts of useful energy that could be accepted by the battery, are lost. It is beneficial therefore to extend the time of continuous ON mode, before the VR is reached. This depends not only on the value of VR, but also on the available current and the internal resistance of the battery, not favouring systems designed with a low level of autonomy. For this type of controller a higher value of VR may be generally accepted than for constant voltage controllers, where the battery is held at this value for a longer time. The decline of useful capacity has been found to have a strong relation with the voltage reconnect value [15,16].

The other most common PV charge controller is the constant voltage charge controller of PWM type (pulse-width modulation). For this type of controller, the value of reconnect voltage is very close to the VR, and the controller actually switches between ON and OFF operation at a high frequency (usually in the range 5 to 100Hz). This improves the solar energy utilization and reduces the decline of useful capacity under solar charging. There is a trend, however, for using high VR values (when this is applicable, as in flooded batteries) for better utilisation of solar energy and fast recharge of the battery.

In order to achieve fast and efficient charge, and at the same time to prevent the battery from harmful conditions for lifetime expectancy, such as extensive overcharge, stratification etc., more complex charging algorithms are required. These may include the utilisation of several voltage thresholds, fixed or adjustable, combined with timers, to allow e.g. for various steps in the charging procedure, regular overcharge etc.

III.3. BATTERY LIFETIME EXPECTANCY

III.3.1 Battery types

Batteries are classified roughly in terms of the following applications:

- SLI (Starting-Lighting-Ignition) (approx. 50 % of the market)
- Traction (e.g. forklift trucks, about 25 % of the market)
- Stationary (approx. 25 % of the market)
- Solar (approx. 1 – 2 % of the market)

Stationary batteries cover a wide range of applications, from stand-by (float) to cyclic use.

SLI and stationary batteries for stand-by use are used only for a short duration. They are characterised also as shallow cycle batteries, and are usually avoided in PV systems.

Traction and stationary batteries for cyclic use are designed for deep-discharge, high cycle life.

Solar batteries in developing countries are mainly modified SLI batteries, designed with thicker plates, to meet the special conditions occurring in small PV applications. In Europe solar batteries are also often modified stationary batteries with tubular plates. Therefore it needs to be examined very carefully, what the manufacturer means and sells as a “solar battery”.

The lifetime of a battery in cycling applications is mostly determined by its cycle life, i.e. the number of cycles a battery can withstand before the end of its life. Battery capacity is gradually decreasing with cycles, with an end of life to be reached when the capacity falls below a given value, usually 80% of the rated capacity.

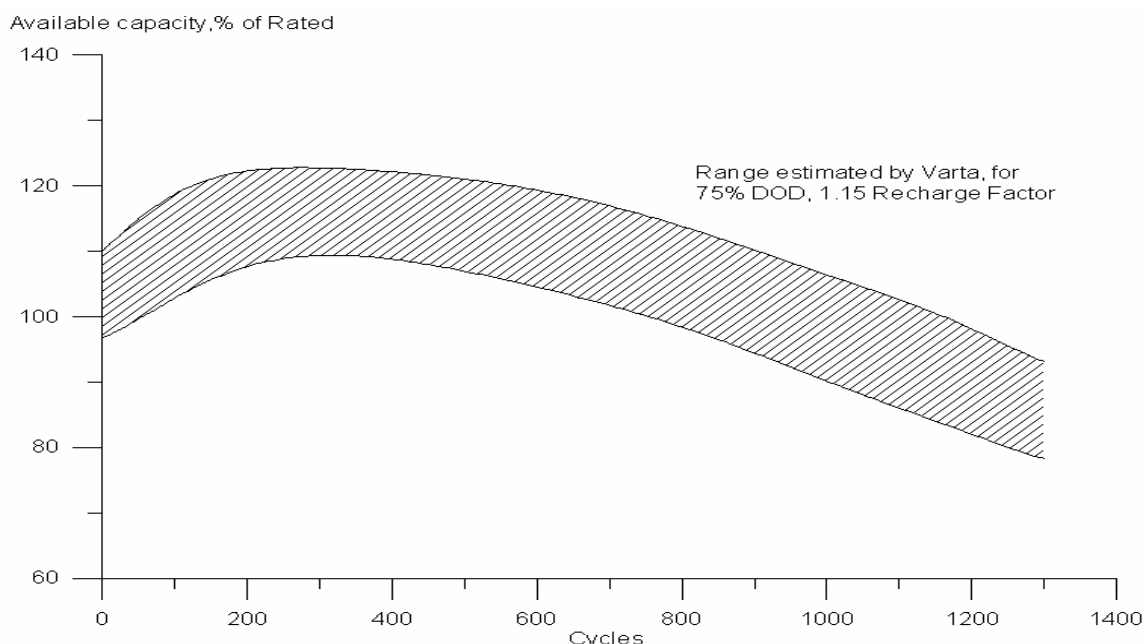


Fig 1. Variation in Available Capacity with Cycling, as estimated by Varta [18].

Manufacturers usually give cycle-life data via curves of cycles vs. DOD or via values of cycles at specified DOD (at specified temperature). This gives the battery cycle-life when operating with repeated cycles of discharges at the same specified DOD and full recharge.

The cycle-life is inversely related to DOD and temperature. A typical curve of cycles versus DOD is shown in Fig 2

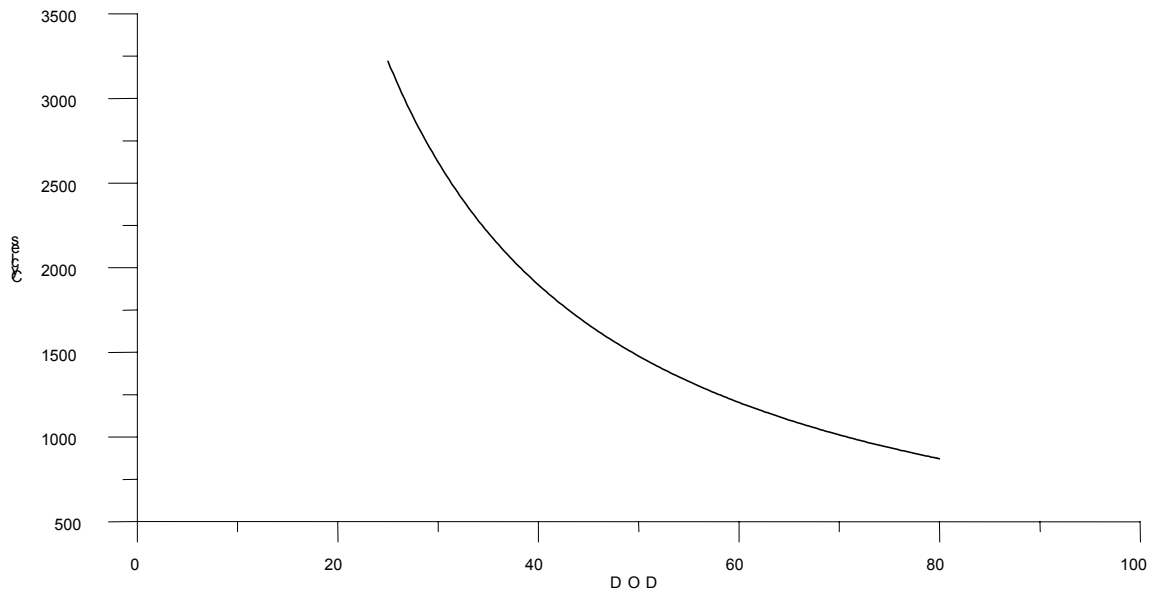


Fig 2. Cycle Life as a Function of DOD.

A rough estimation can be made that the product of cycles and DOD is constant [19]. The result is the nominal cycling capability, e.g. number of equivalent 100% nominal capacity cycles.

Lead-acid batteries are designed to meet specific application requirements, and so a variety of cycle-life characteristics exists. SLI batteries have a cycle life of about 100 nominal cycles, while with solar design cycle life is improved to 200-300 nominal cycles. Traction batteries usually have cycle-lives of over 1200 nominal cycles.

A list of various types of batteries suitable for RES applications and their cycle-lifetime as reported by their manufacturers' is presented in Table 1.

The calendar lifetime of a battery under floating conditions is another limit of battery lifetime, related to corrosion. Due to corrosion's dependence on temperature, the battery lifetime is strongly related to temperature operating conditions. Battery floating lifetime is usually considered to half for each 7 to 10 K rise of temperature. Solar modified SLI batteries have a floating lifetime around 5 years [20]. Solar modified stationary batteries usually have lifetimes under floating conditions of more than 10 years.

Table 1. Cycle life data of various batteries.

Battery Manufacturer.-type	Battery details	Cycle-life	Conditions (DOD)	Nominal cycles
Sunlight SPA (greek manufact.)	VRLA AGM lead calcium grid alloy	210 450 920	100% 50% 30%	210-280
Fullmen Solar	Vented Tubular, low antimony	1500 2000 3500	75% 50% 30%	1000-1125
Fullmen TXE stationary batteries	Vented Tubular	1000	75%	750
CFEC Steco3000	Solar battery, MFX* alloy	250 500 1500 5000	80% 50% 19% 8%	200-400
Sonnenschein dryfit solar	VRLA, gel flat	400 1250 2000	100% 40% 30%	400-600
Sonnenschein dryfit solar block	VRLA, gel flat	1200 2000 4000	100% 50% 30%	1000-1200
Sonnenschein A600 solar	VRLA, gel tubular	1600 3000	100% 50%	1500-1600
Sonnenschein A500C	VRLA, gel	800	100%	800
GNB Absolyte IIP Photovoltaic	VRLA-AGM Pos-MFX* grid alloy Neg-lead-calcium grid alloy	1200 5000	80% 20%	960-1000
GNB Absolyte XL	VRLA AGM	1200	80%	960
GNB 12-5000X Photov. Reserve Battery	VRLA AGM Pos-MFX* alloy Neg-lead-tin	300 600 1000	80% 50% 20%	200-300
GNB RC12-110 Photov. Reserve battery	Vented, lead antimony	280	80%	230
GNB OpzS-block battery	Vented Tubular- low antimony	900	80%	720
Neste-Naps A-series for PV applications	Vented Tubular	800 2000 10000	50% 20% 5%	400-500
SEC Solar POWR Battery	Vented -Flat plate -low antimony	2000 2400 4200 5500	80% 50% 20% 10%	600-1600
SEC Cellyte Block-gel	VRLA, gel	300 600 1100 2100	100% 80% 50% 10%	210-550

*MFX: Special grid alloy

Battery Manufacturer.-type	Battery details	Cycle-life	Conditions (DOD)	Nominal cycles
SEC Microlyte	VRLA	200 400 900	100% 50% 30%	200-270
Accu-solar 140	Vented	200 500	70% 50%	140-250
BAE Nova solar Block	VRLA, gel tubular	550 1000 2000 6000	80% 50% 30% 10%	440-600
BAE Solar OpzS	Vented,tubular	1500 5000	80% 20%	1000-1200
BAE Solar OpzS-block	Vented, tubular	1200 4000	80% 20%	800-960
Hagen CSV	VRLA gel, tubular Neg grid:copper	1200	80%	960
ERGON (greek manufacturer) Varta OpzS-Solar	Vented –tubular plates, low antimony <3%	>1200 >2000 >4000	80% 50% 20%	>800-1000
Tudor EAN	Vented Tubular	1200	80%	960
Tudor SGV-S	VRLA gel Tubular, lead- calcium	2000 3000 5000	75% 55% 46%	1500-2300
Trojan L-16	Vented	750 2000	75% 30%	560-600
Trojan T-105	Vented	1000 2000	75% 40%	750-800
Baren SGi Solar	Vented	300 450 700 1200	80% 60% 40% 20%	240-280
C&D VRSolar	VRLA	1600 1000 800 500	30% 60% 70% 90%	450-600
C&D CPV PV batteries	Vented Low antimony / selenium	6000 1500- 2000	20% 80%	1200-1600
C&D ORION	VRLA	2700 1500 1200 500	20% 50% 80% 100%	500-960
C&D Liberty2000	VRLA, Proprietary Calcium Alloy	2000 4000	50% 20%	800-1000
Northwest Energy Storage Hup Solar-One	Vented ,High Utilization Positive Positive Teflon/Lead Antimony	2100	80%	>1680

III.3.2 Classes of PV-hybrid plant operation

Working conditions of batteries in PV-hybrid systems can have large variations, depending on the type of system, the design, the weather conditions and load.

A systematic effort to group operation into classes was made in [21,22]. From the study of various systems in Germany four classes were distinguished. Characteristics of each class concerning solar fraction, storage size (in days), currents, daily cycle depths and a typical number of equivalent battery cycles per year (calculated as the total discharged Ahs from the battery in one year divided with the nominal capacity) are shown in the following table.

Table 2. Characteristics of classes of PV-Hybrid plant operation.

Class	Solar fraction (%)	Storage size (days)	Currents	Daily depth of discharge (DDOD)	Typical equivalent cycles
1	100	>10	Small	2-5 %	15
2	70-90	3-5	Small	10-20 %	59
3	About 50	1-3	Medium	About 30 %	138
4	<50	About 1	High	>30 %	171

Typical conditions of battery operation during one year, regarding the SOC of the battery are shown in the following figures for each class.

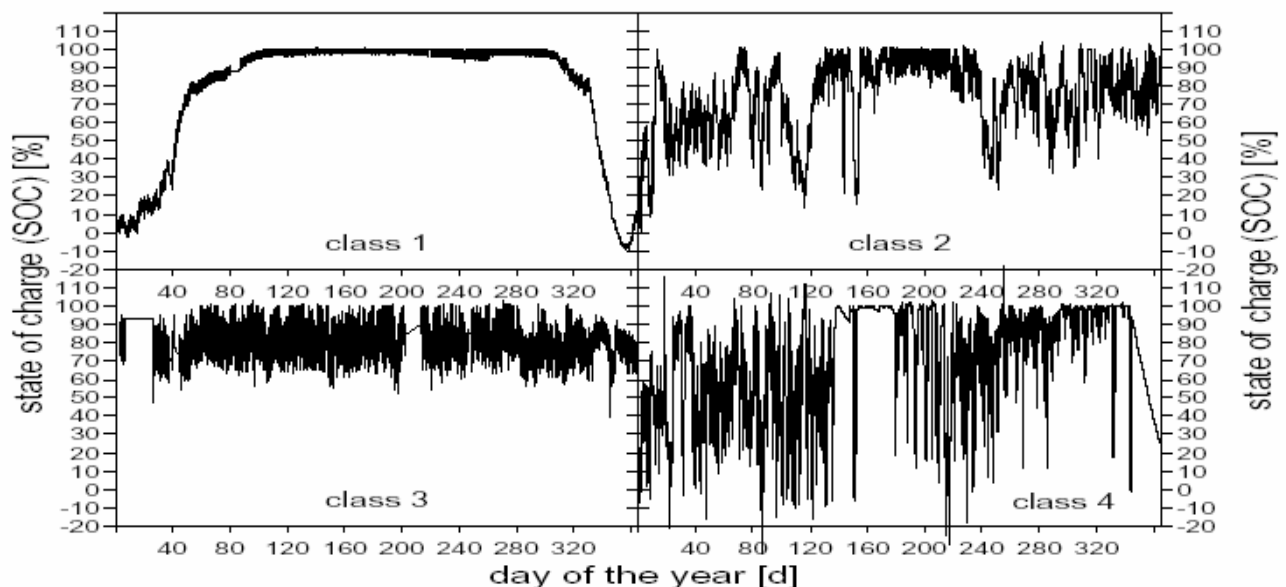


Fig. 3. Typical SOC variation during one year, for the 4 operation classes of PV plants [22].

Class 1 systems, which are pure PV (100% solar fraction), are characterised by one yearly cycle, with the battery remaining a long time in low SOC and a long time being in almost floating operation.

Other classes (hybrid systems) do not experience yearly cycle due to the utilization of other power sources. In class 2 systems, the battery is cycled at different SOC, including low SOCs, while in class 3 systems the battery is cycled at favourable SOC. Operating currents for class1 and class2 systems are usually below $0.25 I_{10}$.

III.3.3 Lifetime expectancy in RES applications

For an estimation of the lifetime expectancy of a battery in an application the data available by the manufacturers should be used. As the operating conditions in RES applications have large variations, and so have battery characteristics, lifetime can be limited by either the cycle-life of the battery or by its floating service-life, so both should be considered.

The data given by manufacturers, however, refer to optimum conditions and should be considered as upper limits only. Cycle-life data for various DODs are obtained from regular cycling of batteries with full recharge after each discharge. The special conditions in RES systems with irregular cycling and mostly an incomplete recharge, affect the ageing of batteries and result in a reduced actual cycling performance. The floating service-life, which represents the resistance to corrosion, refers to operation of batteries at optimum conditions regarding floating voltage and temperature. In RES applications, batteries spend more time at other voltage values, depending on the type of system, and operate definitely at various temperatures, which results in shorter lifetimes. On the other hand, in practice in most RES applications the battery can be used far below the theoretical end-of-life strict criterion of 80% actual capacity without major complains from the user.

Nevertheless other factors, such as deep discharges, charge controller operation, intervals between full recharges etc., have a large influence on lifetime.

A simple procedure for the estimation of battery lifetime in PV systems has been presented in [20]. It requires only limited data such as cycle-life and floating service life of a battery, plus site annual average ambient temperature and daily average DOD (which is related to days of autonomy of the system). By implementation of this method for pure PV systems, the following were concluded:

- In systems utilizing high cycle-life batteries (tubular vented), especially in systems having an autonomy of more than 5 days, the battery lifetime is controlled by the float service life (resistance to corrosion), and usually a value of more than 6 years is expected. In these systems the battery operating temperature is the critical parameter, while end-of-charge voltage seems to be an important parameter also. Corrosion is also the determinant factor in very shallow cycling applications, independent of type of battery.

- In systems utilizing low cycle-life batteries (flat plate solar), especially in cases with less than 5 days autonomy, battery lifetime is more likely to be controlled by the cycle life. In this case a service life of 1.5-3 years is expected. (An estimation of a float lifetime around 5 years at 20°C for solar batteries has been used).

The implementation of this procedure also requires the use of some reducing factors in order to compensate for the special operating conditions in PV systems, such as irregular cycling, opposed to regular cycling used to obtain cycle life data, and for operation at various voltages, opposed to the optimum floating voltage used to obtain float life. Another approach is to use cycle-life data resulting from cycling of battery under conditions resembling those of a PV application. A cycling procedure has been proposed in the recent IEC 61427(1999-11), "Secondary cells and batteries for solar PV energy systems. General requirements and methods of tests, with shallow cycling at both low and high SOC". This, however, is intended to be an accelerated test, performed at 40°C, and test results for various types of batteries according to this standard are not yet available.

A more accurate prediction of battery lifetime can be done by taking into account the various DODs of cycles and the various temperatures during battery operation. This is accomplished with the use of time-step simulation and mathematical models for the battery lifetime depending on operating conditions, as e.g. [23,24,25]. Most of the programs, used to simulate the performance of PV systems use models for battery lifetime prediction that take into account both the wear of battery from each cycle, depending on cycle DOD, and ageing through corrosion, depending on operating temperature. By using such a commercial simulation, the lifetimes of a low cost battery (Battery1) and a stationary tubular battery for cyclic use (Battery2) have been estimated for two systems resembling class 1 and class 4 respectively. The results obtained are presented in Table 3.

Table 3. Results from simulation.

Battery	System	Estimated lifetime
Battery1	Class1	4.7 years
Battery2	Class1	11.5 years
Battery1	Class4	1.6 years
Battery2	Class4	4.5 years

However the ageing effects caused by the special PV conditions are not taken into account, and usually battery lifetime is overestimated. Specific simulation programs with emphasis on battery ageing models have been developed by researchers, which take into consideration also effects such as stratification, sulphation, corrosion rate etc. according to operating conditions [26],[27]. These tools give more realistic results, and allow also the testing of several charging strategies and their effect on battery lifetime. For example, for one specific case studied in [26], best results concerning lifetime were obtained with an end-of-charge voltage around 2.35V/cell and a gassing interval of more than 2 weeks. However further work is required for the validation of such models through real applications.

III.4. FIELD EXPERIENCE

Information on lifetime of batteries in RES applications is not very often presented in the literature. The information is difficult to acquire as systematic long-term monitoring of the plant is required. The end of life of a battery usually is not determined by the criterion of an actual capacity value lower than a threshold, as this requires a capacity test, which is not easy to perform in the field. Therefore, the end of life is determined empirically, usually when the battery cannot fulfil its scope anymore.

The reported lifetimes also are difficult to evaluate and compare without knowing the battery history concerning all factors affecting lifetime, as battery lifetime is greatly influenced by operating conditions. Special operating conditions such as daily DOD, temperature, charge-controller limits and charging strategy, malfunction of any peripheral component etc. may lead to large variations of the resulting lifetimes. That is why a wide range of reported results are often found and sometimes contradictory to each other. In addition it would require measuring the capacity of the battery after its replacement and before disposal and it is necessary to know what the capacity was when the battery was new. Some solar batteries are considerably over dimensioned!

First experience came from the demo projects founded by the EC [18,28]. These were usually relative large 'professional' PV or hybrid plants installed all over Europe in the early '80s, utilizing large strings of battery banks. All of the batteries used were vented, most of them of flat plate and some of tubular positive plate construction. The battery charge control method, used in the plants, is of the constant voltage limiting type with the current tapering when the battery voltage reaches the preset voltage limit. In some of the plants an array shedding approach has been adopted, by switching array subgroups on and off for controlling the charging procedure.

After more than six years of operation the initially installed batteries were still in use. The main problem, up to then, has been single cell failures, featuring mainly internal short circuits or low capacity. In two plants with simple on-off control of the entire PV array, a larger percentage of cell failures (10%), was encountered. A large number also of cell failures was due to case cracking (in 3 plants), probably due to corrosion and growth of positive plates. In one plant 20 cells (out of over 100 cells in series) were damaged due to explosions of several cells. Primary cause of these failures was concluded to be the blockage of the small holes in the vent plugs which increases internal pressure as a result of continuous float charging by a rectifier. Proper use of rectifiers however, used to recharge batteries from auxiliary sources, like wind and diesel generators, or from the grid, showed to improve performance and lifetime of batteries.

In the framework of the EC founded project JOU2-CT92-0120, entitled 'Concerted action on PV systems technology-PV plant performance assessment', several European PV plants were evaluated. The results of evaluation from five PV plants in Greece have been presented in [29]. The PV plants were installed in late 80s, ranging from 3 to 28 kWp. The batteries were of the vented type and were subject to rather intensive cycling, as the plants were used for the electrification of remote communities on a permanent basis. After 4 to 8 years of operation the batteries were still in use, with no major complains by the users. The more recent ones were in good

state of health, while older ones (6-8 years old) were in rather poor condition, presenting positive active material deposited on the bottom of most cells and low electrolyte densities.

In the same project, performance of several PV plants has been assessed [30]. Many of these plants were professionally designed and installed through EC projects, and a lot of batteries installed in these plants have presented long lifetimes. Batteries installed at an alpine refuge (Refuge des Evettes) in France were replaced after 13 years of operation, due to freezing of battery during the winter. They were operating only during the summer season at a daily DOD less than 10%, while temperature ranged in -30° to 15° C. Batteries of the PV plant of Zambelli in Italy, used to supply power to pumping station, operated 10 years after installation at a capacity of about 50%. A real-time monitoring system of battery and cell performance (2 strings of 108 cells) allowed for early diagnosis of cell deterioration and replacement. Average daily DOD was in the range 13-17%, while batteries were charged up every morning before the pump inverters started.

Other work for the evaluation of battery lifetimes in PV systems was carried out by CSIRO, including laboratory and field tests [31,32]. Laboratory tests included cycling of various types of batteries at two different profiles simulating operation of PV systems. A 7-day profile, with gradual decrease of SOC to 30% over 7 days, then a return to full SOC, and a more intensive 1-day profile, with gradual decrease to 25% and then a return to 100% on a daily basis, were used. Results from these laboratory tests showed that AGM batteries had a low performance (less than 30 weeks for 7-day profile) due to heavy sulphation of positive plates, and so they are not well suited for such applications. Lower performance of AGM batteries under PV cycling has been also reported in [33] and [34]. Flooded tubular and flat plate batteries as well as gel batteries were found to be more suitable to such applications, giving lifetimes from 100 to 300 weeks, before reaching 75% capacity, under 7-day profile. For flat plate batteries, it was concluded also that the plate thickness is an important parameter for long cycle-life besides the grid antimony content. Major failure modes for flooded batteries were degradation of positive active mass and shedding, then corrosion, and for flat plate batteries also sulphation of positive and negative plates. For gel batteries with flat plates, similar failure modes as for flooded type batteries were observed, while for tubular-plate design capacity loss was mainly due to sulphation. Lower lifetimes were observed for the 1-day profile (70 to 90 weeks), with shedding being the major failure mode for flooded type batteries, and degradation of positive active mass, corrosion and sulphation of both plates for the gel type batteries. In the field, results are reported from a PV system installed in a small family home. The initial battery bank consisting of flooded flat-plate low Sb batteries, failed after 121 weeks (2.3 years) due to intensive corrosion and growth of positive grids, resulting in short-circuits. It was replaced by a gel type flat-plate battery, which performed satisfactorily after 5 years of operation.

Results from a systematic examination of a large number of batteries taken out of the field from four specific groups of PV applications in the Netherlands were presented in [35]. Flat plate Pb-Ca batteries used in the maritime sector in buoys and beacons with daily DOD less than 1% presented no problems in operation for 8 to 10 years, though some batteries suffered from sulphation. Flat plate low antimony Pb batteries in the recreational and agricultural sector used in summer with daily DOD between 2

and 10% presented low to modest capacity loss after 4-5 years, due to sulphation. In the demo PV-hybrid project of Terschelling, the rod plate Pb batteries with low antimony grids presented premature deterioration after 8 years of operation, due to severe corrosion. Finally in barges and the house boat sector, flat plate and tubular Pb batteries with low and high Sb, used for domestic electricity supply with a daily DOD between 10 and 40%, presented premature deterioration, some even after 2.5 years, mainly due to sulphation.

Results from the evaluation of thirty stand-alone systems in Germany were presented in [36]. Most of the systems were installed around 1990. More than half of these systems concern lodges and huts belonging to the German Alpine Club used only during the summer months. The rest of the systems operate throughout the year and concern various applications from private residences to fully operational farms. The average number of battery replacements per year in these systems was reported to be around a value of 0.15. This can be interpreted as an average lifetime of batteries of 6.6 years. The average operation time of the systems under concern, however, was about 7 years, with a lot of systems having operation life shorter than this value. In another report also [5], lifetimes of 2-3 years for car batteries and 3-7 years for batteries in hybrid systems, have been reported, as a result of experience from a number of PV-hybrid plants in Germany.

Experience from the 9-year old operation of solar home and street lighting systems in Sukatani, Indonesia is presented in [37]. A large number of such systems has been examined. Solar home systems included 2 PV panels of 40Wp, one battery 100Ah flooded flat plate with low Sb, designed for shallow cycling like solar energy systems, and a charge regulator. Average daily DOD was 12.7% for solar homes and 5.7% for street lighting systems. Most of the systems had used up two batteries. The initial solar batteries were replaced by cheaper car batteries, some of them of lower capacity. Average lifetime of solar batteries was 4.2 years, while car batteries had an average lifetime of 3.5 years. End of life capacity however was not known. One discharge test performed on a 3.5 years old solar battery gave a 68% actual capacity.

A large number of batteries used in Mexico as part of PV lighting kits (PV 50Wp, electronic charge controller of the on-off shunting type, 60 W load, and a lead acid battery, mostly flooded car type), has been evaluated in [38]. A grading technique was adopted using criteria based on visual inspection, voltage measurements and density measurements where applicable. In the above systems, batteries older than 18 months were graded as "fair", indicating a life expectancy of about 2.5 years.

Experience from solar home systems installed in Bolivia (PV 45Wp, 5 lights, charge regulator and battery 120Ah) is presented in [39]. The batteries were supposed to operate at a daily DOD of less than 10%. Most of the initial batteries were still in use, giving an operational time of 6-9 years. Some capacity tests however have shown that the batteries were operating at an actual capacity far below 50% of the rated value. The main degradation mechanism was strong corrosion due to overcharge.

A list of battery lifetimes in various installations all over the world has been presented in [20] and updated in [40], to validate the battery lifetime prediction model proposed by the author. The installations concern pure PV systems, and the battery lifetime theoretically is predicted to be determined by the temperature-dependent corrosion in

all systems. The reported lifetimes are in good agreement with the predicted values according to the temperature at the site. In 13 systems utilizing tubular batteries with regular load (mostly telecom applications with more than 4 days autonomy), most of the initial batteries are in use, presenting lifetimes of over 6 years (for 8 systems over 8 years). Lifetimes of vented tubular batteries for several systems of variable load, installed at 6 locations, have been presented also. The lifetime of replaced batteries (5-7 years) is in close agreement with the prediction based on location temperature. The lifetime of batteries in use (>7 years) is approaching or has exceeded the predicted value.

The Greek Navy operates about 1000 solar powered lighthouses and beacons. Most of these systems use maintenance free batteries, typically 100Ahs, which are charged, mostly unregulated, by solar panels, 20-50Wp, and which operate at a low depth of discharge, about 2%. Battery replacement is scheduled every 4 years maximum. There are complains however that old batteries have problem in covering the load during subsequent cloudy days. In a larger lighthouse at Lithari, utilising a 4.7kWp PV array, the battery bank, composed of vented tubular stationary cells, operated for 10 years.

Operation time of about 10 years has been achieved by the battery bank installed at the hybrid system of the Simonos Petra Monastery at Mountain Athos, Greece. The battery bank of 400V, 1000Ah is composed of stationary vented tubular cells. The stand-alone hybrid system concerns a PV power plant of 45kWp, a small hydro-plant of 40kVA and a diesel generator of 63kVA, with the diesel covering only a small fraction of energy (usually <10% per month).

Various collected information on battery lifetimes in RES applications, from literature or contacts, is finally presented in the following Table 4.

Table 4.1 Field experience

Plant	Battery lifetime	Battery type	Condition (at time of relevant report)	Other information
Europe 16 PV plants Installed early '80s [18], [28]	>6	Vented, mostly flat	In use Single cells replaced In 5 systems capacity<60%	30-300kWp 250-3000Ah
Greece 5 PV plants Installed 1987-90 [29],[30]	>4	Vented	4-6 years in good cond. 6-8 years in poor cond.	3-28kWp Electrification of small communities
Vulcano (IT) Installed 1984 [30]	8	Vented, tubular	Replaced in 1992 by new one, cells with cracked cases Poor performance after 5 years	80kWp Stand alone (SA) and grid- connected(GC) mode 40% DDOD
Zambelli (IT) Installed 1984 [30]	10	Vented	Several cells replaced	70kWp, pumping SA
Refugee des Evettes(FR) Installed 1979 [30]	12	Vented, tubular	Replaced in 1993 due to freeze	5kWp SA -30 to 15 deg C DDOD<10%, unused in winter
Gross Bessillon(FR) Installed 1986 [30]	8	Vented tubular	Replaced in 1994, in satisfactory condition	3.8 kWp +Diesel Telecom system 15% DDOD
Farm Pozoblanco (SP) [30]	>4	Vented	C<50%	12kWp +Diesel Operation at extreme conditions
Landenberger (DE) [21]	3		Replaced	
Street-lamp (DE) [21]	3		Replaced	
Self-sufficient house, Freiburg(DE) [21]	3 3.5	Vented, tubular	C10<75% C10<40%	
Haus-Langer (DE) Installed 1991 [21],[43]	8	Vented	Replaced	Isolated house, 1.8kWp,
Oberlinhaus (DE) [21]	6		Replaced	Youth center 1.5kWp
Rappenecker Hof (DE) [21]	4.5		Replaced	Isolated house, 3.8kWp
Brunnenbach (DE) Installed 1989 [21],[30],[43]	8	Vented,flat	Single cells replaced	10.4kWp + Diesel DDOD 25-30%

Table 4.2 Field experience

Plant	Battery lifetime	Battery type	Condition (at time of relevant report)	Other information
Biohof Stein (DE) Installed 1992 [21],[30],[43]	7		Stratification, sulphation	5kWp Hybrid
Solar tower (DE) [30]	3	Vented flat	Loss of capacity, 8/37 cells defects	12kWp GC with batteries for SA mode
Flanitzhuette (DE) Installed 1992 [41],[43]	>9	VRLA gel tubular	In use, good condition	40kWp, hybrid with gas engine SOC range:90-40% Regular full charge
Kindestagsstaete Niederrad (DE) Installed 1990[30]	>4	Vented, flat	In use, 8 of 108 cells with lower density	9.8kWp SA, GC
Talbot, Victoria Australia [31], [32]	2.3 >5	Vented flat low Sb Gel flat		
French island Australia [32]	>3	Gel flat		
Netherlands, maritime sector [35]	10	Flat Pb-Ca		DDOD<1%
Netherlands, agricultural sector[35]	5	Flat, Pb low Sb		2%<DDOD<10%
Netherlands, Terschelling Installed 1983 [30],[35]	8	Vented, rod plate Pb low Sb	Premature deterioration due to corrosion	Grid+PV(43kWp)+Wind 92/93 new design
Netherlands, house boat sector [35]	2.5	Flat and tub, low and high Sb	Sulphation due to undercharging	10%<DDOD<40%
Germany [5]	2-3 3-7	SHS car bat. Hybrid		Experience from about 50 systems
Germany [36]	6.6			30 SA systems
Sukatani, Indonesia [37]	4.2	Solar batteries, flat-vented		Solar Home Systems DDOD 10% approx.
Sukatani, Indonesia [37]	3.5	Car, flat-vented		Solar Home Systems DDOD 10% approx.
Bolivia [39]	6-9	Car batteries	In use, far below 50% of capacity	Solar Home Systems

Table 4.3 Field experience

Plant	Battery lifetime	Battery type	Condition (at time of relevant report)	Other information
Mexico [38]	2.5	Car batteries, vented		In PV lighting kits 555 batteries examined
13 systems various sites [40]	>6 >8 (for 8 systems)	Vented tubular	In use in 10 systems	Pure PV, 4-20 days autonomy, Regular load, mostly telecom
6 sites several systems [40]	5-7 >7	Vented, tubular	Replaced (2 sites) In use (4 sites)	Pure PV Variable load
Norway [40]	13	Solar, flat	In use	Pure PV Holiday cottage Aver. Temp. <10°C
Navigational buoys, USA[42]	6 3	Maintenance free, car Sealed		Charging by unregulated solar panels 10Wp
Switzerland1 [43]	3	Vented, tub	Replaced	PV+diesel DDOD:50-80%
Switzerland2 [43]	7 (1st) >5 (2nd)	Solar		PV for lighting DDOD 2-5%
Switzerland3 [43]	2	VRLA		DDOD 2-5%
Solar Lighthouses (GR) [43]	3-4	Maintenance free	Poor performance of old batteries	Charging mostly by unregulated solar panels, DDOD about 2%
Lithari (GR) [43]	10	Vented, tubular		4.7 kWp Solar powered Lighthouse DDOD about 10%
Simonos Petra Monastery (GR) [43] Installed 1993	>10	Vented, tubular	In use	Hybrid (PV 45kWp +Hydro 40 kVA +Diesel 63 kVA)
Denmark [44]	>4	VRLA, AGM	No capacity loss after 4 years	SA telecom application PV+Diesel Battery 650Ah SOC:100-60%

Table 4.4 Field experience

Plant	Battery lifetime	Battery type	Condition (at time of relevant report)	Other information
EVS Laichingen1 [43]	9 (360 cycles)	Vented, flat	Bad condition	48V, 120Ah DOD 15% With acid circulation system Single cells replaced at 5 th year
EVS Laichingen2 [43]	9 (360 cycles)	VRLA AGM, flat	Medium condition	48V, 143Ah DOD 15% Same system as 1 With charge equalizer
EVS Laichingen3 [43]	9 (360 cycles)	VRLA gel, tub	Medium condition	DOD 15% Single cells replaced at 5 th year
Sulina (RO) [43]	>5	Vented, tubular	In good condition 8 years expected	Hybrid (PV+Wind+diesel), DDOD:11%
Costinesti monastery (RO) [43]	>4	Vented, flat,SLI	In medium condition 5-6 years expected	PV+Wind DDOD<20%
Agigea (RO) [43]	4	Vented, tubular	Bad condition	PV DDOD<30%
Lampung,Indonesia [45]	1.6	Locally produced car battery	27% in bad condition	Solar Home Systems 100Ah
Swaziland [46]	2	Modified and ordinary car batteries	16% Worn out 10% low electrolyte 14% loose connections 7% corroded terminals	Solar Home Systems 60-100Ah

Table 4.5 Laboratory experience

Plant	Battery lifetime	Battery type	Condition	Other information
Ulm [33]	>5yrs 4yrs <1yr 5yrs	Vented flat Vented tub VRLA AGM VRLA gel	Corrosion Cell connection failure	Simulated cycling. Results of float test: Vented: no degradation VRLA: decrease in capacity.
Universitaet Stuttgart [34]	1.5 year of testing	Vented VRLA AGM VRLA gel	No degradation Capacity loss (cell failure) No degradation	Simulated cycling AGM fail probably due to large differences between cells, due to oxygen cycle VRLA: problem with drift of cell voltages
ZSW1[43]	6	Vented, flat		Simulated solar test DDOD 25% Acid circ. system
ZSW2[43]	3.5	Vented, tubular		Simulated solar test DDOD 25%
ZSW3[43]	1	VRLA AGM flat		Simulated solar test DDOD 25%
ZSW4[43]	6	VRLA gel, tubular		Simulated solar test DDOD 25%
CSIRO1[32]	Best:5.7 2 nd : 2.3	Vented flat		7-day profile
CSIRO2[32]	Best:4.6 2 nd : 2.5	Vented tub		7-day profile
CSIRO3[32]	2.1-4.2	Gel		7-day profile
CSIRO4[32]	1.3-1.7	Vented flat		1-day profile
CSIRO5[32]	1.3-1.7	Vented tub		1-day profile
CSIRO6[32]	Upto 1.8	Gel		1-day profile
Sandia1 [16]	800 cycles at 15% DOD	Vented, Flat, thin plates, 6% Sb pos.	7 systems>50% 2 systems>80%	7 systems outdoors testing, solar panel and resistor loads Temperature<35°C
Sandia2 [47]	1001 cycles equivalent to 2.74 years	3 VRLA types	Capacity loss 2-33%	Simulated Cycling
JRC1 [43]	2	Vented, solar batteries		2 systems, indoor test conditions draft IEC 62124
JRC2[43]	>2	Vented	In medium condition	1 system, indoor test conditions draft IEC 62124

III.5. FAILURES OF OTHER PV SYSTEM COMPONENTS

Besides batteries other components of PV-hybrid systems suffer also failures.

Experience from 30 stand-alone systems indicates that inverters and charge controllers are the components with the highest frequency of faults that require repair or replacement (20-30% of systems per year) [36]. This is also confirmed by the experience from large residential PV programs, concerning grid connected systems, where a percentage of 15-30% of systems suffer a failure or trouble each year [48]. In the majority of these failures the inverter is involved, while the solar generator has proven to be the most reliable component. The rate of inverter failures, however, tends to decrease in recent years as a result of technology maturing.

From the inspection of 200 systems from the German '1000-Roofs-Programme', the following problems, besides component weakness, have been reported [49].

System defects and deficiencies:

Installation problems	
Shading	41%
Unsuitable string fuses and overvoltage shunts	15%
Unsuitable insulation devices	56%

Operation problems	
Soiling of PV modules	12%
Loose terminal connections	5%
Corrosion and defects in solar generator mounting	19%
Solar generator cabling not mechan. fastened	24%
Defect decoupling diodes	<2%
Lack of heat dissipation of diodes	60%
Defective string fuses	4%
Defect surge arrester	<1%
Faulty modules (broken glass, open circuit, discoloration)	<2%

Most of the problems encountered during operation of a PV plant are related to the harsh environment (outdoors) that materials and components are exposed to, and to improper installation practices for such conditions. It is very usual that water leakage in junction boxes and of defects in connectors, cabling, diodes, etc. are reported after some years of operation [30,48].

A very frequent source of faults and damage is water penetration into junction boxes or terminal boxes. This can lead to insulation defects and corrosion of the connections, terminals and diodes. Most of these faults are caused by poor installation practices (inadequate sealing, wires lead into junction box from the top). However ambient conditions often lead to condensation of water and thus corrosion of connections and diodes.

Other causes for defective diodes, besides moisture and failing soldering connections, can be overtemperature or overvoltages induced by lightning.

Another cause of damage is presented by loose or broken connections. These seem to be caused mostly by poor workmanship during installation. However, these defects can be caused also by high thermal cycling which work the screwed connections loose with time. In some cases broken PCBs in junction boxes were reported.

Lightning strikes also have been reported to damage power conditioning and control/monitoring systems.

Very extreme weather and environmental conditions also have been reported to cause damages to PV components (heavy storms, snow, hail, salty environment).

The support structures generally remain in good condition. Screws, bolts and braces from stainless steel do not experience problems, galvanised steel may have problem with corrosion [18].

Soiling on the modules' surface can only result in a temporary small loss of output power, as it is a reversible effect. It is strongly site dependent, and also depends on array inclination and on type of module (frameless or not). The most critical part of the module is the lower edge. Usually, rain provides a good degree of cleaning for dust. In some environments, pollution can be more persistent, resulting in increased power loss (10% in 5 years reported in [50]), requiring more often manual cleaning. In the German '1000-Roof' program, soiling affected 10% of the systems, but with an average energy loss of less than 2%.

III.5.1 PV modules

The PV modules are the most reliable components of a PV system. Experience from a large number of small systems but also from large PV plants show a failure rate of PV modules usually less than 0.1% per year [48]. Faults in PV modules are usually located at module connection box.

During its lifetime (more than 20 years) however, the PV module shows a degradation, which depends on module type. Experience from tested crystalline silicon modules of old plants indicates small values of power degradation after many years of operation. In the Vulcano PV plant, 50 modules tested after 10 years operation had a power decline of less than 5% [51]. In the TISO-Lugano PV plant, after 20 years of operation, the majority of modules (59%) had a power decline of less than 10%, and 35% of modules had a decline between 10% and 20% [52]. Similar results were obtained at the Swedish test site Sandkullen over a period of 22 years [48]. Outdoors measurements on strings of 15-years old modules were performed at the Delphos power plant. Results showed a decrease of string power in the range of 11% to 21% during the last 10 years, including losses by dust and by-passed modules [53].

In recent module and array tests, a reduced power output from the early time of operation of a PV plant has been reported [49, 54]. This is caused by the fact that many manufacturers provide modules with less power at STC than stated, and by the fact that some crystalline silicon modules, besides amorphous silicon modules, during the initial installation have been found to suffer power degradation, but after a period of outdoors exposure the output is stabilised. Power degradation in crystalline silicon modules is related to decrease of short circuit current. In amorphous silicon module degradation is related to decrease of the fill factor of the current-voltage curve, and varies widely among modules.

After some years of outdoors operation of PV modules, visual signs of degradation are developed, mainly the following:

- Discoloration of cells, encapsulation material or cell front contacts
- Delamination of encapsulation
- Air bubbles
- Glass (front and back) cracking
- Cracked cells
- Water infiltration

Most of the modules, however, when presenting visual degradation signs do not show any meaningful power loss.

Hot spots on modules represent a principal cause of power degradation. Field experience from typical crystalline silicon modules shows, that the cell in front of the junction box operates at a temperature higher than the rest (about 4 °C). Most of the hot-spot cells have been found to be the cells in front of the junction box, presenting an increased overheating under real operating conditions and resulting in significant loss of module performance (for example 20% or 30%) [52].

III.5.2 Power conditioning

From a survey on a large number of small grid-connected systems, it has been found that inverter reliability has improved in recent years as a result of technology development and maturity [48]. For recent years a value between 8 and 12 failures per 100 inverters and year can be considered representative for these systems. Also results from a number of various types of grid-connected inverters, monitored by HTA Burgdorf's PV laboratory, show that the rate of hardware defects of inverters has been reduced in recent years, in a range of 10 to 20 failures per 100 inverters and year [55].

A major cause of failure of grid connected inverters is grid irregularities or lightning induced voltage spikes, usually affecting the control-board and leading to destruction of the switching devices.

Usual inverter problems are:

- Electrical shorts due to corrosion in printed circuit cards
- Sensitivity to high temperatures, dust, and humidity
- Explosion of filter capacitor

Regarding charge controllers, there is a variety of products for small PV systems. Besides the large differences in values of voltage thresholds used, that affect the performance of batteries, some poorly designed products are also prone to failures. This can be caused, for example, due to the low degree of enclosure environmental protection, or due to failure of the switching device at high current and temperature as a result of insufficient heat dissipation design [56].

IV. Conclusions

Lifetimes of batteries in different RES applications can be quite different depending on quality of batteries and operating conditions.

It is difficult to extract quantitative results from the collected information, but some general conclusions can be drawn. Also a lot of results are quite old, and battery technology has been improved in many aspects, as for example concerning the quality of AGM batteries or the quality of grids with higher resistance to corrosion.

One conclusion that is pointed out is that in most RES applications the battery can be used at a significantly reduced actual capacity with no major problem for the user.

The cycle-life capabilities of batteries are usually sufficient to provide long lifetimes in most RES applications. In systems with long service-life, corrosion is a usual failure reason. So care should be taken to reduce rate of corrosion in systems where a long service life for the battery is expected. However sulphation is very often reported in RES applications as a reason for low performance of a battery. The frequent occurrence of sulphation, which has been validated by plate analysis of batteries after service, is probably related to the inability of the battery to get fully charged in such applications.

What seems to be important is the system designer to have the knowledge of the factors that affect the performance of batteries and select the components and charge parameters that best suit the particularities of the application. For example, the availability of a back-up generator that can be used for a regular full battery charge may be an important factor for selecting the PV charge controller settings.

Regarding other components, power conditioning equipment represent a major source of failures in RES systems. The progress in technology and the experience gained has, however, led to the improvement of products and to the increase of inverters' reliability in recent years.

Regarding PV modules, some manufactures have been found recently to provide products with less power at STC than stated. PV modules however are the most reliable components, featuring low rate of failures and stable performance for a long time.

Abbreviations

AGM	=	Absorbed Glass Mat
DDOD	=	Daily Depth of Discharge
DOD	=	Depth of Discharge
GC	=	Grid-connected
PV	=	Photovoltaic
RES	=	Renewable Energy Sources
SA	=	Stand-alone
SOC	=	State of Charge
STC	=	Standard Test Conditions
VRLA	=	Valve Regulated Lead Acid

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