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BENCHMARKING

Work Package 4.3: Benchmarking process and recommendations

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Abstract

This document and the related web based tool RESDAS give information on the selection, testing and usage of storage devices in renewable energy systems. Since the lead-acid battery is the most widely applied storage technology, this battery type is addressed in much more detail than the other storage devices.

The lifetime of a lead-acid battery is affected by various ageing mechanisms that are influenced by various stress factors. Since the effect of the stress factors on the ageing mechanisms may counterbalance or amplify each other, it is the combination of stress factors that provokes certain ageing mechanisms.

Stress factors were defined, quantified and combined into 6 categories. The categories are associated with similar battery usage and with similar ageing phenomena. For each of the categories recommendations are provided concerning selecting, testing and using the battery for optimal battery lifetime expectancy.

Procedures in the report and in RESDAS are provided to attribute existing or newly designed renewable energy systems to one of the six categories, enabling the designer or end user to find the appropriate recommendations for his situation. Two procedures are provided for this purpose. One procedure requires only information on the concept of the renewable energy system. The other procedure requires detailed information on the battery loading. Although the latter procedure gives a better judgment for the categorization process, both procedures lead to the category-specific recommendations.
In case no information on the renewable energy system is available of course no specific recommendations can be given. However in that situation general recommendations are provided on the selection and usage of batteries in renewable energy systems.

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1. INTRODUCTION

In renewable energy systems there is generally a mismatch between the instantaneous power requirements and the instantaneous power availability. In grid-connected systems this mismatch may be balanced by power on the grid but in stand-alone, off-grid systems some means of electric energy storage is usually required to smooth out power variations. This report intends to provide the relevant information for designers of renewable energy systems to be able to answer the questions: What type of energy storage is most appropriate for my application? If batteries make the most sense, which type of battery, with what characteristics, is the most suitable energy storage system for my application and what charge/discharge strategy should be followed?

Many electric energy storage technologies are available for renewable energy systems and it is not always easy for a system designer to make a considered choice for his particular application. After selection of the technology and the required capacity, the remaining choices are often even more difficult, especially in case of the lead acid battery.
This report gives guidance in the selection of the most suitable energy storage device for the intended application. The same guidance with some additional features is available as an expert tool on the Internet (Renewable Energy Smart Design Assistant RESDAS; www.ecn.nl/resdas).
All relevant storage technologies are addressed but the electrochemical storage is treated in more detail than the other technologies. In the group of electrochemical batteries the lead acid battery is treated with the most detail. This distinction is made because lead-acid is the most common storage technology for renewable energy systems with a wide selection of products.

2. ELECTRICAL ENERGY STORAGE TECHNOLOGIES

Electrical energy can be stored using a variety of technologies, for example:
- Electrochemical storage (conventional chemical batteries)
- Super capacitors
- Fly wheels
- Pumped water
- Super conducting magnetic energy storage
- Electrolyzer/Fuel cells

Detailed descriptions of the different storage technologies can be obtained from the website of the Investire project and from other Internet resources (see references) and so are not discussed in more detail in this text.

Electrochemical storage can be achieved with various technologies:
- Lead-Acid Battery (LAB)
- Flow batteries
  - Polysulfide Bromide Battery (PSB)
  - Vanadium Redox flow Battery (VRB)
  - Zinc Bromide battery (ZnBr)
- Nickel Cadmium battery (NiCd)
- Lithium-ion battery (Li-ion)
- Sodium Sulphur or Sodium Nickelchloride battery (NaS or $NaNiCl_2$)
- Nickel Metal-Hydride (NiMH)

Each of these battery technologies are discussed in more detail below:

The **lead acid** battery is the most developed and the most applied technology. For most Renewable Energy Systems (RES) up to a power rating of approximately 100 kW and energy content up to about 200 kWh, the lead acid battery is usually the preferred solution for RES.
Lead acid batteries are available in many designs suited for various applications (e.g. UPS applications, cars, solar energy). The car starter battery is the most widely available type and generally has the lowest initial costs. However, car batteries are optimised for providing high currents for starting engines. They perform well under a regime of very shallow cycles, up to about 5000 cycles at 3% Depth of Discharge, (DoD[1]). Car batteries are ill suited for renewable energy applications that usually require deep cycling. Batteries that are designed for deep cycling applications will last longer in renewable energy systems, generally leading to lower life cycle costs and a lower environmental impact.
Links to manufacturers can be found in the references.

Flow batteries, a battery technology that uses a special ion exchange membrane separating two electrolyte solutions, are still in development and are not yet generally mature for wide spread application in renewable energy systems. Flow batteries have two external reservoirs of rechargeable electrolyte. Since the dimensions of these reservoirs can be chosen at will the energy storage capacity is independent of the power of the battery. There are no commercial products for small scale RES, however, in the long term there is a high potential for storage systems with a high ratio of energy content (kWh) to power rating (kW).

The **nickel cadmium** battery is a well-developed and widely used technology. The type used for energy systems are vented, in contrast to the well-known small batteries for electronic equip-

[1] Depth of Discharge: discharged part (in %) of the battery capacity (= 100% - State of Charge, SoC).

ment, which are sealed. Although the initial cost of the NiCd battery is higher than that of the lead-acid battery, the life cycle costs can be lower because of the longer life, in some cases up to 20 years in certain applications. Disadvantages include lower energy efficiency[2], higher costs and more severe requirements for recycling, because of the environmental aspects of cadmium. An advantage of the NiCd battery, again in comparison to lead-acid battery technology, is its higher temperature tolerance, which makes the NiCd battery particularly suited for arctic climates. In addition, NiCd batteries have higher discharge current capabilities allowing them to supply large power applications. In applications where battery currents are usually in the range of the $I_{1/4}$ [3] current, NiCd should be considered.

Nickel-Metalhydride batteries (NiMH) do not have the advantage of the large temperature operation range of NiCd, but have a much higher energy density and therefore they can be interesting for some small applications. As energy density is usually not a key parameter for stationary applications, NiMH are not used for stationary applications.

The **Lithium-ion** battery has a large market share for small portable equipment because of its high energy density and high efficiency. Large Li-ion batteries are not yet commercially available. Due to the interest of car manufacturers in Li-Ion battery technology for hybrid vehicle operation, if they are generally accepted, their cost and performance will probably make them very attractive for a number of RES applications in the next 5 to 10 years.

The **Sodium Sulphur** or **sodium nickel chloride** battery operates at a temperature of approximately 300ºC. This makes application in most renewable energy systems unpractical if there are long periods of time without surplus power from renewable sources. The thermal insulation and the battery management system that is required leads to relatively large minimum sizes of batteries. The NaS /$NaCl_2$ battery is used at the moment in a number of demo-projects with high power ratings for peak shaving. It is not clear what the potential for this battery technology is in renewable energy systems.

A summary of characteristic data of the different mentioned storage technologies is given in Table 2.1 and Table 2.2 and Figure 2.1 and Figure 2.2. The comparison of the various storage technologies is complicated by the differences in the required inverters or control equipment.

[2] Energy efficiency (Wh-efficiency): ratio of discharged energy to charged energy in one charge/discharge cycle. Charge efficiency (Ah-efficiency): ratio of discharged Ah to charged Ah in one charge/discharge cycle.

[3] I_X current is the value of the current (in A) that discharges the battery completely within x hours.

A current of $I_{1/4}$ results in a complete discharge of the battery in 15 minutes.

Table 2.1 *Some characteristics of electricity storage technologies*

	Typical Application power range (W)	Specific Energy (Wh/kg)	Temperature range (°C)	Investment (€ / kWh)
Lead acid	1W - 100 kW	25 - 45	-20 / 50	50 - 150
Lithium Ion	1W - 50W	80 - 150	-30 / 60	700 - 1000
Super capacitor		0.1 - 5	-60 / 70	50 000 - 150 000
Nickel: NiCd	1mW - 10kW	20 - 40	-40 / 50	200 - 600
Nickel: Ni-Mh	1mW - 10kW	45 - 75	-20 / 50	600 - 750
Nickel: Ni-Zn		50 - 60	-20 / 50	50 - 200
Flywheel	40kW-480kW	30 - 100	-20 / 50	1000 - 5000
Redox flow: Vanadium	1-250 kW	25 - 35	5 / 45	360 - 1000
Redox flow: Polysulfide Bromide				
Redox flow: Zinc Bromide	50kW-4MW	75 - 85		
Pneumatic storage		21 - 45	-10/50	100 - 1750
Zinc air		200 - 300	-20 / 50	50 - 200

Table 2.2 *Some characteristics of electricity storage technologies*

	• E (%)	Self discharge (% / month)	cycle life (cycles @ 100%DoD)	Float life (years @ 90%SoC)
Lead acid	60 - 95	2 - 5	300 - 500 100 car batt.	5 - 15
Lithium Ion	90 - 100	1	>1500	5 - 15
Super capacitor	85 - 98	50	100 000 - 500 000	10
Nickel: NiCd	60 - 80	5 - 20	300 - 1500	15 - 20
Nickel: Ni-Mh	65 - 70	15 - 25	300 - 600	15 - 20
Nickel: Ni-Zn	80	<20	500	15 - 20
Flywheel	90	0.1% / hour!	>10k	20
Redox flow: Vanadium	75-85	negligible	> 13342	5 - 15
Redox flow: Polysulfide Bromide	60 - 75	negligible		5 - 15
Redox flow: Zinc Bromide	70 - 75	negligible	>1500	5 - 15
Pneumatic storage	55 - 72	negligible	15k - 99k	20
Zinc air	50	8	30 - 50 equiv. @10% DoD	

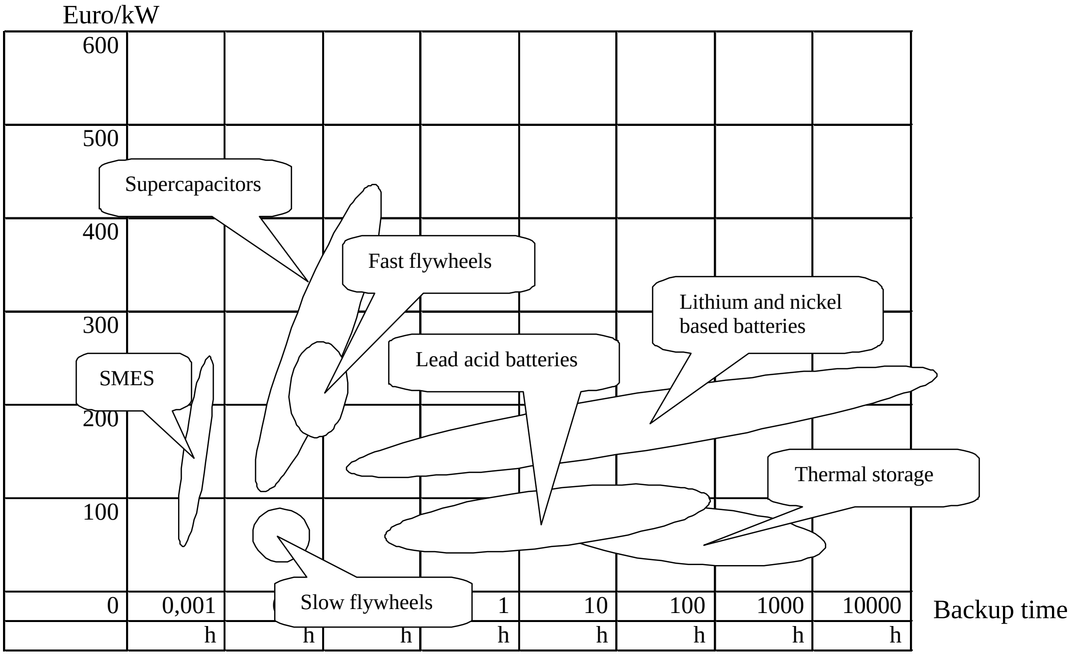


Figure 2.1 *Energy storage costs for different technologies (without power electronics to connect the storage device to the application, but including all auxiliary components necessary for safe and reliable operation of the storage device, e.g. cooling systems, temperature and voltage equalisation, etc.)*

Source: reference [6]

Note that the costs of SMES (super conducting magnetic energy storage), supercapacitors and fast flywheels are caused by low production quantities. In addition, supercapacitors are not yet sold commercially except for demonstration projects. Note also that the power levels of the energy storage technologies which are shown here are very different and often do not compete with one another.

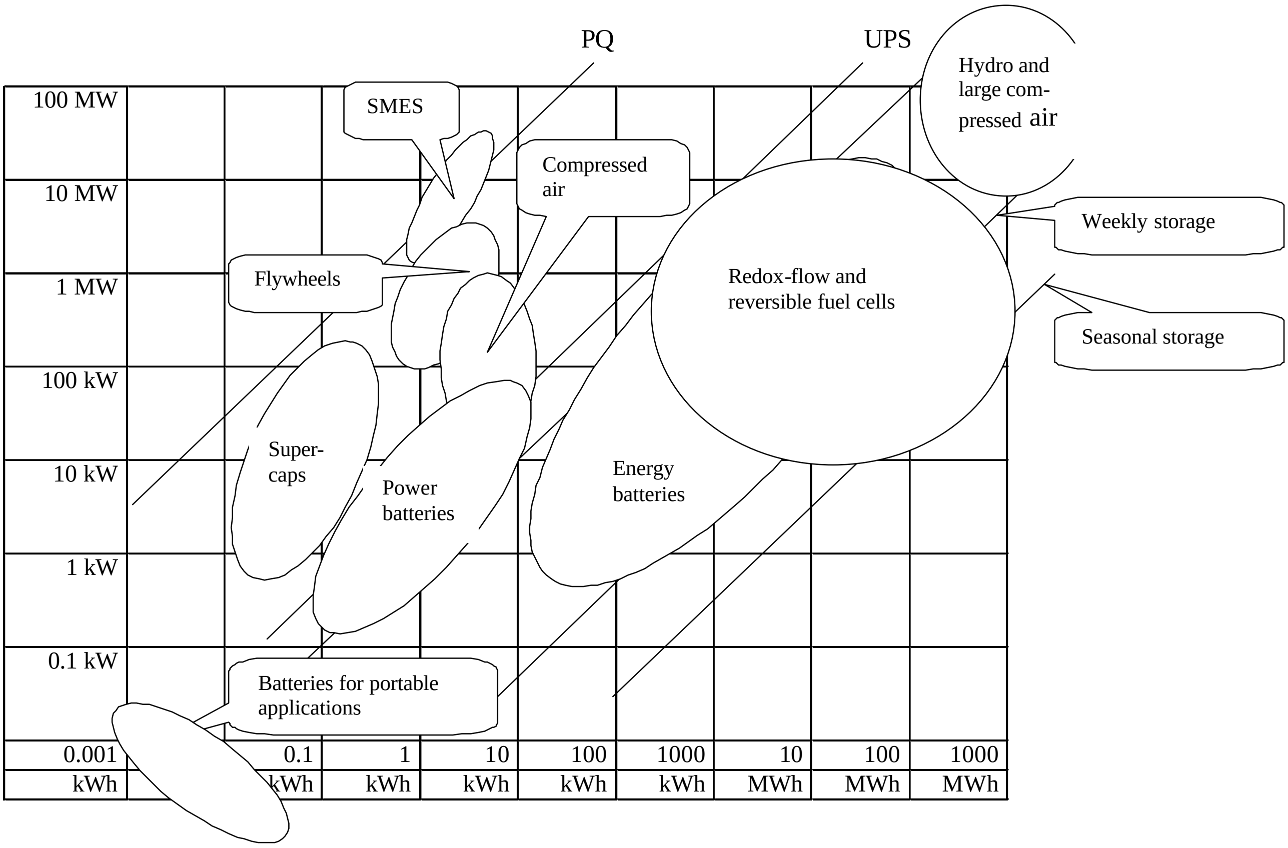


Figure 2.2 *Energy content and power output of different storage technologies*

(Source: reference [6]). Note that the size of the area indicates the energy and power range for which an energy storage technology may be suitable, not its economic importance. The lines mark a constant ratio of power to energy content.

3. LEAD ACID BATTERY DESIGN FEATURES

Lead acid batteries are the common means of energy storage used in renewable based rural energy systems. The following section provides information on design features of lead-acid batteries that are of importance for a proper understanding of this report.

Basic battery information

- Batteries produce direct current and are measured by a capacity, specified as the ability to supply a specific current for a specified length of time (Amp-hours or Ah) and a direct current voltage (Volts DC, or VDC)
- A specific battery is made up of individual cells that can be combined in series arrays to achieve a desired voltage. A cell voltage will depend on the battery type, generally around 2.0 VDC for lead acid technology and 1.2 VDC for NiCd technology. For example, a 12 VDC lead-acid battery will be made up of six individual cells in series while a 6 VDC battery will have three cells. The term volts per cell (V/Cell or V/C) is used to specify a specific voltage for each cell of a battery in place of specifying different voltages for different sized batteries; 6, 12, and 24 VDC batteries for example.
- As with battery cells, batteries can be connected in series to increase the battery bank voltage. Two 12 VDC, 500 Ah batteries placed in series will provide a battery bank providing a nominal 24 VDC, 500 Ah supply.
- Batteries can also be connected in parallel to increase the capacity of the array. Placing two 12, VDC, 500 Ah batteries in parallel will provide a nominal 12 VDC, 1000 Ah supply. If a larger capacity battery bank is required, this can be achieved by increasing the capacity of the specific battery or by increasing the number of batteries in the battery bank. Note that the energy storage capacity of the battery is the same in both of the last cases, 24 VDC time 500 Ah provides the same number of watt-hours as a 12 VDC battery with 1000 Ah capacity.

General types and battery casing

- Vented (flooded) battery: the cells of the battery are filled with a liquid electrolyte and have caps that can be opened to replenish the electrolyte with purified water.
- Valve-regulated lead-acid battery (VRLA): pressure-release valves seal the cells and loss of water is prevented by internal recombination of hydrogen and oxygen.
- Batteries are provided in hard plastic (PVC) or metal casings. Additionally PVC casings can either be opaque or translucent (clear) that allows one to view the battery plates and electrolyte level.

Electrolyte mobility

- Vented / flooded: the electrolyte is free to move between the plates.
- VRLA / AGM: the electrolyte is immobilised in Absorptive Glass Mats between the plates.
- VRLA / GEL: the electrolyte is immobilised in gel between the plates.

Plate design

- A battery cell contains positive plates connected in parallel and negative plates connected in parallel. Among other parameters, the surface area of the plates determines the maximum current that the battery can deliver.
- Pasted plate: the plates are made of a grid with a lattice structure on which the active mass, a metallic paste, is spread. As a battery undergoes deep charge and discharge cycles the plate structure degrades, leading to battery failure. Starter batteries are designed to provide high current in a limited space, so the plates are typically very thin and spaced close together to provide a very large surface area. Deep cycle batteries, typically used for renewable energy systems, are designed with thicker plates that are widely spaced to provide

higher capacity and longer cycle life. Heavy-duty starter batteries for lorries and other large vehicles usually have thicker plates than starter batteries for cars.
- Tubular plate: the grids of the positive plates are made of spines around which the active mass is retained by polyester or glass-fibre sleeves. The negative plates are commonly pasted plates.

Plate material
- The grid is made of a lead-alloy that can contain materials such as antimony for flooded batteries, calcium for VRLA batteries, tin and other metals. The choice of the alloy is a compromise between resistance to corrosion, mechanical strength and the rate of electrolysis (hydrogen/oxygen production; gassing). An alloy without antimony reduces the rate of electrolysis with respect to an alloy with (low) antimony content. However, antimony generally improves the cycling behaviour of batteries.

The active mass[4] on the plates (lead and lead oxide with additives called a paste) must have a spongy structure with a certain porosity. A high porosity structure has more surface which enables high currents (for starting engines). A less porous, more compact structure however is better for deep cycle purposes such as for renewable energy applications.

Capacity
- The nominal capacity C_N is the amount of charge that a fully charged battery can deliver at standard conditions and at a constant rate in which the complete capacity is discharged over N hours. The standard conditions depend on the application and are generally defined by the manufacturer. For stationary applications the standard conditions are 25°C and a 10h discharge rate. In some cases the nominal capacity for solar batteries is based on the 100h or the 120h discharge rate. The end of discharge is always defined by a voltage limit, such as 1.8 V/Cell.
- The available capacity depends on the discharge rate. Batteries are typically rated by the manufacture for a specific capacity at a specific current. If the discharge current is higher (more current) than the rated current, the capacity will be reduced. If a lower current is being used, a higher capacity can be expected. To estimate the capacity at other currents than the rated current Peukert's law can be used: $t_X / t_N = (I_N / I_X)^n$. Here t_X is the discharge time at a current of I_X A. The value of n is in the order of 1.15 for small currents. Using this estimate the C_{20} rate (the current that it takes to discharge a battery over a 20 hour period) of a battery would be 11% higher than its C_{10} rate (the current to discharge the battery over 10 hours).
- The capacity depends on the battery temperature: at low temperature the capacity is reduced. Below 25 °C the capacity drops with about 0.6% /°C. However at lower temperatures the dependence is much stronger. Although this dependency differs per battery type some figures are given here as an indication: around 0°C the capacity is about 75% and at -25 °C about 50% of the capacity at 25°C.
- A new battery may have a considerably higher capacity than the nominal capacity, sometimes more than 50 % higher. Battery manufacturers sometimes try to achieve lifetime guarantees by oversizing the batteries. Additionally, due to the variability's in the battery manufacturing process, even batteries of the same model can have very different capacities. Finally, it is common that the capacity of a battery will increase during the initial charge and discharge cycles before settling out to a constant value.

[4] AM: Active Mass; PAM: Positive Active Mass on the positive plates and NAM: Negative Active Mass on the negative plates

4. STRESS FACTORS AND AGEING MECHANISMS OF LEAD ACID BATTERIES

Stress factors
Stress factors are all conditions that either directly or indirectly contribute to ageing (irreversible degradation) of the battery but are not in themselves an ageing mechanism. The operation of a battery can be described by its time series of temperature, voltage, current and SoC (state of charge), the latter being a parameter calculated from the time series of the first three values. Stress factors are statistical parameters derived from these time series. The stress factors make it easier to characterise the operating conditions and to link them to ageing conditions. In lead acid batteries stress factors are for instance total Ah throughput[5], charge factor[6] and time between subsequent full charges. The stress factors are addressed in more detail in paragraph 5.
Stress factors have a relation to ageing mechanisms. This does not mean that a specific stress factor causes the ageing process and the removal of that stress factor would stop the process. A schematic overview of the interrelations between stress factors and ageing mechanisms is given in appendix 4.

Ageing Mechanisms
The ageing mechanisms of batteries are the actual chemical or mechanical events that cause battery failure. These failures may be long processes of degradation or short catastrophic events and in some instances a combination of the two. In this text we are concentrating on the longer processes that lead to battery failure. Regarding lead acid batteries the ageing mechanisms are quite well known, if not completely understood. It should be noted that different battery designs are inherent resistant to different ageing mechanisms making the choice of that battery preferable if one ageing mechanism, or a specific combination of ageing mechanisms are expected to be critical.

- Corrosion of the positive grid

A process where the positive plate or the battery posts, usually near the connection to the casing, corrodes causing a restriction in the current flow and eventually failure either by not allowing current to pass or cracking the outer casing.

- Hard / irreversible sulphation

A build-up on the active mass of the plates of that prevents the chemical exchange between the electrolyte and the active material. Some sulphation can be reversed, but hard sulphation permanently reduces the available capacity of the battery.

- Shedding

A process where the active mass of the plates falls off and collects at the bottom of the battery. This reduces the amount of active mass and thus the available capacity of the battery. It can eventually cause battery cell shorting if enough material builds up at the bottom of the battery case to cause an electrical short circuit between the positive and negative plates.

- Water loss / drying out

When a battery is being charged while at a high state of charge some of the water in the electrolyte is split into hydrogen and oxygen (gassing[7]) and can escape the battery casing. In flooded

[5] The Ah-throughput over a defined period of time (e.g. one year) is the delivered charge (in Ah) in that period of time.
[6] The charge factor over a defined period (e.g. one year) is the ratio of the charged Ah to the discharged Ah in that period of time.
[7] Gassing: the production of oxygen and hydrogen gases at the positive and negative plates during (over)charging

batteries the top of the plates can be exposed causing a drying out of the active material, which permanently damages the battery. As water is lost in sealed batteries it reduces the available electrolyte, thus reducing the available capacity of the battery.

- AM degradation

Over time the Active Mass on the battery plates degrades and changes structure, loosing some of the electric transfer properties and reducing the capacity of the battery.

- Electrolyte stratification

As a battery rests, the electrolyte in the battery separates by density with the higher density electrolyte settling to the bottom. As the battery undergoes charge and discharge cycles, different parts of the battery are exercised, focusing activity on very specific parts of the battery plates causing them to wear faster. The electrolyte can be mixed actively, using bubblers or other means, or passively, such as by charging flooded batteries at a high voltage to cause gassing, which mixes the electrolyte.

5. OPERATION WITH A SIMILAR COMBINATION OF STRESS FACTORS

All renewable energy systems can be sorted into a number of categories of "similar use" based on how the batteries are used (stressed) in the energy system. These categories are thus subjected to a similar combination of stress factors. It is possible that different applications (e.g. wind or solar) result in the same category. Also similar applications (e.g. two solar home systems) can be sorted in different categories as a result of differences between the user's behaviour. Batteries can belong to the same category irrespective of other physical parameters such as size, capacity or voltage.
The categorisation of battery use in an application can be performed using measured or simulated time series of the battery's operating conditions. The categorisation process is described in detail in reference [1]. A summary is provided in below.

The number of selected stress factors was kept low to maintain independent stress factors with relatively clear effects of the factors on the ageing mechanisms and to maintain a good overview of the categorisation. The individual stress factors determined during the categorisation process are: charge factor; time between full charge; Ah throughput; time at low SoC; highest discharge rate; and partial cycling. Additionally two temperature-related stress factors were defined. Each of these stress factors is described in the following sections.
The individual stress factors are calculated by a simple statistic analysis of data for the time period concerned, which is typically a year or more.

The intensity of each individual stress factor must be evaluated in order to quantify the influence of the stress factors on ageing. A five level intensity index was used (1: Very low intensity; 2: Low intensity; 3: Medium intensity; 4: High intensity; and 5: Very high intensity). In most, but not all, cases a low intensity level is associated with a small effect of the stress factor on the ageing mechanisms. An exception is the Charge Factor: both low and high intensity level of the CF provokes (different) ageing mechanisms.
A single stress factor intensity level does not simply indicate the significance of that stress factor for an ageing mechanism. Depending on the ageing mechanism the combination of certain stress factors can have a counterbalancing effect or an amplifying effect. Only the combination of all stress factor intensities indicates the impact of a particular ageing mechanism. The performance fading and life limitation in a real RES system by a particular ageing mechanism depends on the battery technology, design and quality. The ageing mechanisms are benchmarked by the combination of the stress factors intensities.

- Charge factor

The charge factor is defined as the Ah charged divided by the Ah discharged over the period of analysis. It represents to Ah-losses associated with battery usage.
Indexation of the charge factor:

5: very high intensity	>130 (%)
4: high intensity	(115; 130]
3: medium	(108; 115]
2: low	(102; 108]
1: very low	<=102

- Ah throughput

This factor is defined as the cumulative Ah discharge in a one-year period normalised in units of the battery nominal capacity.
Indexation of the Ah throughput:
5: very high intensity >100 (C_{10})

4: high intensity (70; 100]
3: medium (40; 70]
2: low (10; 40]
1: very low <= 10

- Highest discharge rate

This factor is defined by the highest current at which at least 1% of the Ah throughput was discharged. The current is expressed in the units of the nominal current ($I_{10} = C_{10}$ / 10h).
Indexation of the highest discharge rate:
5: very high intensity > 1.7 (I_{10})
4: high intensity (1.4; 1.7]
3: medium (0.5; 1.4]
2: low (0.1; 0.5]
1: very low <=0.1

- Time between full charge

This factor is the average time between recharges above 90% SoC.
Indexation of the time between full charge:
5: very high intensity >8 (days)
4: high intensity (2.5; 8]
3: medium (1.2; 2.5]
2: low (0.7; 1.2]
1: very low <=0.7

- Time at low SoC

This factor is the percentage of a year during which the battery remained below 35% SoC.
Indexation of the time at low SoC:
5: very high intensity >25 (%)
4: high intensity (15.5; 25]
3: medium (4.5; 15.5]
2: low (1; 4.5]
1: very low <= 1

- Partial cycling factor

Cumulative Ah throughput (in units of C_{10}) sorted in the following SoC ranges:
A (100 – 85%), B (85 – 70%), C (70 – 55%), D (55 – 40%), E (40 – 0%)
The partial cycling factor is calculated by the weighting function:
PC=(A*1 + B*2 + C*3 + D*4 + E*5)/5
Partial cycling at a low SoC results in a higher "Partial cycling factor".
Indexation of the partial cycling factor:
5: very high intensity >70 (C_{10})
4: high intensity (50; 70]
3: medium (40; 50]
2: low (30; 40]
1: very low <= 30

- Temperature acceleration factor

The effect of elevated battery temperature is expressed in the temperature acceleration factor.

$$T_{ac} = \frac{\int a * e^{k(T-T_0)} dt}{\int dt}$$

T = battery temperature; T_0 = 20°C

10°C increase double the factor (a=1, $k = \frac{\ln 2}{10}$)

Indexation of the temperature acceleration factor:
5: very high intensity >1.6
4: high intensity (1.15; 1.6]
3: medium (0.85; 1.15]
2: low (0.4; 0.85]
1: very low <= 0.4

- Low battery environmental temperature

The lowest operating battery temperature maintained for at least 12 hours (average over a 12 hour period).

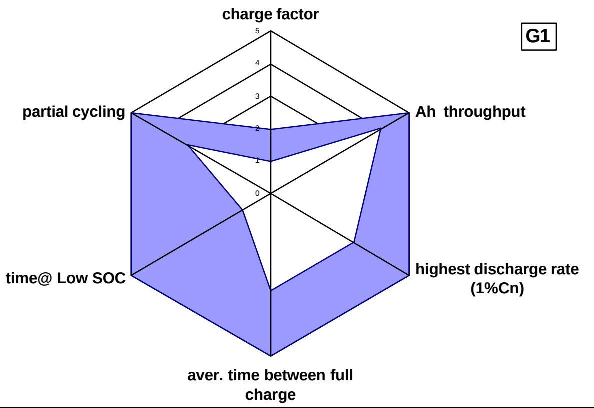
Indexation of the low battery temperature:
5: very high intensity <-9 (°C)
4: high intensity [-9; -5)
3: medium [-5; 0)
2: low [0; 5)
1: very low >= 5

Categories of similar combination of stress factors

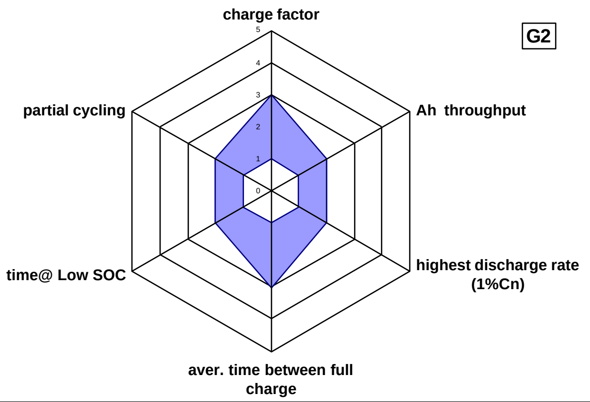
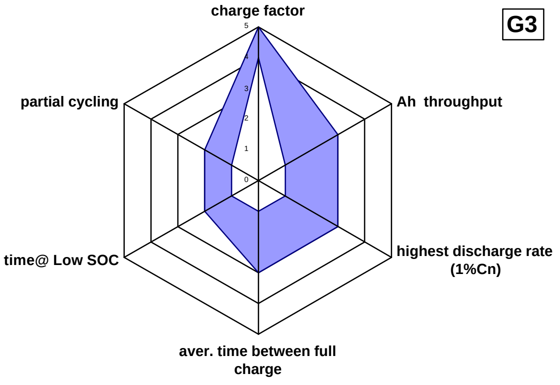
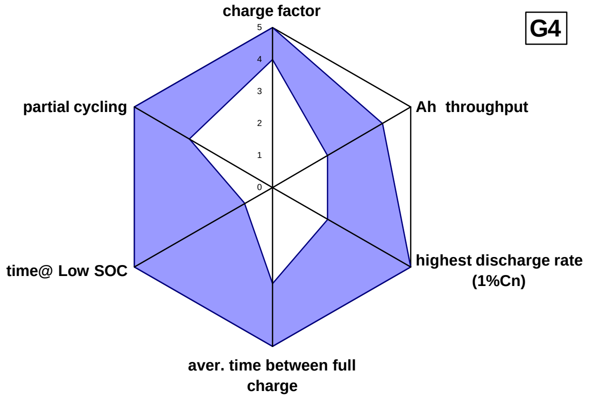
The stress factors of over 150 scientifically monitored RES were analysed in the project. The stress factors were visualized by the means of a radar plot in which six intensity evaluated stress factors are depicted. The two temperature-related stress factors were not used in the categorization. The individual stress factors in the radar plots were ordered in accordance to the related ageing mechanisms. Thus the resulting shapes in the radar plots are relatively compact and allow easier visual comparison of the shapes.

A significant number of randomly selected data sets were depicted in the radar plots and printed. The radar plot shapes were visually sorted on the base of the resulting shape area appearance. Six categories were recognised and described by the individual stress factors intensity bands. The radar plots with the intensity bands of all the six categories are shown on the pictures in Table 5.1.

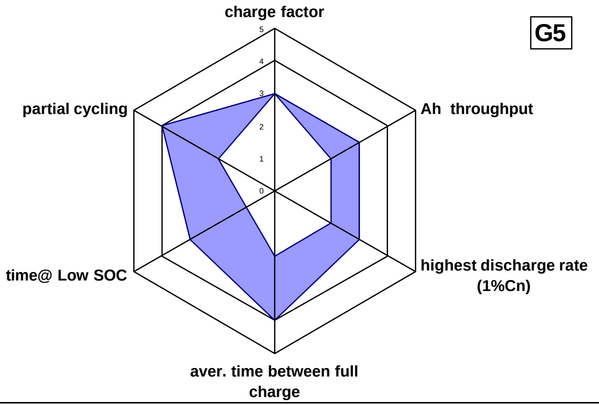
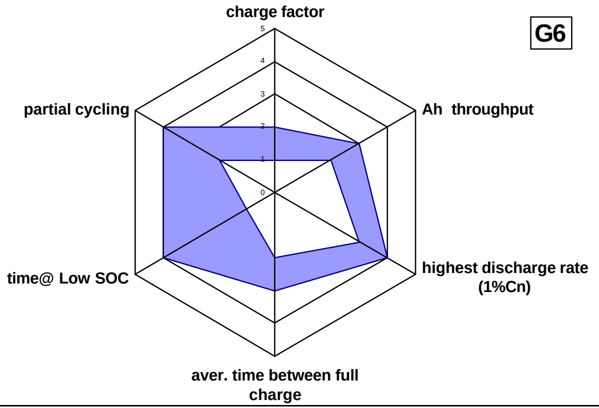
Table 5.1 *Radar plot diagrams for categories of similar use (G1 to G6), based on six stress factors*

Radar plot diagram	***Characteristic operation and ageing risk***
	- very seldom full recharge - very high or high Ah throughput (full cycling operation) - low charge factor - PSoC operation - high charge and discharge current rates - very high risk of hard/irreversible sulphation - very high risk of electrolyte stratification - very high risk of AM degradation - a high risk of AM shedding - very high risk of weak cell reverse polarisation[8]

[8] Reverse polarisation: change of polarity of a cell (positive plates become negative and negative plates become positive), which is highly damaging for the cell

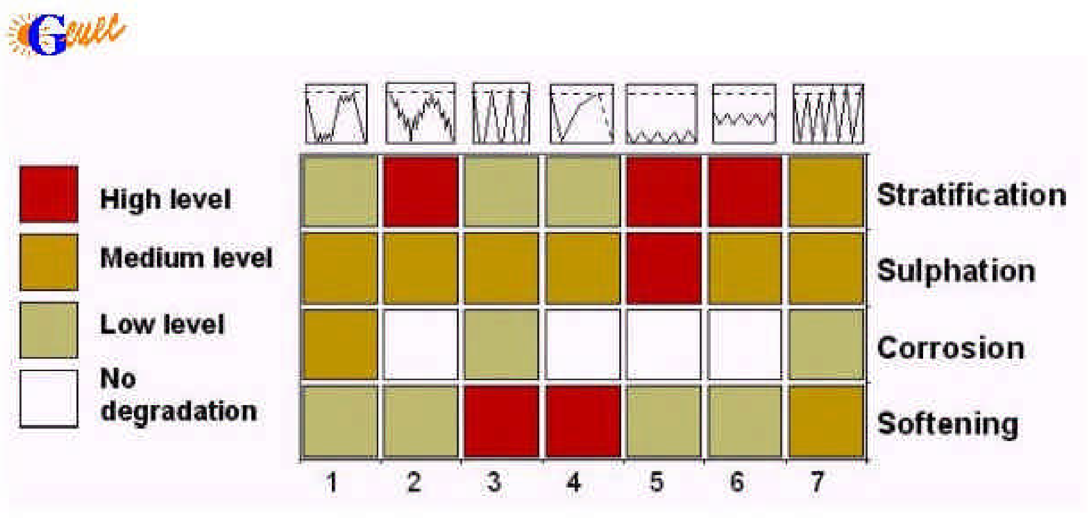
	-frequent recharge -very low to medium charge factor -very low or low Ah throughput -very low or low discharge rate -mild cycling at a high SoC level (shallow cycling at 100%SoC) -very low risk of hard/irreversible sulphation -very low risk of electrolyte stratification -very low risk of AM degradation -high risk of corrosion -high risk of water loss, for VRLA drying out and thermal runaway[9]
	-very low to medium throughput operation -battery is charged with high or very high charge factor -full recharge happens usually very often -battery may stay for some time period at discharged state <35%SoC -battery is shallow cycled in a few % of the top SoC range -very low risk of hard/irreversible sulphation -very low risk of electrolyte stratification -very high risk of corrosion -very high risk of water loss, for VRLA drying out and thermal runaway -a high risk of AM shedding
	-medium to high throughput operation -PSoC cycling -long time between full recharge -high charge factor. -battery doesn't operate/stay long at SoC<35% -discharge rate may be high immediately followed by some recharge that frequently does not bring the battery to 100%SoC -when the full charge is realised then the charge factor is too high. -high risk of electrolyte stratification -high risk of hard/irreversible sulphation -very high risk of AM shedding -very high risk of AM degradation -high risk of water loss, for VRLA drying out and thermal runaway -high risk of corrosion.

[9] Thermal runaway: the recombination of hydrogen and oxygen in a VRLA causes some increase in temperature. This increases the rate of gassing and recombination. At high gassing rate this self-accelerating effect may result in an overheated (ultimately exploded) battery.

	-medium throughput operation -PSoC cycling -without frequent deep discharge and resting in SoC<35% -medium charge factor -medium risk of hard/irreversible sulphation -medium risk of electrolyte stratification -medium risk of AM degradation -RES system seems to be very well optimised.
	-medium throughput operation at a PSoC cycling -very low or low charge factor -there may be some time period of operation/rest at SoC<35%. -very high risk may of hard/irreversible sulphation -very high risk of electrolyte stratification

6. ACCELERATED TESTING PROCEDURES FOR LEAD ACID BATTERIES

The most relevant characteristic for selecting the most suitable battery in a renewable energy application is its lifetime. In general, testing procedures do not give very reliable information on the lifetime expectancy for the tested batteries. This is caused by the complexity of the (combination of) stress factors and ageing mechanisms. In theory the only reliable way of lifetime testing of the battery in a certain application is to subject the battery to the very same conditions as in the intended application.
As a consequence of this the testing period would last as long as the battery's lifetime in the real application. Of course this is not very practical. For this reason various accelerated lifetime testing procedures were developed, each reflecting a certain way of application of the battery or focusing on a certain stress factor or ageing mechanism. An overview of existing lifetime testing procedures and how strong they provoke four ageing mechanisms, from "no degradation" to "high level", are given below (ref. [7]).



Short description of the test procedures (the numbers refer to the figure):

1. IEC 61427
   - Reproduces seasonal cycles; low and high SoC
   - Accelerates the corrosion mechanism

2. NF C 58-510
   - Reproduces daily and seasonal cycles
   - Cycling conditions of temperate countries

3. PPER
   - Representative of Solar Home System conditions
   - Short test duration

4. QUALIBAT
   - Short test duration

5. Test around 10% SoC
   - Strongly emphasises stratification and sulphation
   - Reproduces situations of prolonged bad weather

6. Test around 40% SOC
   - Emphasises stratification and sulphation
   - Representative of Solar Home System conditions

7. DRE
   - Short test duration
   - Accelerates stratification and sulphation in very few cycles

Shows the ability of the battery to recover from stratification

The designer and user of the renewable energy system must decide which testing procedure or procedures are the most appropriate for the intended application, so that the most suitable battery can be selected by comparing the results of the various candidate batteries from those particular tests.
For each particular category of similar battery use a recommended test procedure was defined to produce comparative test results for the candidate batteries. This assists the designer and user of renewable energy systems with the selection of a suitable battery type and manufacturer.
Some of these "category-specific" test procedures are composed of 2 of the 7 above-mentioned procedures (combinations). The ratios for combinations of test procedures were determined on the basis of the normalised ageing effects resulting from use of the individual procedures. These ratios have to be adapted to give the time ratio for combining test procedures, by taking the duration of lifetime tests into account. The duration of test procedures can be found in ref. [7] and the ratios of time durations are shown in Table 6.1.

Table 6.1 *Ratios of time durations of the combined test procedures*

Combination of test procedures	ratio of normalised ageing effects	ratio of time duration of test sequences
IEC61427 plus Qualibat (1 :1.5)	1 : 1.5	1 : 0.57
IEC61427 plus Qualibat (1 : 0.3)	1 : 0.3	1 : 0.11
NFC58-510 plus PPER (1 :1)	1 : 1.0	1 : 0.41

More information on the "category-specific" test procedures is given in ref. [3].

The recommended test procedure for each of the 6 categories of similar battery use is given in appendix 2.

7. RECOMMENDATIONS ON LEAD ACID BATTERIES IN RENEWABLE ENERGY APPLICATIONS

Recommendations on the use of lead acid batteries are given on 3 levels, depending on the available information on the renewable energy system. The higher the level, the better the recommendations suit the specific renewable energy system.

Level 1: General recommendations
If no information on the renewable energy system is available the general recommendations on lead acid batteries should be followed. These recommendations are provided in Appendix 1.

Level 2: Specific recommendations for systems with limited design information
If limited information about the design of the renewable energy system is available, such as the source of energy, the daily electricity consumption, and some more general parameters, it is recommended to use a simulation tool to choose the sizing of the various components, including the battery. Some more information on simulation tools for renewable energy systems is given in Table 7.1. The output of such a design tool can be used to estimate the stress levels of the battery and the category of similar battery use. The procedure for this is provided in Appendix 3. After that, the specific recommendations for the renewable energy system use can be found in Appendix 2. The benchmarking web site RESDAS provides an automated tool for the complete procedure from the output of the simulation tools to the arrival at the specific recommendations.

Table 7.1 *Capabilities of different hybrid systems simulation tools*[10]

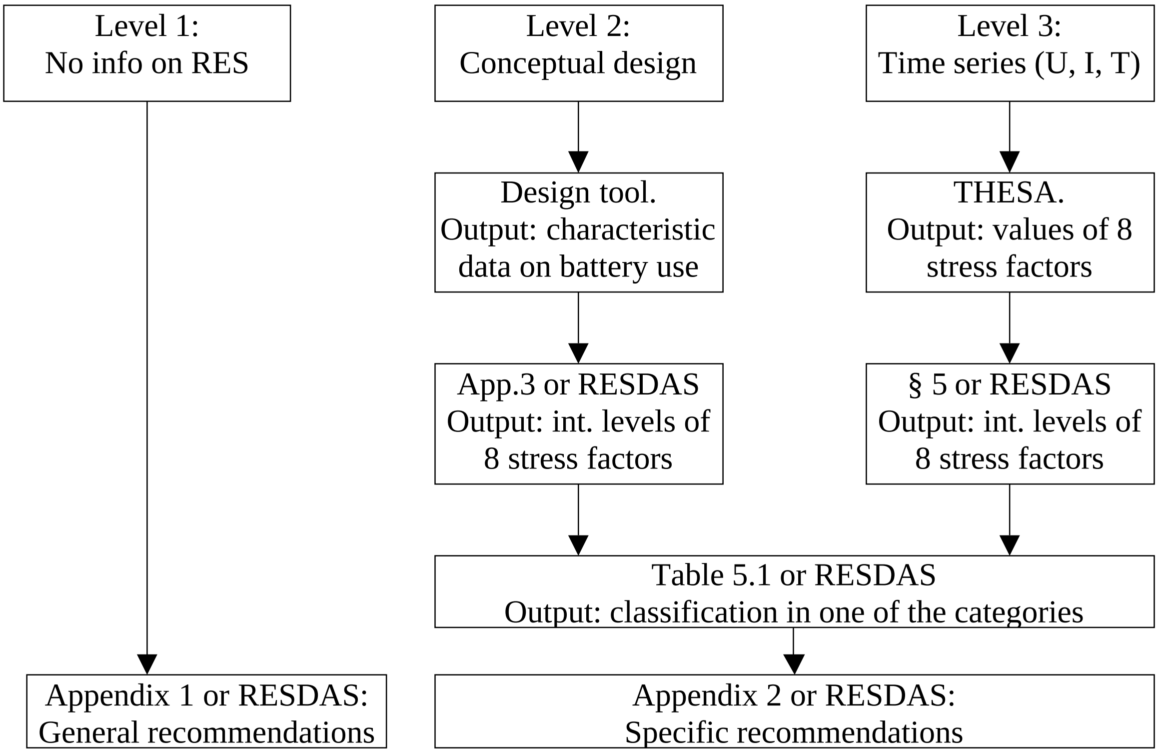
Program	link	PV ?	Wind ?	Backup generator ?
HOMER2.1	http://www.nrel.gov/homer/	Y	Y	Y
Hybrid2 1.3	http://www.ecs.umass.edu/mie/labs/rerl/hy2/	Y	Y	Y
Modes 1.1	http://ewis.fh-konstanz.de/modes.htm	Y	Y	Y
PV-design Pro 5.0	http://www.mauisolarsoftware.com/	Y	Y	Y
PVS 2.001	http://www.econzept.de/start.htm	Y	-	Y
PV*Sol pro 2.2	http://www.valentin.de/	Y	-	Y
PVsyst 3.21	http://www.pvsyst.com/	Y	-	Y
RETScreen	http://www.retscreen.net/ang/d_o_view.php	Y	Y	Y
SolSim	http://ewis.fh-konstanz.de/solsim.htm	Y	Y	Y

Level 3: Specific recommendations for systems with detailed design information
Detailed information on the renewable energy system may be available in the form of time series from battery current, voltage and/or temperature. This information may originate from a simulation tool or from measurements on a similar renewable energy system.
If time series data is available one can use the publicly accessible evaluation tool called THESA (http://www.solar-monitoring.de/ithesa/) developed by the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany, to produce a comprehensive evaluation of the way the battery is used. This evaluation has been called a Standard Evaluation Report (SER) and includes the values of the 8 stress factors previously discussed. With the values of the stress factors the associated intensity levels of the stress factors can be determined, using the indexation values given in Appendix 3, or using RESDAS. With the intensity levels of the stress factors the usage of the battery can be assigned to one of the 6 categories of similar use using the "radar plot diagrams"

[10] RESDAS is not intended to replace these tools but is complementary to them. The design tools are very useful for system sizing while RESDAS gives specific information on the selection, testing and usage of the battery.

in appendix 2 or using RESDAS. This will lead to specific recommendations for the renewable energy system, given in appendix 2.

This paragraph is summarised in the following flow chart:



8. REFERENCES AND USEFUL BATTERY INFORMATION SOURCES

[1] Vojtech Svoboda: "Benchmarking project; WP3.1; Definition of performance requirements for energy storage systems in each category"; Centre for Solar Energy and Hydrogen Research Baden-Württemberg, March 2004

[2] L.W.M. Beurskens et al: "Economic performance of storage technologies", ECN-C--03-132; Petten, December 2003

[3] Alan Ruddell: deliverable WP 3.2 of the Benchmarking project (in preparation)

[4] Dirk Uwe Sauer et al, 14th PVSEC Conference, Barcelona, 1997, pp.1348 - 1353

[5] Dirk Uwe Sauer et al, " Charge strategies for valve-regulated lead/acid batteries in solar power applications" Journal of Power sources 95 (2001) 141-152

[6] Energy storage – A key technology for decentralised power, power quality and celan transport, published by the European Commission, Energy, Environment and Sustainable development, EUR 19978, ISBN 92-894-1561-4;

[7] Testing of storage batteries used in stand alone photovoltaic power systems; Test procedures and examples of test results; IEA PVPS T3-11:2002; http://www.oja-services.nl/iea-pvps/ products/download/rep3_11.pdf).

General information on storage technologies can be found in:
http://www.itpower.co.uk/investire/
http://www.energystorage.org/index.html
http://www.greennet.at/Investire network
The technology reports are particularly useful

IEA PV power systems programme:
http://www.oja-services.nl/iea-pvps/intro/index.htm
Recommended Practices for Charge Controllers IEA PVPS T3-T05:1998
http://www.oja-services.nl/iea-pvps/products/download/rep3_05.pdf
Lead-acid battery guide for stand-alone photovoltaic systems IEA PVPS T3-T06:1999
http://www.oja-services.nl/iea-pvps/products/download/rep3_06.pdf

Sandia labs have a number of relevant reports which can be downloaded
http://www.sandia.gov/ess/Publications/pubs.html

PV Battery Handbook, Hill & McCarthy, Hyperion Energy Systems Ltd, March 1995; The handbook describes the use of batteries in Photovoltaic applications Compiled under EC contract JOU-CT92-0120 'Concerted action on PV systems: Task 3 (Batteries); http://www.hyperion.ie/index.htm)

A well-updated list of battery manufacturers can be found on the site of Bill Darden:
http://www.uuhome.de/william.darden/batbrand.htm#selectors

Bill Darden also maintains a site with information to select the right car and deep-cycle battery:
http://www.uuhome.de/william.darden/index.htm

9. GLOSSARY AND ABBREVIATIONS

Ageing mechanism
Under normal conditions irreversible changes of components of the battery and its materials that eventually lead to a loss of performance.

Ah-throughput
Delivered charge (in Ah) in a defined period of time.

Category (of similar battery use)
A specified group of RES systems with typical operating characteristics and typical operating stress for batteries

Charge factor
Ratio of the charged Ah to the discharged Ah in a defined period of time.

Charge efficiency (Ah-efficiency)
Ratio of discharged Ah to charged Ah in one charge/discharge cycle.

Energy efficiency (Wh-efficiency)
Ratio of discharged energy to charged energy in one charge/discharge cycle.

Equalisation voltage
A relatively high charging voltage that must be maintained only during a limited period of time. Charging at the equalization voltage brings all cells to the same state of charge and removes electrolyte stratification in flooded cells

Float charging is charging at a relatively low voltage. It is applied after a full battery charge at normal (bulk) charge.

Gassing
Production of oxygen and hydrogen gases at the positive and negative plates during (over)charging.

Recombination
Recombination of the oxygen and hydrogen produced by gassing inside a VRLA.

Reverse polarisation
Change of polarity (positive plates become negative and negative plates become positive), which is highly damaging.

Stress factor
A classification parameter used in the categorization process; the stress factors influence batteries ageing but do not in themselves lead to irreversible degradation of components of the battery.

Thermal runaway
The recombination of hydrogen and oxygen in a VRLA causes some increase in temperature. This increases the rate of gassing and recombination. At high gassing rate this self-accelerating effect may result in an overheated (ultimately exploded) battery.

Trickle charge

A charge at a low rate to maintain a cell or battery in a fully charged condition.

AGM Absorptive Glass Mat (for immobilizing the electrolyte in a LAB)

AM Active Mass

C_N Nominal capacity related to the N hours rate discharge (I_N)

DoD Depth of Discharge: discharged part (in %) of the battery capacity
(DoD = 100% - SoC)

I_{10} 10 hours discharge current
(at which a battery is completely discharged in 10 hours)

I_x x hours discharge current
(at which a battery is completely discharged in x hours)

LAB Lead Acid Battery

NAM Negative Active Mass (AM of the negative electrode)

PAM Positive Active Mass (AM of the positive electrode)

PQ Power Quality

PSoC Partial State of Charge

RES Renewable Energy System

RESDAS: http://www.ecn.nl/resdas/
Renewable Energy Systems Design Assistant for Storage

SoC State of Charge (SoC = 100% - DoD)

SLI car battery (Starting, Lighting and Ignition)

UPS Uninterruptible Power Supply

VRLA Valve-Regulated Lead-Acid battery

APPENDIX A GENERAL RECOMMENDATIONS ON BATTERIES IN RENEWABLE ENERGY SYSTEMS

(see chapter 7, level 1)

A.1 General recommendations for selection and usage of batteries

<u>Battery application types (see also paragraph 3):</u>

SLI:	car battery (Starting, Lighting and Ignition)
Heavy duty SLI:	car battery for more cycling, typically for taxis
Industrial:	stationary standby applications
Traction:	fork-lift trucks

<u>Battery technology types:</u>

VRLA:	(valve-regulated lead-acid) where the electrolyte is immobilized in a gel or absorptive glass mat (AGM)
Flooded:	where the electrolyte is liquid, and the cells are freely vented
Flat (pasted) plate:	where the lead grid is pasted with the active material. Always used for the negative plate, sometimes used for positive plate.
Tubular plate:	where the electrode consists of small lead rods, surrounded with active material, held within tubes. Used only for the positive electrode. In a tubular plate battery, the negative plate is always flat (pasted) plate.

Recommendations:

1. The battery technology (VRLA-GEL, VRLA-AGM, or flooded) should be selected using table A.2.

2. From a performance standpoint, tubular plate batteries are preferred, as they will probably last longer than flat (pasted) plate batteries.

3. Within technology types it is preferable to choose batteries which are labelled "solar" or "deep cycle", in that order. “Solar” batteries have been designed for renewable energy applications while “deep cycle”, although more general, are designed for usage profiles that are similar to ones that are expected in renewable based applications.

4. In flat plate batteries thick plates are a better choice than thin plates.

5. In flooded batteries, the ratio of electrolyte volume to nominal capacity should be as high as possible.

6. In general the ratio of battery mass to nominal capacity (kg/Ah) should be high.

7. In most renewable energy systems, industrial batteries will perform better than car batteries, even in systems where cycling is shallow.

8. It is preferable to avoid the use of car batteries for renewable energy applications if there is an alternative. The common car battery (SLI) battery is not able to withstand many deep cycles and long periods at low SoC, as required by many renewable energy applications. As a consequence the common car battery is likely to fail within a short time (about 1 - 2 years) due to sulphation, corrosion, or shedding of the active mass from the plates.

9. If the use of a common car battery (SLI) in the renewable energy system cannot be avoided, the following points should be considered:
    a. SLI batteries for taxis, lorries or heavy-duty applications usually have thicker plates and are more suitable.
    b. It is essential to keep an SLI battery close to a fully charged condition and not to discharge more than 30% of its capacity. This generally requires the use of a battery with a higher capacity than would normally be called for.

10. Recommended maximum Depth Of Discharge (DoD):
    Table A.1 provides a maximum discharge threshold below which different batteries should not be discharged. This Depth Of Discharge (DoD) value is general in nature and battery manufactures should be consulted for specific battery types or brands. As discussed previously, expected battery life is a factor of many different issues, specifically the aging mechanisms. Given normal operation, battery life is represented as a curve of the number of discharge and charge cycles to a specific DoD that the battery can supply against that specific DoD. This curve, called a cycles to failure curve, is available from manufactures for most common batteries. Generally speaking, as the DoD of a cycle increases, the number of times the battery can withstand that cycle decreases. This curve is not linear, meaning that five cycles to a 90% DoD does not do the same damage as one cycle to 50% DoD, but it is close and in some models it is assumed to be linear. Generally speaking, limiting the discharge a certain maximum DoD will increase the life of the battery bank but it will also increase the initial cost since a larger battery will have to be used to keep the same available battery capacity.

Table A.1 *Maximum discharge thresholds for different battery types*

Battery type	Maximum DoD
Industrial, tubular plate	80%
Industrial, flat plate	80%
SLI	30%

11. To achieve proper life and performance, batteries must be carefully treated:
    - Do not short-circuit the battery terminals. This can cause or the plates to buckle and the battery to explode, which may expose people to battery acid.
    - The battery should be transported carefully and not subjected to sharp movements as the case or active plate matter may be damaged)
    - Do not subject a battery to temperatures above 30 °C when in storage or during operation. Efforts should be made to be sure that batteries are stored and operated in the temperature range specified by the manufacturer. If no detailed information by the manufacturer is given, 15 - 20°C should be used for RES batteries.
    - Do not subject batteries to excessive overcharge, specifically VRLA batteries that will vent and dry out. Flooded batteries will require more distilled water and excessive overcharge will damage the battery plate active material.
    - Do not tamper with the vents on a VRLA battery (gassing may then occur rather than recombination, and the battery may dry-out more quickly).

12. If a battery is stored, then it should be recharged every 6 months, and kept in a cool place below 25 deg C.

Table A.2 supplies a summary of important parameters of the lead acid battery types.

Table A.2 *Comparison of the three main types of lead acid batteries: flooded, AGM and gel*

	Valve Regulated Battery		
	AGM	Gel	Flooded
Self discharge losses [%/month]	1-3%	1-3%	3-5%
Gassing	Almost absent, but safety regulations need to be observed	Almost absent, but safety regulations need to be observed	Can be substantial and leads to water loss which must be replaced.
Spilling	Spill proof	Spill proof	Spillable
Orientation	Can be placed upright or on its side	Can be placed upright or on its side	Can only be placed upright
Water consumption	No additional water is required nor possible to add	No additional water is required nor possible to add	Dependent on the use, topping up with distilled water required.
Safety in marine environment	No chlorine forming as a result of mixing of sulphuric acid and salt water	No chlorine forming as a result of mixing of sulphuric acid and salt water	Possible formation of chlorine
Air transport possible	Yes	Yes	Yes, but only in dry charged state
Over voltage tolerance	Less tolerant, temperature compensation for charging required.	Less tolerant, temperature compensation for charging required.	Good: accepts higher recharge voltages
Susceptibility to electrolyte stratification	Upright tall cells are sensitive Otherwise low sensitivity	No sensitivity	High sensitivity (requires active or passive electrolyte mixing)
High Temperatures	Can be damaged by high temperatures	Can be damaged by high temperatures	Can withstand high temperatures though it may decrease expected life
Initial cost comparison	100 – 150 Euro/kWh	150 – 200 Euro/kWh	50 – 100 Euro/kWh
Shelf life of new battery	6 months	6 months	Filled: 3 months Dry: 2 years
Cycle life with moderate charge / discharge cycles	Medium	Good	Car batteries: Bad Flat plate, industrial and traction batteries: Good Solar and tubular batteries: Very good

A.2 General recommendations for selection of charge controllers

1. It is essential to use a charge controller that protects the battery from both overcharging and deep discharging (by disconnecting the load).

2. It is preferable to use a charge controller with adjustable set points. The choice of the settings of the charge controller is important for all battery types and must be chosen in accordance with the specifications of the battery manufacturer for RE systems. The charge controller should allow the battery to reach an equalization[11] voltage from time to time. Some charge controllers lower the charge voltage after reaching full charge (float charging[12]). If no recommendations for the battery are given then following settings should be used.

Table A.3 *Default battery voltage set points*

Battery type =>	Vented / Flooded V per cell at 25°C	Sealed/VRLA V per cell at 25°C
Bulk/boost charge 2 hours / day[13]	2.4	2.4
Equalization[13] 6 hours / month	2.45 to 2.55	2.45
Low voltage disconnect, for discharge current I10	1.80 to 1.85	1.80 to 1.85
Low voltage disconnect, for discharge current 10% of I10	1.95 to 2.0	1.95 to 2.0
Float charge	2.35	2.30

3. If the battery will be operated outside the temperature range of 20-30 degrees it is preferable to use a charge controller that compensates for the effect of the battery temperature. It will adjust the controller settings to ensure that charge and discharge cycles are modified based on temperature. The sensor should be attached to or placed in the electrolyte of a battery in the middle of the array to ensure that the actual battery temperature is measured instead of the ambient temperature. The control algorithm of the charge controller can be based on a SoC calculation or on voltage settings. It is preferable to use a charge controller that protects the battery from a low state of charge by calculating the SoC of the battery. The settings of the controller must be chosen in accordance with the specifications of the battery manufacturer. If no specification is given, typically a minimum SoC value of 70% for the common car battery and 20% for batteries designed for deep discharge operation should be used.

4. It is preferable to use a charge controller with separate voltage sense-terminals. Otherwise the resistance of the cable between the battery and the charge controller, in combination with the charge or discharge current, can result in an incorrect voltage measurement.

5. It is essential to ensure that the charge controller has a means for selecting the applied type of battery (i.e. vented or sealed) to ensure that the correct charge regime is applied

[11] Equalisation voltage is a relatively high charging voltage and must be maintained only during a limited period of time. Charging at the equalization voltage brings all cells to the same state of charge and removes electrolyte stratification in flooded cells

[12] Float charging is charging at a relatively low voltage. It is applied after a full battery charge at normal (bulk) charge. It is sometimes called "trickle charge".

[13] These are cumulative values: 2 h/day means that it is recommended to keep the battery in the specified situation during a total of 2 hours per day, not necessarily consecutively. The values are target values, not minimum or maximum values.

for battery type. This is especially important for VRLA batteries since overcharging will dry out the battery electrolyte.

A.3 General recommendations for system design

All battery installations should be complete to meet any local or national standards or building codes. If none are locally available, international standards can be considered, such as EN 50272-2:2001 or IEC 62257 for off grid power systems.

1. Always install a battery in a well-ventilated container or room. There must be sufficient airflow, which is top-vented to the outdoors to allow the gas to escape. Never install any battery inside a completely sealed container since all batteries will produce hydrogen and oxygen and may cause a risk of explosion. Industrial standards allow for VRLA batteries to be installed in areas with a reduction of the air exchange rate by a factor of four in comparison with flooded batteries.

2. Never mix different types and sizes of batteries in the same battery bank. Putting a new battery in an old battery bank should be avoided.

3. It is not recommended to buy a flooded battery when it is more than 3 months old unless it has been recharged periodically or it has been stored dry-charged, without electrolyte. Depending on the storage temperature AGM and gel batteries can be stored up to 6-18 months before internal damage has occurred. Always commission a battery properly by giving it a full charge (according to DIN EN or battery manufacturer recommendations)

4. In a renewable energy system without a backup generator the battery capacity and size of the photovoltaic (PV) array and/or the wind generator must be matched to make it possible for the generators to fully charge the battery regularly (at least monthly).

A.4 General recommendations for battery operation and maintenance

There is no such thing as a "maintenance-free" technical product. In cases where regular maintenance is not guaranteed it is better to choose a Valve Regulated Lead Acid battery (VRLA). In cases where regular maintenance (once every six months) is guaranteed, the vented battery is a good choice.

1. For vented batteries the electrolyte levels should be topped up to the maximum level indication at every maintenance interval. Distilled (or deionised or demineralised) water must be used for this. Using ordinary tap water will reduce the lifetime of the battery considerably and this damage cannot be repaired. If possible allow for full recharge after topping up with water.

2. Never add acid to the battery.

3. Keep the battery clean and dry.

4. Terminals should be kept clean and connected tightly to the leads. Anti-corrosion materials can be used to protect battery terminals and leads.

5. Make all attempts to keep the battery within the temperature range as specified by the manufacturer.

6. Batteries should be kept in a thermally insulated location whenever the ambient temperatures may go above 30°C frequently and/or there is a risk of temperatures below 0ºC. Batteries should always be protected from direct solar radiation or other heat sources. For example batteries can be placed in insulated containers buried in the ground.

7. Even a stored new battery will lose charge due to self-discharge. Store the battery in a cool place and recharge it once every three months for flooded types and once every six months for VRLA.

A.5 General recommendations for safety

1. Health and safety regulations of the country should be observed at all times.

2. Lead-acid batteries contain sulphuric acid (H_2SO_4), which is corrosive and can cause skin burns and dermatitis by skin contact. Follow all safety recommendations of the manufacturer. At the least gloves and eye protection should be worn when handling batteries. Further information can be found on the "Safety data sheet on accumulator acid (diluted sulphuric acid)" (http://www.zvei.org/uploads/tx_ZVEIpubFachverbaende/04E_01.pdf).

3. Cigarettes, naked flames or sources of electrical sparks must be kept well away from the batteries. This is due to hydrogen and oxygen being formed during charging and so creating an explosive hazard. Synthetic fibres can generate static electricity, an explosion risk near batteries, so such clothes should not be worn when working on batteries.

4. Remove all metallic objects such as rings, wristwatches and neck and wrist chains before commencing any work on batteries.

5. Wear protective rubber gloves to minimize the possibility of electric shock.

6. Always isolate batteries before working on them. Break live connections at furthest point from the battery.

7. Always use insulated, open-ended tools while connecting or disconnecting batteries or cells to guard against shorting the battery.

8. All battery rooms and storage lockers should be properly labeled with warning signs indicating the presence of acid and danger of explosion.

9. A fire extinguisher and acid neutralizer should be kept in close proximity to the battery bank.

10. It is recommended that a secondary container be used to prevent damage caused by spilled acid.

Further information: Instructions for the safe handling of lead-acid accumulators (http://www.zvei.org/uploads/tx_ZVEIpubFachverbaende/01E.pdf)

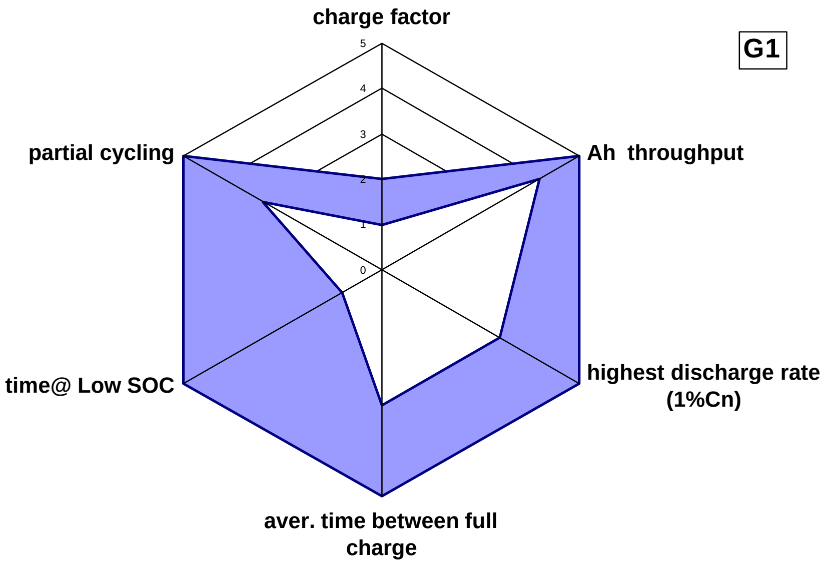
APPENDIX B SPECIFIC RECOMMENDATIONS FOR THE VARIOUS CATEGORIES OF SIMILAR BATTERY USE

(see chapter 7, levels 2 and 3)

Information on category G1

The typical operation of such of RES may be characterised as a relatively full cyclic operation with battery deep discharge. The charge factor is low and the full recharge happens relatively seldom. The battery may also rest a long time in discharged state below the specified 35% SoC. The RES battery operates often at partial SoC at a high discharge rate.

Intensity levels of stress factors of category 1



Ageing mechanisms risk of category G1

The category is associated with a very high risk of the hard/irreversible sulphation, the electrolyte stratification, the AM degradation and also the weakest cell to deep discharge and reverse polarisation. There is a high risk of AM shedding.

- The high risk ageing mechanisms may cause relatively fast fading of the battery power performance that may already start to influence the RES performance due to medium to high discharge current. Also the capacity fade appears parallel with the power fade that limits the RES performance.
- Due to the limited recharge and deep discharge at high current rate the weakest cells may be reverse-polarized at discharge particularly in case of a higher voltage (many cells in series) battery. The reverse polarisation accelerates ageing of the battery.
- A risk that the shed AM may short circuit the cells exist and depending on the battery type and quality it may be the life limiting ageing mechanism.

Ageing mechanism	*Risk of ageing mechanism*
Corrosion of the positive grid	low
Hard/irreversible sulphation	very high
Shedding	high
Water loss/drying out	very low
AM degradation	very high
Electrolyte stratification	very high
Reverse polarisation of cell	very high
Electrolyte freezing	very high at low environment temp.

Recommendations for category G1

Test procedure for category G1:

NFC58-510 plus PPER (Combined test procedure, ageing ratio 1:1, ref. [3])
See chapter 6 and ref. [3].
As long as no results are available for this combined test procedure, select the battery that has the best results (longest life time) for the two separate test procedures.

Selection of battery and charge controller for category G1:

- It is essential to use a charge controller that protects the battery from deep discharging. The control algorithm of the charge controller can be based on a SoC calculation or on voltage settings. The recommended end-of-discharge-settings of the controller are the following:
  - Low voltage Disconnect, for discharge current I10: 1.80 to 1.85 V/cell
  - Low voltage Disconnect, for discharge current 10% of I10: 1.95 to 2.0 V/cell
- It is essential to use a charge controller that protects the battery from overcharging. The recommended end-of-charge-settings of the controller depend on the type of battery and the category of battery usage. The recommended batteries are given below, in order of preference, together with the recommended voltage settings for the charge controllers at charging.

Recommended battery in order of preference	Controller settings (in V/cell at 25°C)	maint.months
VRLA, tubular plate	Charge: 2.4 V equalisation: 2.5 V (10 h / month)[14]	6
Flooded, tubular plate with electrolyte mixing	Charge: 2.35 V equalisation: 2.45 V (10 h / month)	6
Flooded, tubular plate without electrolyte mixing	Charge: 2.4 V equalisation: 2.55 V (8 h / 2 weeks)	6

- If the battery will be operated outside the temperature range of 20-30 degrees it is preferable to use a charge controller that compensates for the effect of the battery temperature. It will typically adjust settings to ensure that charge and discharge cycles are modified based on temperature and voltage or state of charge. A separate battery temperature sensor should be used.
- It is preferable to use a charge controller with separate voltage sense terminals.

[14] These are cumulative values: 10h/month means that it is recommended to keep the battery in the specified situation during a total of 10 hours per month, not necessarily consecutively. The values are target values, not minimum or maximum values.

More specific recommendations for category G1:

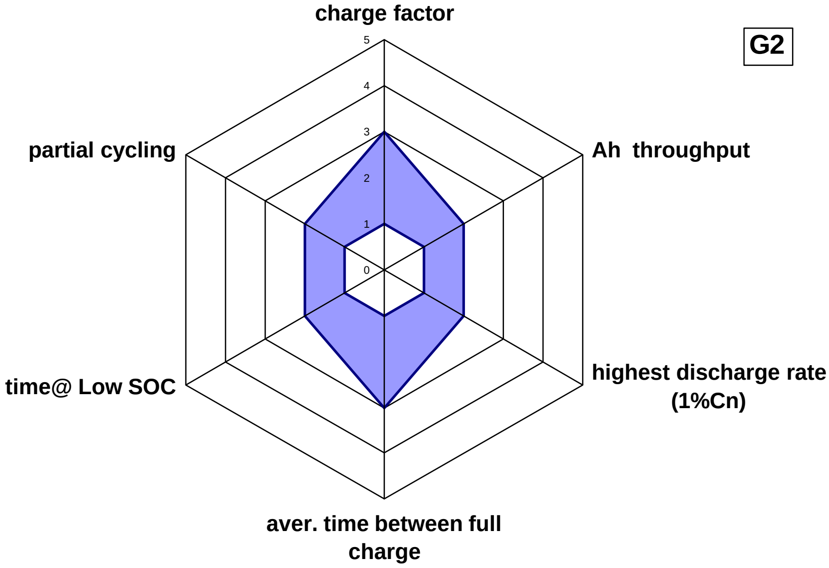
The main battery issues of category G1 are the high energy throughput and the low charge factor. For such systems, the main improvement is the increase of the charge factor. To achieve this the following actions should be considered.

1. Apply the recommended values for the setpoints of the charge controller in the table above.
2. Use a charge controller with a low self-consumption and with a high efficiency.
3. Reduce the load (e.g. by replacing appliances by more efficient ones)
4. Increase the electricity generation of the renewable energy sources
5. Use (or increase the use of) a back-up generator. The most efficient way is to use the back-up generator starting early in the morning and, once the threshold voltage of the battery is reached and the power output of the back-up generator is beginning to fall, continue charging the battery by means of the renewable energy source.
6. Replace the battery with a battery of lower capacity if this is possible. Due to the low charge factor, the capacity of the battery is likely to decrease quickly and therefore a battery with a lower nominal capacity but proper charge factor is likely to offer a better long-term security of supply.
7. In the case of a low ambient temperature (high value of the low environmental temperature factor) the battery should be thermal protected to avoid electrolyte freeze that may happen due to the deep discharge conditions, possibly long time at a low SoC and the electrolyte stratification

Information on category G2

The typical operation of such of RES may be characterised as a stand-by or a very mild operation. The battery is only very seldom discharged and the battery is mostly kept at high SoC.

Intensity levels of stress factors of category 2



Ageing mechanisms risk of the category G2

- The category is associated with a very low risk of hard/irreversible sulphation that may be mostly driven by the charge parameters and also with a very low risk of the electrolyte stratification and the AM degradation. On the other hand there is a medium risk of corrosion and water loss, for VRLA drying out and thermal runaway.
- Water loss is reduced by optimal charge control and reliable automatic water refill. The battery life is mostly driven by corrosion. The corrosion process is accelerated by voltage and temperature among other parameters.

Ageing mechanism	*Risk of ageing mechanism*
Corrosion of the positive grid	medium
Hard/irreversible sulphation	very low
Shedding	very low
Water loss/drying out	medium
AM degradation	very low
Electrolyte stratification	very low
Reverse polarisation of cell	very low
Electrolyte freezing	very low

Recommendations for category G2

Test procedure for category G2:

IEC61427
See chapter 6 and ref. [3].

Selection of battery and charge controller for category G2:

- It is essential to use a charge controller that protects the battery from overcharging. The recommended end-of-charge-settings of the controller depend on the type of battery and the category of battery usage. The recommended batteries are given below, in order of preference, together with the recommended voltage settings for the charge controllers at charging.

Recommended battery in order of preference	Controller settings (in V/cell at 25°C)	maint.months
Flooded, Industrial, thick flat plates, large electrolyte reservoir	Charge: 2.4 V (2h / day)[15] Float 2.3 V equalisation: 2.55 V (5 h / 2 weeks)	3
VRLA, Industrial, thick flat plates	Charge: 2.4 V (2h / day) Float 2.3 V equalisation: 2.5 V (5 h / 2 weeks)	12

- It is essential to use a charge controller that protects the battery from deep discharging. The control algorithm of the charge controller can be based on a SoC calculation or on voltage settings. The recommended end-of-discharge-settings of the controller are the following:
    - Low voltage Disconnect, for discharge current I10: 1.80 to 1.85 V/cell
    - Low voltage Disconnect, for discharge current 10% of I10: 1.95 to 2.0 V/cell
- If the battery will be operated outside the temperature range of 20-30 degrees it is preferable to use a charge controller that compensates for the effect of the battery temperature. It will typically adjust settings to ensure that charge and discharge cycles are modified based on temperature and voltage or state of charge. A separate battery temperature sensor should be used.
- It is preferable to use a charge controller with separate voltage sense terminals.

[15] see note 14

More specific recommendations for category G2:

The main battery issue of category G2 is the range of low charge factor (levels 1, 2 and 3). For VRLA batteries systems with charge factor levels 1 or 2 and for flooded batteries with charge factor levels 1 to 3 the main improvement is the increase of the charge factor. To achieve this the following recommendation is given.

1. Apply the recommended values for the setpoints of the charge controller in the table above.

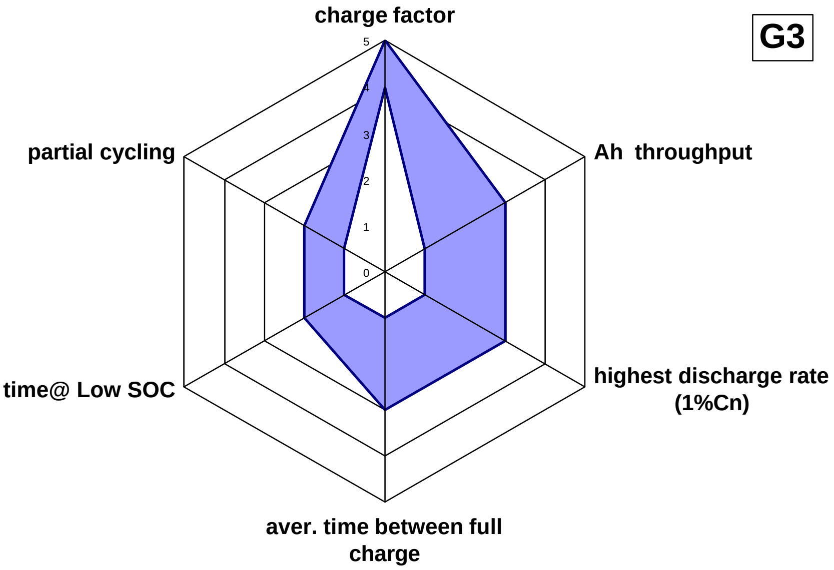
If this first recommendation does not improve the charge factor, consider the following recommendations:

2. Use a charge controller with a low self-consumption and with a high efficiency.
3. Reduce the load (e.g. by replacing appliances by more efficient ones)
4. Increase the electricity generation of the renewable energy sources
5. Use (or increase the use of) a back-up generator. The most efficient way is to use the back-up generator starting early in the morning and, once the threshold voltage of the battery is reached and the power output of the back-up generator is beginning to fall, continue charging the battery by means of the renewable energy source.
6. Replace the battery with a battery of lower capacity if this is possible. Due to the low charge factor, the capacity of the battery is likely to decrease quickly and therefore a battery with a lower nominal capacity but proper charge factor is likely to offer a better long-term security of supply.

Information on category G3

The typical operation of such of RES may be characterised as a very low to medium throughput operation. The battery is charged with very high charge factor and the full recharge happens usually very often.

<u>Intensity levels of stress factors of category G3</u>



<u>Ageing mechanisms risk of category G3</u>

The category is associated with a very high risk of the corrosion and the water loss, in VRLA the drying out and the thermal runaway. The category has a high risk of the AM shedding. On the other hand the category is associated with a very low risk of the electrolyte stratification and the AM hard/irreversible sulphation.

- The very high risk of corrosion and water loss/drying out and the high risk of AM shedding may lead to an internal short circuit and a sudden death of the battery. In this case the corrosion process is accelerated by a very high charge factor (high charge voltage). The very high charge factor in the case of VRLA battery may lead to very fast drying out or thermal runaway. The extensive water loss/drying out results in power properties fading, the danger of a high gas evolution and later to a fast capacity fading.
- Particularly in areas with a high environmental temperature a thermal management may be a significant issue in this case. Due to the high charge factor an extensive heating may be expected at charge and appropriate heat dissipation should be guaranteed. Otherwise, gassing is even more accelerated and the battery may be destroyed by overheating (thermal runaway at VRLA). A high battery temperature accelerates corrosion and accelerates degradation of the AM (expander degradation etc.).

Ageing mechanism	*Risk of the ageing mechanism*
Corrosion of the positive grid	very high
Hard/irreversible sulphation	very low
Shedding	high
Water loss/drying out	very high
AM degradation	very low to medium
Electrolyte stratification	very low
Reverse polarisation of cell	very low to medium
Electrolyte freezing	very low to medium

Recommendations for category G3

Test procedure for category 3:

IEC61427 plus Qualibat (Combined test procedure, ageing ratio 1:0.3)
See chapter 6 and ref. [3].
As long as no results are available for this combined test procedure, select the battery that has the best results (longest life time) for the two separate test procedures.

Selection of battery and charge controller for category G3:

- It is essential to use a charge controller that protects the battery from overcharging. The recommended end-of-charge-settings of the controller depend on the type of battery and the category of battery usage. The recommended batteries are given below, in order of preference, together with the recommended voltage settings for the charge controllers at charging.

Recommended battery in order of preference	Controller settings (in V/cell at 25°C)	maint. months
Flooded, Industrial, thick flat plates, large electrolyte reservoir	Charge: 2.4 V (2h / day)[16] Float 2.3 V equalisation: 2.55 V (5 h / 2 weeks)	1
Flooded, Industrial, thick flat plates, Automatic water topping	Charge: 2.4 V (2h / day) Float 2.3 V equalisation: 2.55 V (5 h / 2 weeks)	6

- It is essential to use a charge controller that protects the battery from deep discharging. The control algorithm of the charge controller can be based on a SoC calculation or on voltage settings. The recommended end-of-discharge-settings of the controller are the following:
  - Low voltage Disconnect, for discharge current I10: 1.80 to 1.85 V/cell
  - Low voltage Disconnect, for discharge current 10% of I10: 1.95 to 2.0 V/cell
- If the battery will be operated outside the temperature range of 20-30 degrees it is preferable to use a charge controller that compensates for the effect of the battery temperature. It will typically adjust settings to ensure that charge and discharge cycles are modified based on temperature and voltage or state of charge. A separate battery temperature sensor should be used.
- It is preferable to use a charge controller with separate voltage sense terminals.

More specific recommendations for category G3:

The main battery issue of category G3 is the high charge factor. For flooded batteries[17] the optimum is about 120% (intensity level 4) and for VRLA batteries about 110% (intensity level 3). For flooded batteries with a charge factor intensity of 5 and VRLA batteries with a charge factor intensity of 4 or 5, measures should be taken to reduce the charge factor such as:

1. Apply the recommended values for the setpoints of the charge controller in the table above.
2. Optimise the orientation (tilt and azimuth) of the PV-module for the period of low irradiance (e.g winter).
3. Check whether the capacity of the renewable energy generator is not unnecessarily high for the required loss-of load probability. This can also lead to reduced investment costs.

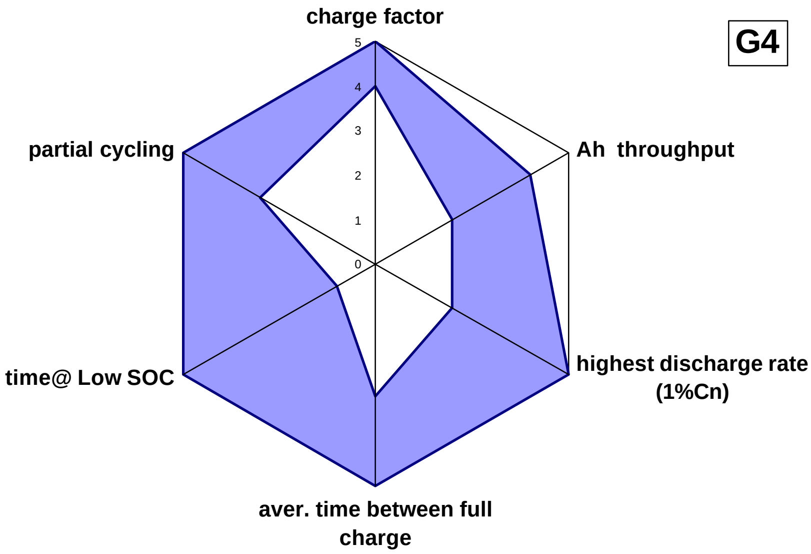
[16] see note 14
[17] Combined with the Ah-throughput of up to 70 times the nominal battery capacity, the amount of water that will be lost per year is at the most ca. 8 g of distilled water per cell per Ah of nominal capacity (0.3 x 70 x 0.336g)

4. If a backup-generator is installed, consider reducing its operating time and making sure that the generator is not operated in the morning to increase the state of charge of the battery. PV production during the day will then likely lead to this considerable overcharging.

Information on category G4

The typical operation of such of RES may be characterised as a medium to a high throughput operation at PSoC cycling with a long time between full recharge and high charge factor. The discharge rate may be high immediately followed by some recharge that frequently does not bring the battery to 100%SoC. If the full charge is realised then the charge factor is too high.

<u>Intensity levels of stress factors of category 4</u>



<u>Ageing mechanisms risk of the category G4</u>

- There is a complex of different dominating ageing mechanisms at batteries operating in this category, these are:
- The very high AM shedding reduces the amount of available AM and reduces the electrode-electrolyte interface properties
- The high corrosion limits particularly the life of the positive electrode
- Corrosion products and shed AM may cause an internal short circuit and a sudden death of the battery
- The high electrolyte stratification decreases the power performance and capacity
- The high water loss decreases power performance and capacity
- The high charge factor leads to the battery overheating and in the case of VRLA battery it may lead to thermal runaway
- Possibly the battery performance may be limited by the AM degradation (AM porosity change, recrystallisation and particle size, reduction of the active AM surface, etc.)

Ageing mechanism	*Risk of ageing mechanism*
Corrosion of the positive grid	high
Hard/irreversible sulphation	medium
Shedding	very high
Water loss/drying out	high
AM degradation	low to high
Electrolyte stratification	high
Reverse polarisation of cell	medium
Electrolyte freezing	medium

Recommendations for category G4

Test procedure for category G4:

IEC61427 plus Qualibat (Combined test procedure, ageing ratio 1:1.5)
See chapter 6 and ref. [3].
As long as no results are available for this combined test procedure, select the battery that has the best results (longest life time) for the two separate test procedures.

Selection of battery and charge controller for category G4:

- It is essential to use a charge controller that protects the battery from overcharging. The recommended end-of-charge-settings of the controller depend on the type of battery and the category of battery usage. The recommended batteries are given below, in order of preference, together with the recommended voltage settings for the charge controllers at charging.

Recommended battery in order of preference	Controller settings (in V/cell at 25°C)	maint. months
Flooded, tubular plate with electrolyte mixing	Charge: 2.45 V (2h / day)[18] Float 2.35 V equalisation: 2.55 V (8 h / 2 weeks)	6
VRLA, tubular plate	Charge: 2.45 V (2h / day) Float 2.35 V equalisation: 2.5 V (10 h / month)	12

- It is essential to use a charge controller that protects the battery from deep discharging. The control algorithm of the charge controller can be based on a SoC calculation or on voltage settings. The recommended end-of-discharge-settings of the controller are the following:
    - Low voltage Disconnect, for discharge current I10: 1.80 to 1.85 V/cell
    - Low voltage Disconnect, for discharge current 10% of I10: 1.95 to 2.0 V/cell
- If the battery will be operated outside the temperature range of 20-30 degrees it is preferable to use a charge controller that compensates for the effect of the battery temperature. It will typically adjust settings to ensure that charge and discharge cycles are modified based on temperature and voltage or state of charge. A separate battery temperature sensor should be used.
- It is preferable to use a charge controller with separate voltage sense terminals.
- In a system with a high charge factor and a long average time between full charge, one can consider to replace part of the storage capacity with a back up generator.

[18] see note 14

More specific recommendations for category G4:

The main battery issues of category G4 are operation at low state of charge, long time between full charge and high partial cycling intensity despite a high charge factor. Such conditions can only exist, if there are distinct differences in operation, e.g. a very high charge factor when the battery is full anyway and very poor operating conditions with cycling at low state of charge and infrequent full charge. To improve battery performance, both conditions have to be addressed.

To improve the low state of charge situation:
1. Apply the recommended values for the setpoints of the charge controller in the table above.
2. Use a charge controller with a low self-consumption and with a high efficiency.
3. Reduce the load (e.g. by replacing appliances by more efficient ones)

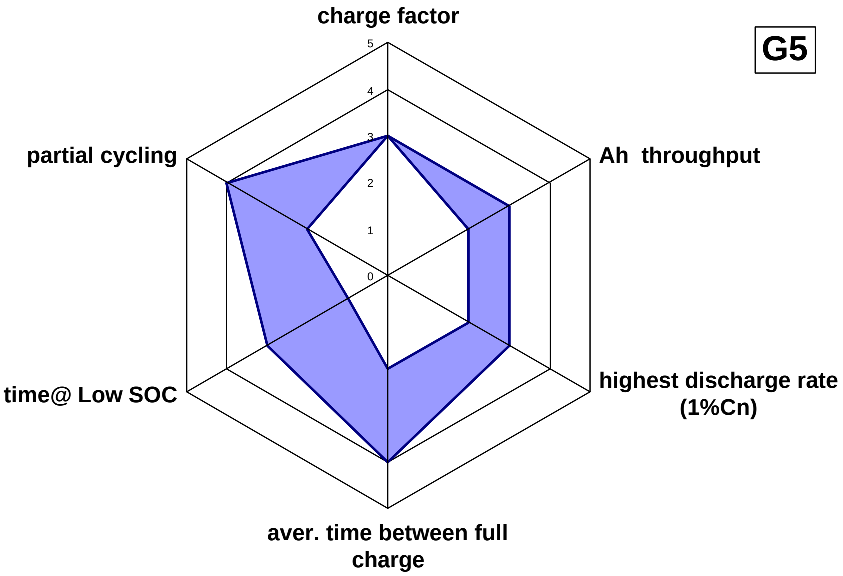
For flooded batteries with a charge factor of intensity level 5 and VRLA batteries with a charge factor of 4 or 5 measures should be taken to reduce the charge factor such as:
1. Optimise the orientation (tilt and azimuth) of the PV-module for the period of low irradiance (e.g. winter).
2. If a backup-generator is installed, consider reducing its operating time and making sure that the generator is not operated in the morning to increase the state of charge of the battery. PV production during the day will then likely lead to this considerable overcharging.

Particularly in a high temperature environment there should be concern about the battery thermal protection. The battery thermal control management particularly of the auxiliary cooling system may be necessary due to the high charge factor possibly leading to an overcharge requiring an extensive heat dissipation. Attention should be paid also to low environmental conditions that would require thermal protection against the electrolyte freeze.

Information on category G5

The typical operation of such of RES may be characterised as a medium throughput operation at partial SoC cycling without a deep discharge or resting in a discharged state. The charge is realised by a medium charge factor. The highest discharge rate is low to medium. The RES systems in this category seems to be well optimised.

<u>Intensity levels of stress factors of category 5</u>



<u>Ageing mechanisms risk of category G5</u>

There is a medium risk of hard/irreversible sulphation, electrolyte stratification and AM degradation.

Ageing mechanism	*Risk of the ageing mechanism*
Corrosion of the positive grid	low to medium
Hard/irreversible sulphation	medium
Shedding	low to medium
Water loss/drying out	low to medium
AM degradation	medium
Electrolyte stratification	medium
Reverse polarisation of cell	low
Electrolyte freeze	low

Recommendations for category G5

Test procedure for category G5:

NFC58-510 plus PPER (Combined test procedure, ageing ratio 1:1)
See chapter 6 and ref. [3].
As long as no results are available for this combined test procedure, select the battery that has the best results (longest life time) for the two separate test procedures.

Selection of battery and charge controller for category G5:

- It is essential to use a charge controller that protects the battery from overcharging. The recommended end-of-charge-settings of the controller depend on the type of battery and the category of battery usage. The recommended batteries are given below, in order of preference, together with the recommended voltage settings for the charge controllers at charging.

Recommended battery in order of preference	Controller settings (in V/cell at 25°C)	maint. months
Flooded, industrial flat plate with electrolyte mixing	Charge: 2.45 V (2h / day)[19] Float 2.35 V equalisation: 2.55 V (8 h / 2 weeks)	6
VRLA, flat plate	Charge: 2.45 V (2h / day) Float 2.35 V equalisation: 2.5 V (10 h / month)	12

- It is essential to use a charge controller that protects the battery from deep discharging. The control algorithm of the charge controller can be based on a SoC calculation or on voltage settings. The recommended end-of-discharge-settings of the controller are the following:
    - Low voltage Disconnect, for discharge current I10: 1.80 to 1.85 V/cell
    - Low voltage Disconnect, for discharge current 10% of I10: 1.95 to 2.0 V/cell
- If the battery will be operated outside the temperature range of 20-30 degrees it is preferable to use a charge controller that compensates for the effect of the battery temperature. It will typically adjust settings to ensure that charge and discharge cycles are modified based on temperature and voltage or state of charge. A separate battery temperature sensor should be used.
- It is preferable to use a charge controller with separate voltage sense terminals.

More specific recommendations for category G5:

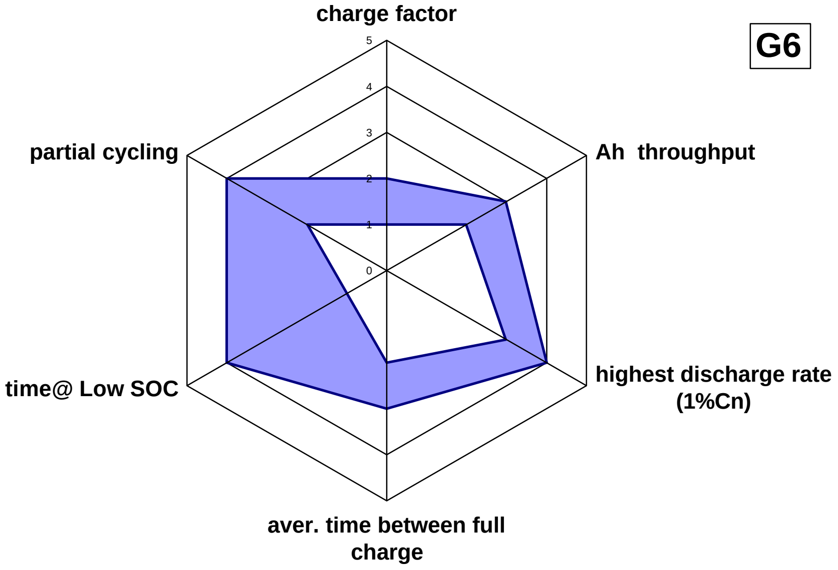
The operating conditions of the battery in category G5 are good. Only in case of flooded batteries a small increase in the charge factor would be beneficial.
The following recommendations are made:
1. Apply the recommended values for the setpoints of the charge controller in the table above.
1. Use a charge controller with a low self-consumption and with a high efficiency.
2. Reduce the load (e.g. by replacing appliances by more efficient ones)

Information on category G6

The typical operation of such of RES may be characterised as a medium throughput operation at a partial SoC cycling with a low charge factor.

[19] see note 14

Intensity levels of stress factors of category 6



Ageing mechanisms risk of category G6

The typical dominating degradation mechanisms of hard/irreversible sulphation and electrolyte stratification leads to gradual fading of the power performance and of the capacity. The slope of the capacity and power fading depends on the battery type and quality; in the best case the slope may be very low.

Ageing mechanism	*Risk of the ageing mechanism*
Corrosion of the positive grid	very low to low
Hard/irreversible sulphation	high
Shedding	low to medium
Water loss/drying out	very low to low
AM degradation	medium
Electrolyte stratification	high
Reverse polarisation of cell	medium to high
Electrolyte freezing	medium to high at a low environmental temperature

Recommendations for category G6

Test procedure for category G6:

NFC58-510 plus PPER (Combined test procedure, ageing ratio 1:1)
See chapter 6 and ref. [3].
As long as no results are available for this combined test procedure, select the battery that has the best results (longest life time) for the two separate test procedures.

Selection of battery and charge controller for category G6:

- It is essential to use a charge controller that protects the battery both from overcharging. The recommended end-of-charge-settings of the controller depend on the type of battery and the category of battery usage. The recommended batteries are given below, in order of preference, together with the recommended voltage settings for the charge controllers at charging.

Recommended battery in order of preference	Controller settings (in V/cell at 25°C)	maint. months
Flooded, industrial flat plate with electrolyte mixing	Charge: 2.45 V (2h / day)[20] Float 2.35 V equalisation: 2.55 V (8 h / 2 weeks)	6
VRLA, flat plate	Charge: 2.45 V (2h / day) Float 2.35 V equalisation: 2.5 V (10 h / month)	12

- It is essential to use a charge controller that protects the battery both from deep discharging. The control algorithm of the charge controller can be based on a SoC calculation or on voltage settings. The recommended end-of-discharge-settings of the controller are the following:
    - Low voltage Disconnect, for discharge current I10: 1.80 to 1.85 V/cell
    - Low voltage Disconnect, for discharge current 10% of I10: 1.95 to 2.0 V/cell
- If the battery will be operated outside the temperature range of 20-30 degrees it is preferable to use a charge controller that compensates for the effect of the battery temperature. It will typically adjust settings to ensure that charge and discharge cycles are modified based on temperature and voltage or state of charge. A separate battery temperature sensor should be used.
- It is preferable to use a charge controller with separate voltage sense terminals.

[20] see note 14

More specific recommendations for category G6:

The main battery issue of category G6 is the low charge factor. To improve this the following actions should be considered.

1. Apply the recommended values for the setpoints of the charge controller in the table above.
2. Use a charge controller with a low self-consumption and with a high efficiency.
3. Reduce the load (e.g. by replacing appliances by more efficient ones)
4. Increase the electricity generation of the renewable energy sources
5. Use (or increase the use of) a back-up generator. The most efficient way is to use the back-up generator starting early in the morning and, once the threshold voltage of the battery is reached and the power output of the back-up generator is beginning to fall, continue charging the battery by means of the renewable energy source.
6. Replace the battery with a battery of lower capacity if this is possible. Due to the low charge factor, the capacity of the battery is likely to decrease quickly and therefore a battery with a lower nominal capacity but proper charge factor is likely to offer a better long-term security of supply.

<u>Specific recommendations regarding the two temperature-related stress factors (applies to all 6 categories):</u>

<u>RE-systems with “low ambient temperature” 4 or 5:</u>

- Low battery temperature lowers the capacity of the battery. This is entirely reversible but it must be taken into account when sizing the battery.
- To prevent damage due to freezing:
    - Consider the use of a NiCd battery.
    - Use a lead acid battery with a relative high electrolyte density and a large electrolyte surplus.
    - Use a packaging for the battery which has a high thermal capacity if low temperature periods last only a short time.
    - Store the battery in a heated room.
    - Prevent a low state of charge of the battery

<u>RE-systems with a high ambient temperature (“temperature acceleration factor” equals 4 or 5):</u>

- Use a flooded battery if regular water topping is guaranteed
- In case of a flooded battery automatic water topping is recommended
- locate the battery outside the direct sunlight in a container with high thermal mass (which leads to temperature-averaging)

APPENDIX C ESTIMATION OF “CATEGORY OF SIMILAR USE” FOR SYSTEMS WITH LIMITED DESIGN INFORMATION

(see chapter 7, level 2)

When time series data of battery currents are available, the computer software ITHESA can automatically generate the indices for the stress factors, which are used for categorisation of systems with similar use (ch. 7, level 3). When no such time series data is available, a design tool can be used to determine system parameters such as the amount of generated electricity by renewable energy sources and the capacity of the storage system (ch. 7, level 2). If these parameters are supplemented with the answers for a number of additional questions, sufficient information can be obtained to estimate the indices for the 8 stress factors and then the applicable category of similar use. The procedure for estimating the category of similar use is facilitated by an automated web based tool in RESDAS. If the automated process in RESDAS cannot be used, the procedure is outlined below.

Table C.1 shows the required information to determine the different stress factors.

Table C.1 *Required information for determining the battery stress factors*

	Required information	Stress factors
1	Average daily load Average daily energy generation	Charge factor Ah throughput
2	SoC curve/distribution	Average time between full charge Time at low SoC Partial cycling
3	Maximum power of the load	Highest discharge rate
4	Battery temperature	Temperature acceleration factor Low battery environmental temperature

Relevant output from a system design tool

With a design tool, a number of system parameters can be determined that provide useful input for finding the battery stress factors. These parameters are:

- Battery capacity C_{10} in Ah or the equivalent amount C_E in kWh;
- Daily average of energy supplied to the load E_{load} in kWh/day;
- Daily average energy generated that is available to the load or can be stored E_{gen} in kWh/day
- Direct use of electricity, not via storage, as a percentage of the energy to the load or in kWh per day E_{dir}

<u>Charge factor</u>

The Charge Factor (CF) is defined as the ratio between the charge entering the battery divided by the charge that can be extracted from the battery.

The charge is calculated as the integral of the current over time and is presented in Amp-hours, Ah. To avoid errors, it is important to use time intervals where the battery has at the beginning and at the end the same state of charge or alternatively long periods where the charge throughput is high in comparison to the differences in state of charge.

$CF = Q_{in}/Q_{out} * 100\%$

A second option (less preferred) to determine the charge factor is by the use of the energy efficiency. As a rule of thumb it is assumed that the charge factor is equal to the reciprocal value of the energy efficiency minus 10%. The 10% correction is due to differences in voltage levels between charging and discharging, which are in the order of about 10%.

- The average daily energy flow into the battery E_{in} is the difference between energy generated E_{gen} and directly used energy E_{dir}: $E_{in} = E_{gen} – E_{dir}$
- The average daily energy flow out of the battery Eout is the difference between the daily energy load E_{load} and the directly used energy: $E_{out} = E_{load} – E_{dir}$

$CF_{estimate} = E_{in} / E_{out} *100\% - 10\%$

Indexation of the charge factor:

5: very high intensity >130 (%)
4: high intensity (115 ; 130]
3: medium (108 ; 115]
2: low (102 ; 108]
1: very low <=102

Ah throughput

The annual Amp-hour Throughput (AT) is defined as:

$AT = Q_{out}/C_{10}$

Where Q_{out} is the charge extracted from the battery per year, and C_{10} the capacity of the battery.

If your design tool cannot provide you with the precise amount of Ah throughput in a year, it can be estimated based on the energy extracted from the battery. As a rule of thumb it is assumed that:

$AT_{estimate} = E_{out} / C_E *1.05$

Where E_{out} is the energy extracted from the battery in a year [kWh/year], and C_E the battery capacity in units of kWh obtained by multiplying battery capacity C_{10} with the nominal voltage of the battery bank.

Indexation of the Ah throughput:

5: very high intensity >100 (C_{10})
4: high intensity (70 ; 100]
3: medium (40 ; 70]
2: low (10 ; 40]
1: very low <= 10

Highest discharge rate

Many appliances require a peak current, usually during starting, that is several times higher than the current associated with continuous operation. The highest discharge rate is defined here as the highest current at which 1% of the Ah throughput was discharged. Starting current peaks typically lasts in the order of seconds. When they occur once every few hundred seconds, these starting peaks are likely to determine the highest discharge rate.

The Highest Discharge Rate (HDR) is equal to the peak current in units of I_{10}:

HDR = peak current / (C_{10}/10h).

If starting peak currents do not occur frequently the highest discharge rate is most likely determined by the situation that all, or most of the appliances are used at the same time. When no information about peak currents are available, as a rule of the thumb, one can use 2x the wattage for small fans, and 7x the wattage for pumps and compressors.

HDR = P_{max} / (C_E/(10h))

Indexation of the highest discharge rate:

5: very high intensity > 1.7 (I_{10})

4: high intensity (1.4 ; 1.7]

3: medium (0.5 ; 1.4]

2: low (0.1 ; 0.5]

1: very low <=0.1

<u>Temperature acceleration factor</u>

The Temperature Acceleration Factor (TAF) is estimated with three values of the averaged ambient temperature, nights included:

- the averaged summer temperature (T_s)
- the averaged winter temperature (T_w)
- the averaged temperature of the spring and autumn($T_{s\&a}$)

TAF = 0.25 * $e^{k(T_s-T_0)}$ + 0.50 * $e^{k(T_{s\&a}-T_0)}$ + 0.25 * $e^{k(T_w-T_0)}$

With T_0 = 20 °C and k = ln(2)/ 10°C

Indexation of the temperature acceleration factor:

5: very high intensity >1.6 (-)

4: high intensity (1.15 ; 1.6]

3: medium (0.85 ; 1.15]

2: low (0.4 ; 0.85]

1: very low <= 0.4

<u>Low battery environmental temperature</u>

The Low Battery Environmental Temperature (LBET) is the lowest ambient temperature that the battery is exposed to during at least one hour per year.

LBET = T_{min}

Indexation of the low battery temperature:

5: very high intensity <-9 (^{o}C)

4: high intensity [-9 ; -5)

3: medium [-5 ; 0)

2: low [0 ; 5)

1: very low >= 5

Three stress factors that depend on SoC patterns

The remaining stress factors depend on the SoC distribution. Three system and environmental conditions are assumed to be crucial in determining in which category of similar SoC pattern the proposed system falls:

- Availability of a back up generator that can be expected to prevent low battery SoC
- Amount of renewable energy supply compared to the daily load
- Size of the battery compared to the daily load (autonomy, expressed in days).

For certain conditions the choice of relevant SoC pattern is relatively straightforward. These are the following situations:

1. In case autonomy is longer than 20 days
2. When there is a back up generator

3. When the renewable energy component is oversized
4. When the renewable energy sources are undersized, AND there is no back up generator

The intensity levels of the three stress factors that depend on the SoC patterns were estimated for a number of typical conditions. These intensity levels are provided in table C.2.

Table C.2 *Division into conditions with similar SoC patterns and corresponding values for the three SoC-related stress factors*

INPUT: Answer 5 questions with yes (Y), no (N) or don't know (Y/N). The combination of 5 answers will result in the intensity levels of the last 3 stress factors.						
a) Autonomy [21]> 20 days?	Y	N	N	N	N	N
b) Backup generator available?		Y	Y/N	N	N	N
c) Oversized renewables: maximum demand is less than minimum supply		N	Y	N	N	N
d) Undersized renewables [22]		Y/N	N	N	N	Y
e) Autonomy < 2 days?		Y/N	Y/N	Y	N	N
OUTPUT:						
Typical intensity levels for the SoC related stress factors						
Time at low SoC	4	1		3	2	5
Time between full charge	3	1		2	3	5
Partial SoC	3	1		4	2	5

With the now available intensity levels of the 8 stress factors the usage of the battery can be assigned to one of the 6 categories of similar use using the "radar plot diagrams" in paragraph 5 or using RESDAS.
This will lead to specific recommendations for the renewable energy system, given in appendix 2. Additionally to these specific recommendations the following applies:

- In case autonomy > 20 days: The battery you selected has a relatively high capacity. Try not to use the battery at a low State Of Charge. It is much better to use the upper part than the lower part of the capacity.
- In case of a back up generator: Consider the possibility to apply "intelligent charging" by taking the weather forecast into account and anticipate or adapt the load pattern.

[21] Autonomy is defined as battery capacity C_{10} divided by the average daily electricity demand from the battery in Ah/d

[22] The renewable energy source is considered undersized if there is at least one month in which the monthly renewable energy supply is less than the demand in that month when there would be no supply restrictions. This means that there is at least one month with some amount of unmet demand when there is no back up generator.

APPENDIX D THE STRESS FACTOR'S RELATIONS TO THE AGEING MECHANISMS

The effect of the stress factors on the ageing mechanisms is indicated with green (no effect), yellow (medium effect) or blue (strong effect); (ref. [1])

	Corrosion of the positive grid	hard/ irreversible sulphation	shedding	water loss / drying out	AM degradation	Electrolyte stratification
discharge rate	Indirect through positive electrode potential	higher discharge rate creates smaller AM sulfate crystals and leads to inhomogeneous current distribution causing inhom. SOC on the electrode	probably increased shedding due to the electrodes outer AM faction higher DOD level cycling	none	increases inner resistance due to AOS-model (agglomerate of sphere)	Higher discharge rate reduces electrolyte stratification. On the other hand less homogeneous current distribution plays negative role.
time at low states of charge	Indirect through low acid concentration and low potentials	A strong positive correlation: longer time at a low SOC accelerates hard/irreversible sulphation.	no direct impact	none	None	Indirect effect Longer time leads to higher sulphation and thus influences the stratification.
Ah throughput	no impact	no direct impact	impact through mechanical stress	no direct impact	loss of active material structure, larger crystals	A strong positive correlation: Higher Ah throughput leads to higher stratification
charge factor	no direct impact. However, high Ah throughput combined with high charge factor indicates a high risk of corrosion	positive impact through regimes with high charge factor	strong impact through gassing	strong impact	no direct impact	A strong positive correlation: Higher charge factor leads to lower stratification
Time between full charge	Strong negative correlation: shorter time increases corrosion.	Strong positive correlation: Frequent full recharge decreases hard/irreversible sulphation.	A negative influence, increasing with decreasing time.	A negative influence, increasing with decreasing time	no direct impact	A strong positive correlation: Higher Ah throughput leads to higher stratification
Partial cycling	An impact through potential variations (depends on frequency, SOC level, ..)	A positive impact. Higher Ah throughput at lower SOC increases sulphation. Partial cycling (f>1Hz) increases size of lead-sulfate crystals.	no direct impact However when partial cycling is minimal, then the Ah throughput runs at very high SOC level and always to full recharge. It is also reflected by the "time between full recharge"	no direct impact However when PC is of e minimal value, then the Ah throughput runs at very high SOC level and always to full recharge. It is also reflected by the "time between full recharge"	no direct impact However certain partial cycling may cause a preferential discharge and faster AM degradation in certain AM fraction.	Higher partial cycling at lower SOC leads to higher stratification.
Temperature	Strong impact, positive correlation	high temperature has negative impact at low SOC high temperature has positive impact during full charging	no direct impact	increasing with increasing temperature	low impact high temperature degrades neg. electrode expanders	no direct impact.