

PART 1

Storage Requirements Characteristics of Secondary Batteries Examples of Use

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Chapter 1

Breakdown of Storage Requirements

1.1. Introduction

Electrochemical electricity storage has been in use for as long as electricity has been industrially used. The earliest secondary battery was introduced by Gaston Planté in 1859, i.e. between the first laboratory primary battery created by Alessandro Volta in 1800 and the industrial dynamo from Zénobe Gramme in 1869.

1.2. Domains of application for energy storage

Energy storage systems are used in many fields of application. Each of these domains is characterized by specific operational profiles and, consequently, different types and technologies of secondary batteries. They are described below.

Of the major domains of application, we might cite:

- starter batteries;
- traction batteries and on-board batteries;
- stationary deep cycle batteries (batteries for storage in decentralized microgrids with photovoltaic generation, for grid support, etc.);

– standby power batteries (batteries for uninterruptible power supply, for safeguarding information, etc.);

– and, more recently, batteries for mobile devices: portable computers and mobile telephones – in billions of units produced each year – digital cameras, audio and video players, camcorders, PDAs (Personal Digital Assistants), etc.

1.2.1. *Starter batteries*

Better known as “SLI” batteries (for “Start, Lighting and Ignition”), these batteries are used to fire up internal combustion engines (in cars and trucks but also tractors, electrogen groups, or even boats or airplanes, etc.) as well as to provide lighting and many other functions. These batteries have an average specific energy¹ and a low cost.

The profile of the current entering² into an SLI battery, and the evolution of the state of charge (SOC, defined in section 2.4.2) are shown qualitatively below (Figure 1.1). Typically, car batteries have a nominal voltage of 12 V. Their capacity is usually between 40 and 80 Ah. Start currents can reach up to several hundred amperes.³ Measured values are given in section 3.1.1.

In a car with a combustion engine, the battery only supplies energy when the engine is not running, or is running at a slowed speed. When the vehicle is moving, it is the alternator which supplies the demands. When the battery is supplying energy, it is usually quickly recharged by the alternator, and is therefore subjected only to a microcycle. Conversely, in certain trucks, the battery may have to supply certain functions such as the raising/lowering of an unloading tailgate, a refrigeration group, a crane, etc. The battery is then subject to deeper discharges (Figure 1.2).

¹ Volume energy or mass energy: the ratio of the energy stored to the volume or mass (see section 2.4.9).

² Here we choose to work with receiver convention, meaning that the current entering at the positive terminal of the battery, i.e. the current that recharges the battery, is counted positively.

³ For motorcycles, we find 6 V and 12 V batteries. The capacities range from a few Ah to over 30 Ah.

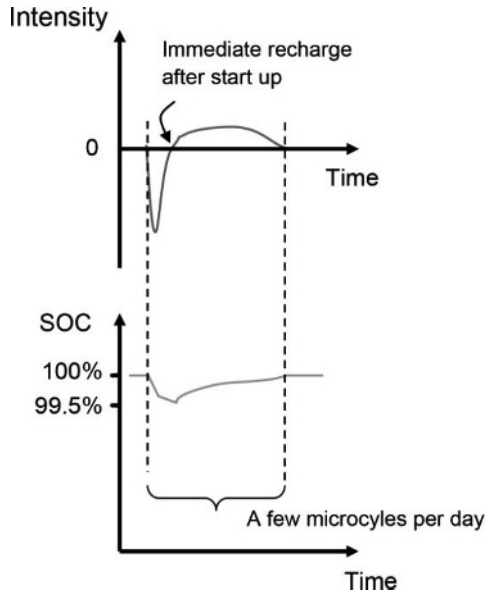


Figure 1.1. Car SLI battery: profile of the current flowing into the battery and change in its SOC

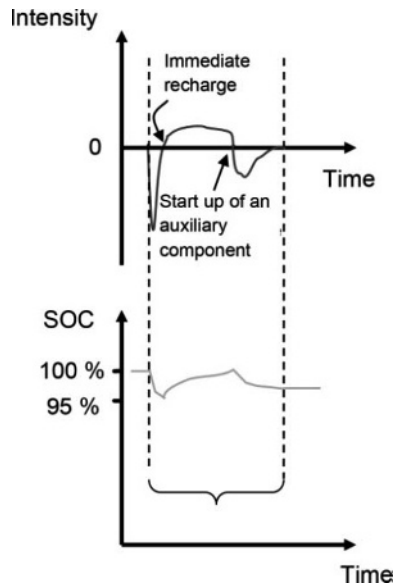


Figure 1.2. SLI battery for a truck with auxiliary functions: profile of current entering into the battery and evolution of its SOC

1.2.2. Traction batteries

Traction batteries are used in forklift trucks, handling and lifting machines, wheelchairs, electrically assisted pedal cycles (EAPCs), electric vehicles (EVs) or hybrid electric vehicles (HEVs), golf buggies, etc. These applications require power to be supplied to the engine but also need sufficient energy to deliver a range (capacity for autonomous operation) which is compatible with their usage.

1.2.2.1. Vehicle batteries without brake energy recovery

The slow speed of certain electrically-motorized vehicles means that, even if the electric power chain is capable of it, kinetic energy is not recovered during braking. Such is the case with many handling and lifting machines, wheelchairs, EAPCs, etc.⁴

For these vehicles, the profile of current running into the battery and the evolution of the SOC are shown in Figure 1.3. They are used in a simple cycle: a discharge of greater or lesser depth, followed by a complete charge. The periods of discharging and charging are thus clearly distinct.

EAPCs have batteries of 24, 36 or 48 V and a capacity of around ten Ah. The batteries used for wheelchairs are generally 12 or 24 V, with capacities of up to a few tens of Ah (usually 20–40 Ah). For handling vehicles such as forklift trucks, several 6 or 12 V batteries are connected in series, with unitary capacities of several hundred Ah.

For this type of application, the technology needs to be adapted: we favor electrode/electrolyte interfaces which offer the largest possible exchange surfaces so as to be able to supply and receive a significant peak power. However, for each application, there is a compromise to be found between the peak power and the stored energy (an explanation of the difference between “energy” batteries and “power” batteries is given in section 5.2.2).

⁴ Motorization by a direct-current (DC) engine and a non-reversible chopper used to be the most widely-used solution. In more modern vehicles, an induction motor is installed, supplied by an inverter. Both the induction motor and the power part of the inverter are naturally reversible, but as yet this possibility has not always been built into the inverter control.

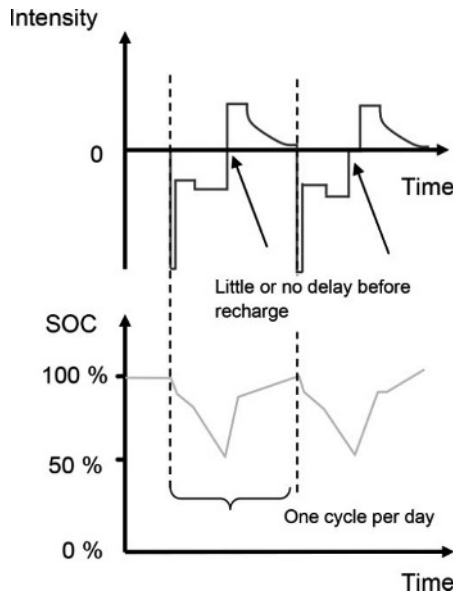


Figure 1.3. *Traction battery: profile of current entering into the battery and evolution of its SOC*

1.2.2.2. *Vehicle batteries with brake energy recovery*

Electric or hybrid cars use batteries whose sizing and design are appropriate to supply the power and/or energy needs to respond to the different usage profiles. In contrast to the applications discussed above, energy is recovered by the battery on braking. Current peaks appear during the phases of braking. The same is true of golf buggies, electric karts, etc. To set these apart from the previous uses, we sometimes find the term “on-board batteries”.

Three usage profiles can be defined for operation in a hybrid vehicle, a hybrid plug-in vehicle (i.e. a rechargeable hybrid) or a pure electric vehicle.

1.2.2.2.1. Hybrid vehicle batteries

Generally speaking, the batteries fitted to a hybrid vehicle tend to be sized for power, because they need to be capable of providing peaks of power during acceleration and being recharged with high intensities during braking. They play the role of an energy buffer between the primary energy source – the combustion engine – and the vehicle’s running needs. The

excursion of the depth of discharge (DOD, see section 2.4.1) is therefore very limited. In order to prevent too high or too low a state of charge (SOC, see section 2.4.2), which may be damaging for the NiMH batteries used, the charge oscillates by a few % around an average state of charge between 40 and 80% (54-56% for the Toyota Prius 2001 in hybrid operation⁵) (Figure 1.4). In the Toyota Prius and the Honda Insight, even with fully electrical operation, the battery management system (BMS) prevents the battery from discharge below a ~40% SOC or from reaching complete charge.

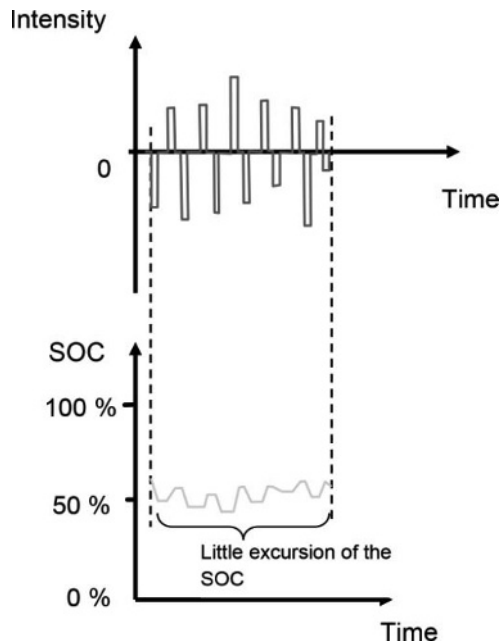


Figure 1.4. *Profile of current entering into the battery and evolution of the SOC for a battery in a hybrid vehicle*

1.2.2.2.2. “Plug-in” hybrid vehicle batteries

For batteries in hybrid vehicles which can be connected to the electrical grid to be recharged (plug-in), the battery can be subjected to a deeper

⁵ K.J. KELLY, M. MIHALIC, M. ZOLOT (National Renewable Energy Laboratory), “Battery usage and thermal performance of the Toyota Prius and Honda Insight during chassis dynamometer testing”, *The Seventeenth Annual Battery Conference on Applications and Advances*, Long Beach, California, 14–18 January 2002.

discharge, because additional recharging from the grid is possible, provided there is a charge point nearby. The batteries have to be able to withstand charge/discharge cycles over a broader range of SOC's used than in the case of batteries for hybrid vehicles (Figure 1.5).

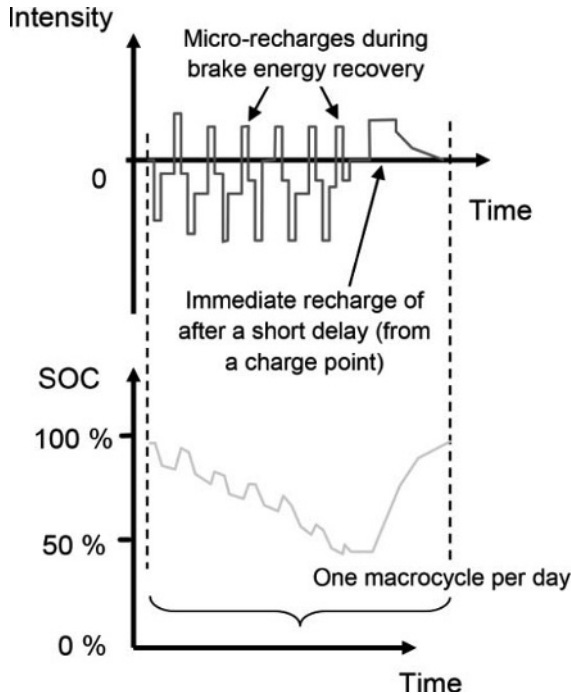


Figure 1.5. Profile of current entering into the battery and evolution of its SOC for a battery in a plug-in hybrid vehicle

1.2.2.2.3. Batteries for all-electric vehicles

The batteries used for an all-electric vehicle tend to be sized for energy (significant capacity) in order to ensure a sufficient range. They undergo a cycle of complete charge and deep discharge nearly every day (see Figure 1.6) and must be designed for such a cycle.

Today, whilst some EVs are to be found which are equipped with lead batteries or ZEBRA batteries (described in Chapter 12), most production uses lithium-ion or lithium polymer metal batteries.

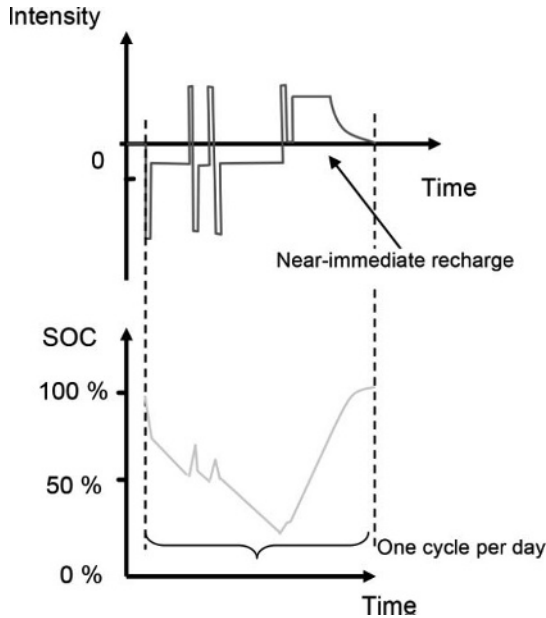


Figure 1.6. Profile of current entering into the battery and evolution of its SOC for an onboard battery in a fully-electric vehicle

1.2.3. Stationary batteries

Stationary batteries are used in very varied applications: Uninterruptible Power Supply (UPS), memory saving, decentralized power supply, grid support, etc.

1.2.3.1. Batteries for autonomous supply

Autonomous supply batteries are usually used when no other source of electricity is available. They are specifically developed to perfectly supply the required cycling profiles. The most apt example is the application of solar power at stand-alone sites, supplying electricity requirements in places far from electrical networks (chalets, mountain shelters, telecommunications outposts, highway information panels, weather stations, etc.).

For a domestic application, the profiles of current entering into the battery and the evolution of the SOC are illustrated diagrammatically in Figure 1.8 and given quantitatively in section 3.1.3.

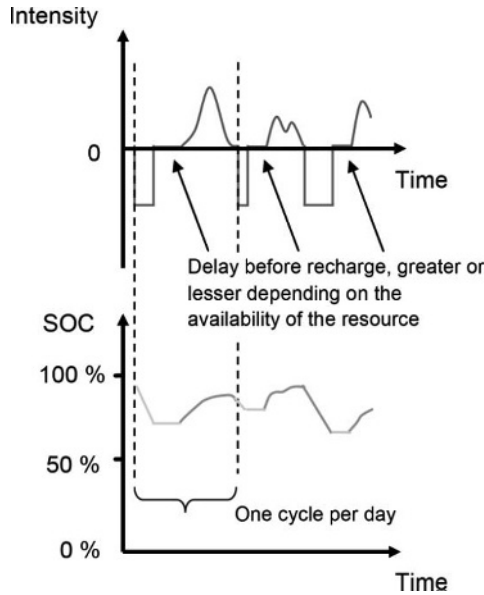


Figure 1.7. *Decentralized domestic power supply battery for an isolated site: profile of current entering into the battery and evolution of its SOC (in reality, the discharge currents have more complex profiles)*

Applications such as transmitters for cellphone networks (BTS: Base Transceiver Station) require a far more regular power supply throughout the day and even throughout the year. For the sizing of a transceiver in an isolated site, we assume a constant power requirement of a few kW. The capacity of the battery is calculated on the basis of the level of sunshine the site receives, the desired level of autonomy in case of lack of sun (e.g. five days or only two or three if the power supply is backed up by an electrogen group). Figure 1.8 shows the profile of current entering into the battery for a purely solar power supply, and the evolution of the SOC. Real-life data are given in section 3.1.2.

However, we can also use autonomous supply in urban areas (street furniture) in order to limit installation and operational costs. Such is the case for many parking meters or streetlamps, whose power is supplied by photovoltaic cells and batteries, preventing the need to dig trenches to lay electrical cables and then resurface the sidewalks. This autonomous power supply also enables us to avoid having to hire an energy meter, the cost of which may be greater than the energy consumed.

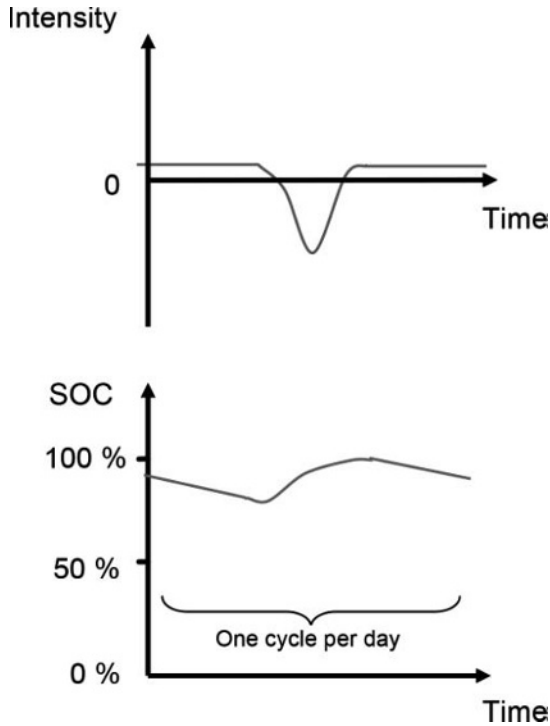


Figure 1.8. *Battery supplying a telecommunications transceiver on an isolated site: profile of current entering into the battery and evolution of its SOC*

With recent urban lighting installations, there have been attempts to decrease energy bills and light pollution during the night. Decreasing energy consumption is even more crucial in autonomous urban lighting with a view to minimizing the size of the battery and those of the photovoltaic modules. For this purpose, the level of lighting is modulated depending on the time and the presence or absence of pedestrians or vehicles. Examples of the profiles of current required from the battery are shown in Figure 1.9.

A real-world example of the current and voltage for an autonomous urban lighting application is given in section 3.1.6.

In an entirely different domain, electricity is supplied to pleasure boats by batteries which are recharged by the alternator of the engine and/or solar panels and/or a wind/water turbine. One might also cite gadgets such as garden lights, pocket torches, etc.

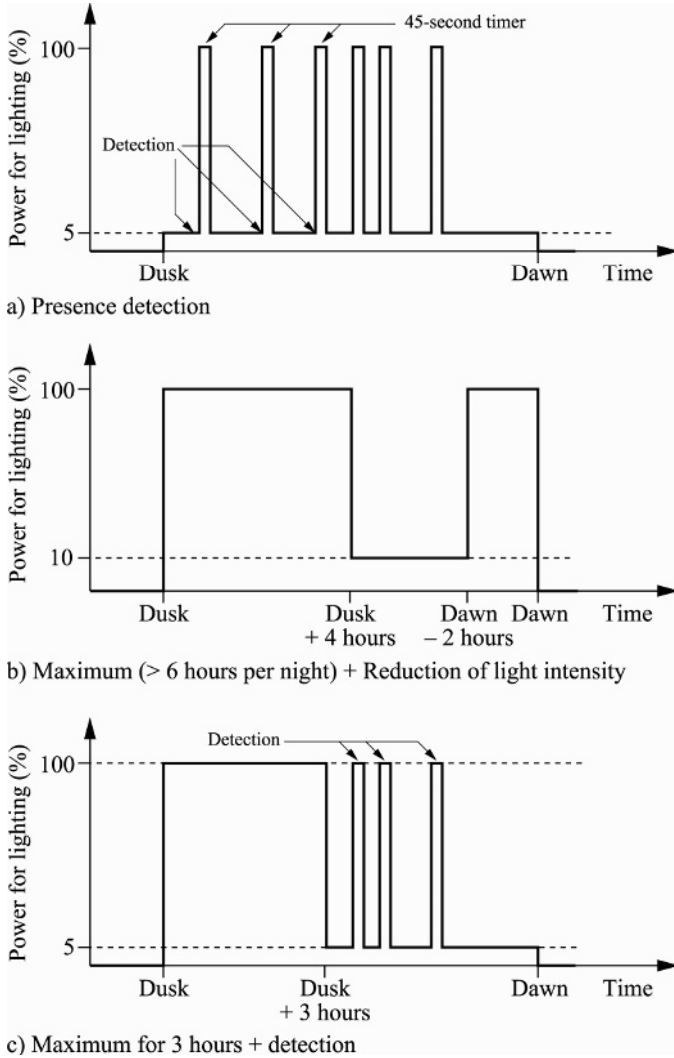


Figure 1.9. Power required of the battery of a streetlamp
(source: Novéa Energies – www.novea-energies.com)

1.2.3.2. Batteries for grid support

Nowadays, the increase in the number of renewable energy systems connected to the electrical grid (solar or wind systems, for instance) makes it more difficult to manage the grid because of the intermittence and variability of production, and because of its unpredictability or prediction errors.

Studies are being carried out and prototypes tested to evaluate the advantage of integrating storage systems into these grid-connected systems, which would help improve the planning of production means, optimize the global energy efficiency of the system and shift the bulk of energy provision to times when the need is greatest.

However, the issue of the stability of power supply grids is not a new one. Electrochemical systems for energy accumulation have been installed on the grid for over 20 years, with lead-acid or nickel-cadmium batteries. More recently, we are witnessing a significant development of sodium-sulfur batteries (which are discussed in detail in Chapter 12). Experiments have been performed with redox flow systems (also detailed in Chapter 12). The unitary powers range from several MW to several tens of MW, and the quantities of energy stored from several MWh to tens of MWh.

Various configurations have been studied, with very different usage profiles, owing to their time constants: smoothing or elimination of the peaks, smoothing of daily consumption⁶, injection into the grid on demand from a distributor, etc. Hence, batteries of very different technologies are capable of responding to the functional requirements.

The profiles of the current entering into the battery and the evolution of its SOC are given in Figure 1.10.

1.2.3.3. *Uninterruptible power supply batteries*

Uninterruptible power supply batteries⁷ are used for communication networks, computers and IT centers, nuclear power plants, etc. They are able to respond to peak power or energy requirements as a function of the reliability of the grid which they are stabilizing. They take over in case of failure of the electricity supply grid, providing power (DC or AC power depending on the application) over a greater or lesser duration (around fifteen minutes for the safeguarding of data and shutdown of a domestic or

⁶ Interseasonal storage by electrochemical batteries is difficult to envisage with the current technologies or those which should emerge in the near future.

⁷ Often incorrectly called “inverters” in ICT-specific language. Indeed, the core of an uninterruptible power supply is constituted by an energy storage device: an electrochemical battery. This battery is kept in the fully-charged state by a charger. If the electrical grid fails, an inverter takes the energy stored in the battery and supplies it as an alternative form (AC) to the charge.

office computer⁸, or up to several hours for strategic applications).⁹ These batteries are usually maintained in a fully charged state by a so-called “floating” current¹⁰, which compensates for self-discharge. Thus, they are fully charged for whenever they are called upon, given that that moment is not predictable. These batteries are identified by the term “floating batteries”.

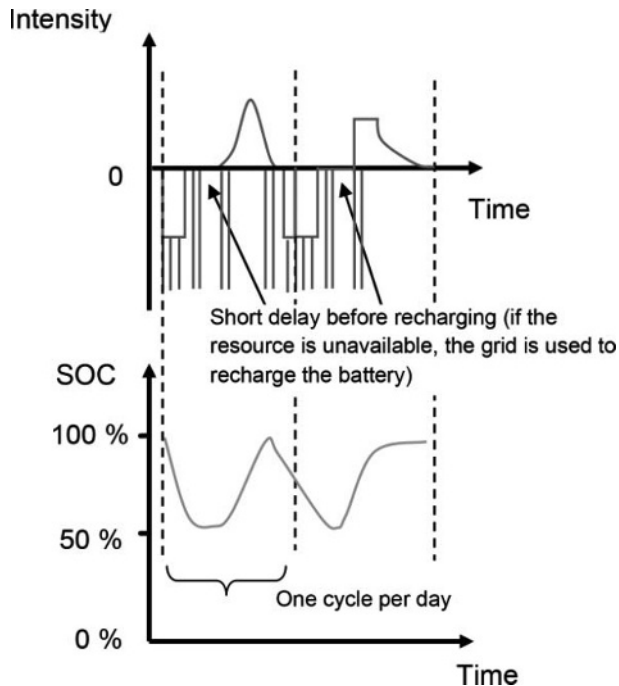


Figure 1.10. *Electricity supply battery connected to the grid for the smoothing or elimination of consumption peaks: profile of current entering into the battery and evolution of its SOC*

In the category of emergency supply batteries, we also find illuminating safety signage. If the general lighting grid fails, these devices (called

8 Such inverters deliver between one and several hundred watts. They use 12, 18 or 24 V batteries of a few Ah.

9 With a view to limiting the size of the batteries, we can use an electrogen group. The battery serves as a power supply until the electrogen group is able to start up and take over.

10 This term stems from the fact that it is a voltage to which the battery is subjected, and the current fluctuates depending on the temperature, the age of the battery, etc.

Standalone Emergency Lighting Units – SELUs) are able to offer sufficient lighting with autonomy of at least an hour to prevent panic and indicate the emergency exits. The battery used is also floating.

With chargers controlled by a microcontroller, there are other types of charge which are more elaborate than floating and which help extend the lifetime of the batteries, decrease maintenance operations and ensure that the batteries are indeed capable of providing the necessary energy if and when required.

The profile of current entering into the battery and the evolution of its SOC are shown in Figure 1.11.

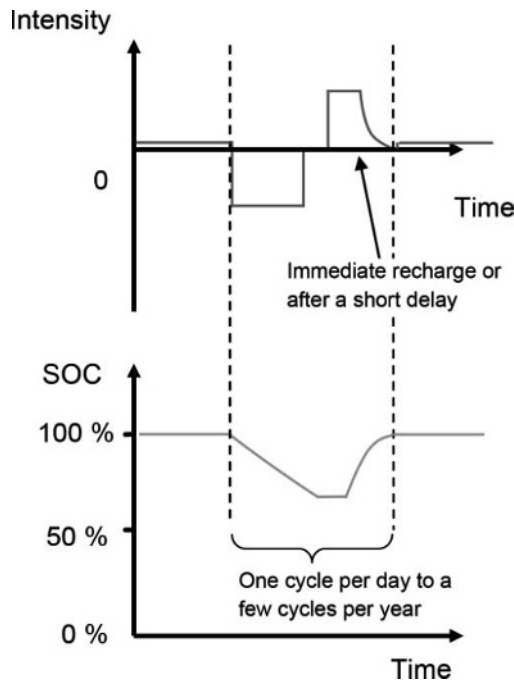


Figure 1.11. *Emergency power supply battery: profile of current entering into the battery and evolution of its SOC*

1.2.3.4. Batteries for memory- and data saving

In the same category of ideas but with extremely low powers and energies, we can cite memory-saving or the operation of the internal

timekeeper in computers or, indeed, no-primary-battery watches (such as the Casio range of photovoltaic watches or the Seiko Kinetic[®]) or other systems requiring some of the electronic components to be powered between the normal operating times. In such cases, an element of a few mAh is used, because the power required is a few μW .

1.2.4. Batteries for mobile or nomadic devices

The design of high-specific-energy batteries facilitated the rapid advent of mobile or nomadic devices. These batteries are used to supply energy to mobile equipment: cellular and wireless telephones, computers, music players, digital cameras, video players, cameras, games consoles, wireless tools, and so on) requiring excellent performances in terms of power, volume- and mass energy and cyclability.

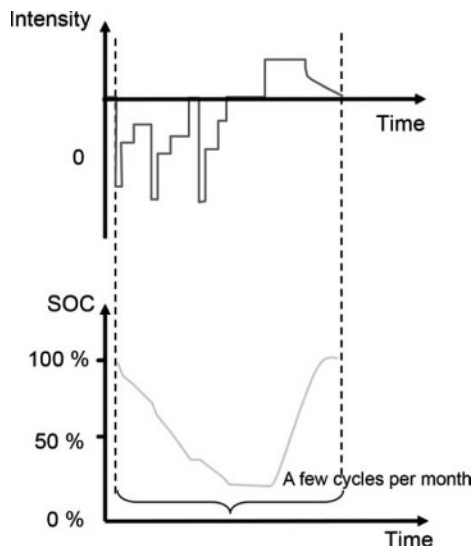


Figure 1.12. Battery for a nomadic device: profile of current entering into the battery and evolution of its SOC

The profile of current entering into the battery and the evolution of its SOC are illustrated in Figure 1.12. In many such applications, we see a succession of periods of slow discharge and periods of rapid discharge. Such is the case, for instance, with a cellphone which goes from standby or receiver mode – which are not particularly energy-hungry – to transmission

mode, which requires a significant power level. The batteries of nomadic devices function in cycling mode (conversation for a cellphone, autonomous operation for a computer, etc.) and then are charged from the mains where they may remain plugged in for long periods of time. For these low-power devices, the management of the charge is usually entrusted to specialized integrated circuits.

1.3. Review of storage requirements and appropriate technologies

Table 1.1 shows different domains which require electricity storage. We have indicated the different battery technologies used or envisaged for each of these domains, on the basis of technico-economic requirements.

	Examples of application	Characteristics important for the design	Technologies used or envisaged
SLI	Automobiles, electrogen groups, etc.	Cost, W/kg no maintenance	Fine-plates flooded lead-acid
	Trucks, tractors, etc.	Cost, W/kg, Wh/kg	Flooded lead-acid
	Boat engines	Cost, W/kg, Wh/kg	Sealed lead-acid. Lithium-ion
Traction	Handling machinery, wheelchairs, electrically-assisted pedal cycles, etc.	Cost, Wh/kg	Tubular-plate flooded lead-acid. Reinforced flat plate flooded lead-acid. VRLA ¹¹ . Lithium polymer
	Electric vehicles: cars, scooters, golf buggies, go-karts	Wh/kg, Wh/L, W/kg, cyclability, little or no maintenance	Flooded lead-acid or VRLA. NiCd, NiMH. Lithium-ion
	Hybrid vehicles	Wh/kg, W/kg, no maintenance	NiMH
	“Plug-in” hybrid vehicles	Wh/kg, W/kg, no maintenance	NiMH. Lithium-ion
	“All-electric” vehicles	Wh/kg, Wh/L, W/kg, little or no maintenance	(Lead). Lithium-ion. Lithium metal polymer

Table 1.1. *Certain storage requirements and the appropriate technologies*

¹¹ Valve-Regulated Lead–Acid battery.

Stationary	Inverters for grid support Emergency lighting	W/kg, lifetime in a floating regime	Sealed lead. NiCd
	Storage for autonomous energy systems (solar, wind, telecommunications, pleasure boating)	Wh/kg, cyclability with no maintenance	Open-circuit lead. VRLA. NiCd. Lithium-ion
	Storage for grid-connected energy systems	Cost	VRLA. Sodium-sulfur. Lithium-ion. Redox flow batteries
Mobile	Mobile devices Wireless tools Autonomous vacuum cleaners Memory preservation	W/kg, Wh/kg, Wh/L, cyclability with no maintenance	(NiCd ¹²). NiMH. Lithium-ion
Aeronautics and space	Autonomous onboard grid	Wh/kg, cyclability with no maintenance	NiCd. Lithium-ion

Table 1.1. (Continued) Certain storage requirements and the appropriate technologies

1.4. Conclusion

Electricity storage requirements are extremely varied, both because of the applications and the amount of energy stored and because of the ways in which that charge is exploited. From data-saving in an electronic device which requires a few mWh with very slow discharge; to grid support which requires storing dozens or even hundreds of MWh¹³; to mobile telephones

12 Replaced by NiMH batteries, and now, increasingly often, by lithium-ion technology.

13 Gravity-based hydraulic storage (pumped storage (hydroelectric) power plants: PSP), is capable of storing an even greater quantity of energy (several tens of GWh). Although this is the device which is capable of storing the largest amount of electrical energy, the principle behind its operation is not electrochemical. Therefore, it will not be discussed in this book. Nor will this book deal with flywheel storage or SMES: Superconducting Magnetic Energy Storage, which – besides capacitors – is practically the only device for quasi-direct electricity storage.

By way of indication, the following figures recorded in 2012 reflect the installed powers the world over for the different storage technologies:

PSP: 140,000 MW;

Compressed Air Energy Storage (CAES): 477 MW;

NaS batteries: 400 MW;

Lead batteries: 45 MW;

Lithium batteries: 45 MW;

Nickel-cadmium batteries: 40 MW;

Redox flow systems: 3 MW.

(a few Wh), portable computers (a few tens of Wh), batteries for combustion-engine cars (a few hundred Wh and very intense peaks of current); electric vehicles (a few kWh to several tens of kWh) – there is no single form of technology that is capable of serving such a vast range of applications. Today, there are many different families of batteries coexisting. Lead and nickel technologies were examined in a previous book.¹⁴ This book deals with recently-introduced technologies such as lithium batteries (Chapters 4–10), hot cells and redox flow systems (Chapter 12). Electricity storage by an “electrolyzer + hydrogen storage + fuel cell” system is not dealt with in this book, because another book¹⁵ is devoted to the topic.

Before going on to give quantified real-world examples of applications using batteries (Chapter 3), it is necessary to lay down a number of definitions and measuring methods. This is the aim of the next chapter.

14 Lead and nickel-based electrochemical secondary batteries are described in detail in: C. GLAIZE & S. GENIÈS, *Lead and Nickel Electrochemical Batteries*, ISTE Ltd, London, John Wiley & Sons, New York, 2012.

15 M.C. PERA, D. HISSEL, H. GUALOUS, C. TURPIN, *Electrochemical Components*, ISTE Ltd, London, John Wiley & Sons, New York, 2013.