This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nº 691768

Recommendations on storage systems for BIPV systems

Project report

CEA, TECNALIA

March 2017

Summary

This document provides a presentation of the battery technologies and their testing in order to choose the best one for BIPV application. The tested batteries are aqueous sodium-ion battery (Aquion Aspen 24S), lithium-ion LFP/G (several suppliers) and Li-ion LFP/LTO batteries. After a review of the existing standards for testing batteries, the IEC 61427-2 clause 6.5 was selected. It was applied to the pre-selected technologies and allowed to choose finally lithium-ion LFP/ G batteries for the application since they provide higher energy densities (300 Wh/L, 120 Wh/kg) than LFP/LTO (100 Wh/L, 50 Wh/kg) and Aquion batteries (13 Wh/L, 11 Wh/kg), and higher efficiency (>94%) than Aquion batteries (83%). The Spanish company SUPPLIER (B) is selected as the battery pack supplier.

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The present report was mainly prepared by PVSITES project partner CEA, with additional contributions from TECNALIA. The report was originally submitted to the European Commission as Project Deliverable D5.1 in March 2017.

Disclaimer

About the PVSITES project

PVSITES is an international collaboration co-funded by the European Union under the Horizon 2020 Research and Innovation program. It originated from the realisation that although building-integrated photovoltaics (BIPV) should have a major role to play in the ongoing transition towards nearly zero energy buildings (nZEBs) in Europe, the technology in new constructions has not yet happened. The cause of this limited deployment can be summarised as a mismatch between the BIPV products on offer and prevailing market demands and regulations.

The main objective of the PVSITES project is therefore to drive BIPV technology to a large market deployment by demonstrating an ambitious portfolio of building integrated solar technologies and systems, giving a forceful, reliable answer to the market requirements identified by the industrial members of the consortium in their day-to-day activity.

Coordinated by project partner Tecnalia, the PVSITES consortium started work in January 2016 and will be active for 3.5 years, until June 2019. This document is part of a series of public reports summarising the consortium's activities and findings, available for download on the project's website at www.pvsites.eu.

The PVSITES consortium:

Tecnalia Research & Innovation	CTCV	FormatD2
Onyx Solar	Flisom	Vilogia
BEAR-iD	Cricursa	R2M Solution Research to Market
Nobatek	CEA	CADCAMation
Film Optics	Acciona Infraestructuras	WIP - Renewable Energies

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1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

This document contains a description of battery technologies, a comparison of them according to BIPV application and then the testing of the pre-selected ones.

1.2 Reference material

Table 1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within PVSITES project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1-Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
T6.1	The battery characterization provided here will be used as an input for the planner tool developed in T6.1.
T8.1	Battery selection during the design of demonstration installations will be carried out according to the recommendations given here.

1.3 Abbreviation list

AGM – Adsorbent Glass Matt
AGV – Automatic Guided Vehicles
AHI - Aqueous Hybrid Ion
BIPV – Building Integrated Photovoltaics
BMS – Battery Management System
DoD – Depth of Discharge
LFP – Lithium Iron Phosphate
LMO - Lithium ion Manganese Oxide
LTO – Lithium Titanate
NMC - lithium Nickel Manganese Cobalt oxide
PV - Photovoltaics
SMES – Superconducting Magnetic Energy Storage
SoC – State of Charge
UPS – Uninterruptible Power Systems
VRLA – Valve Regulated Lead Acid

2 ELECTRICAL STORAGE TECHNOLOGIES

In general, it is necessary to convert electrical energy into other means like mechanical (flywheels, pumped hydroelectric systems, compressed air energy storage), electrochemical (conventional rechargeable batteries and flow batteries) or chemical energy (hydrogen storage with fuel cells) in order to store it. The exception is the case of supercapacitors and SMES (Superconducting Magnetic Energy Storage) where the energy is directly stored in electrical medium. As a result, these are the most efficient electrical storage technologies.

However, electrical storage technologies can be also classified according to their capacity to deliver power and/or energy. Power technologies are, for instance, supercapacitors, SMES, and flywheels. The inconvenience of these technologies is that the amount of stored energy is quite limited and they are not valid for some applications, like PV self-consumption. On the other hand, energy technologies like pumped hydroelectric systems, compressed air energy storage or hydrogen present large energy capacity, but they are not very competitive, in terms of cost and efficiency, in low power applications, like distributed PV systems.

In fact, only electrochemical batteries are currently a reasonable alternative to store electrical energy in distributed PV systems. There is a great variety of electrochemical battery technologies. A preliminary analysis of some of them is shown in this chapter. Instead of focusing on describing the corresponding electrochemical processes, the objective is to list their main performance parameters and features in order to help to select the most suitable one for a concrete application.

2.1 Lead acid batteries

Lead acid batteries are based on the existing reactions among a lead dioxide cathode, a lead anode, and an electrolyte consisting in an aqueous solution of sulfuric acid. There are different types of battery design:

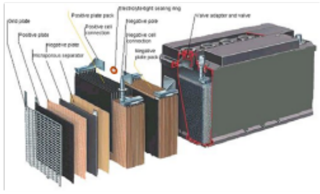
- Vented batteries with free circulation of gases produced by the electrolysis of water from the electrolyte to open-air. The electrolyte is liquid and water can be refilled when it is consumed. They present high maintenance requirements.
- Sealed batteries of Valve Regulated Lead Acid (VRLA) where the circulation of gases to open-air is limited by a safety valve that is only opened in overpressure situations. The electrolyte can be liquid or gelled. Their maintenance is lower than in the case of ventilated batteries.
- Gel batteries where the electrolyte is immobilized as a gel offering a safer battery in case of container break.
- Adsorbent Glass Matt (AGM) where the electrolyte is contained in an adsorbent separator between both electrodes. As a result, these batteries show a longer lifetime and a better discharge capacity in comparison to other lead acid batteries.

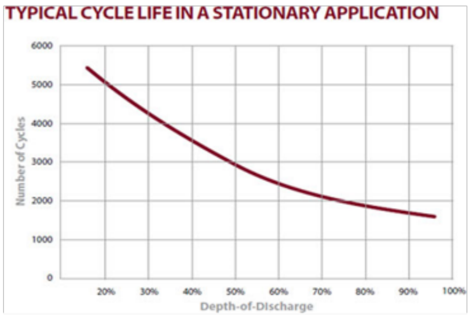
- **Lead - acid batteries**

  – Performance

Specific energy	25-50 Wh.kg^{-1}
Energy density	50- 100 Wh.L^{-1},
Specific power	75 - 350 W.kg^{-1}
Energy efficiency	70 – 85 %
Cycling at 80 % DoD	200 - 1500 cycles
Costs	150 – 600 $.kWh^{-1}

Advantages	Drawbacks
- **Mature technology**	- Low cyclability (depending on operation conditions and DoD)
- **Low cost of production and abundance of raw materials**	- Low specific energy
- **Recyclability (> 98 %)**	-Toxicity of Pb (CMR substance)





Trojan IND27-2V 2V 1520AH (20HR)
Flooded Lead Acid Battery (Trojan 2015)

Figure 1- Main characteristic indicators of lead - acid batteries

Lead acid batteries have been used for more than a century, so it is the most mature technology. Their main advantages are their reliability and low cost. Their main drawbacks are:

- Low energy density.
- Limited cycling.
- Toxicity. Since lead is a highly toxic metal, it has to be recycled (up to 99 % of the lead-acid batteries are recycled in Europe and North America[1]).
- Required ventilation systems. As these batteries can potentially produce an explosive combination of oxygen and hydrogen during their charge process, precautions must be taken to avoid the risk of forming an explosive atmosphere (ATEX). Although sealed versions, and specially AGM, are safer, this question must be also considered during the system design.
- Degradation under low charge levels.

The most suitable applications are those with a limited number of charge/discharge cycles and where weight and volume are not limiting factors, like Uninterruptible Power Systems (UPS) or vehicle starter systems. Though this technology has been overcome by newer technologies in terms of performance indicators, its low cost makes it dominate these two markets.
Since main inconvenience of conventional lead acid batteries is their limited lifetime, advanced lead acid batteries are being developed in order to overcome this barrier.

[1] https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf

2.2 Advanced lead acid batteries

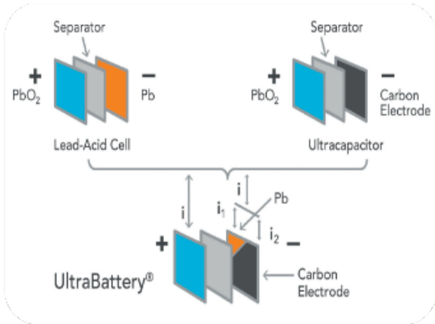
The main advantage of lead acid batteries is their low cost. However, main drawbacks are low energy density and limited lifetime. Therefore, the development of advanced lead acid batteries aims to solve these problems maintaining their low cost.

- **Advanced lead - acid batteries**
  - Principle

Positive: $PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$

Negative: $n\,C_6^{x-}(H^+)_x \rightarrow n\,C_6^{(x-2)-}(H^+)_{x-2} + 2H^+ + 2e^-$

$$PbO_2 + 2H^+ + HSO_4^- + n\,C_6^{x-}(H^+)_x \rightarrow PbSO_4 + 2H_2O + n\,C_6^{(x-2)-}(H^+)_{x-2}$$



  - Performance

Specific energy	20-40 Wh.kg^{-1}
Energy density	60- 80 Wh.L^{-1},
Specific power	70 - 300 W.kg^{-1}
Energy efficiency	70 – 85 %
Cycling at 80 % DoD	1 600 – 15 000
Costs	250 – 500 $.kWh^{-1}

Advantages	Drawbacks
- **Mature technology** - **Low cost of production and abundance of raw materials** - **Recyclability (> 98 %)** - **Cyclability enhanced compared to Pb-acid batteries**	- Low specific energy -Toxicity of Pb (CMR substance)

→ **Low cost**

→ **Highly recyclable : > 95 % (when collected !!)**

Figure 2- Main characteristic indicators of advanced lead - acid batteries

Main technological proposals are listed below.

- Firefly International Energy has developed a material denominated Microcells Carbon Foam Technology [2] improving lifetime, efficiency, power capacity, performance in extreme temperature conditions and the resistance to deep discharges. Improvements are based on larger electrodes and a design more resistant against corrosion and sulphation.
- Commonwealth Scientific and Industrial Research Organisation (CSIRO) has developed a concept called ultra-battery [3], which is a hybrid combining a lead acid battery and an asymmetric capacitor in a single cell. This way, the ultra-battery combines the power of capacitors and the larger energy of batteries. Nowadays, this ultra-battery is commercialized by Ecoult, offering very efficient operation in continuous partial State of Charge (SoC) use without frequent overcharge maintenance cycles. It can be utilized to continually manage energy intermittencies, smooth power, and shift energy.
- Axion Power [4] has developed a technology called PbC, consisting on a multi-celled asymmetrically supercapacitive lead-acid-carbon hybrid battery. Laboratory tests show 2,500 cycles at 100 % Depth of Discharge (DoD).
- Betta Batteries[5] has developed LeadCrystal® technology, that consists of a unique micro-porous high-absorbent mat (AGM), thick plates cast from a high purity lead calcium selenium alloy (which ensures a extended life), and a SiO_2 based electrolyte solution. Main

[2] http://fireflyenergy.com/
[3] http://csironewsblog.com/2013/02/21/ultrabattery/
[4] http://www.axionpower.com/
[5] http://www.bettabatteries.com/

advantages are long battery life, extreme temperature resistance, and up to 99 % recyclable. Main drawback is required charge procedure and electrode degradation under partial power conditions.

- Shin Kobe has developed advanced VRLA batteries with 4,500 cycles at 70 % DoD and a lifetime of 17 years. Improvements are based on redesign of both negative and positive electrodes. Main drawbacks are low energy density and asymmetric operation (it can be discharged in 2 hours but it requires 5 hours for recharging)[6].

2.3 Nickel-cadmium (NiCd) battery

NiCd batteries show higher energy density and cycling than lead acid batteries, but their main inconvenience is the environmental impact of cadmium. Furthermore these batteries suffer from high self-discharge rates and memory effect. Among rechargeable battery technologies, NiCd rapidly lost market share in the 1990s, due to the development of NiMH and Li-ion batteries.

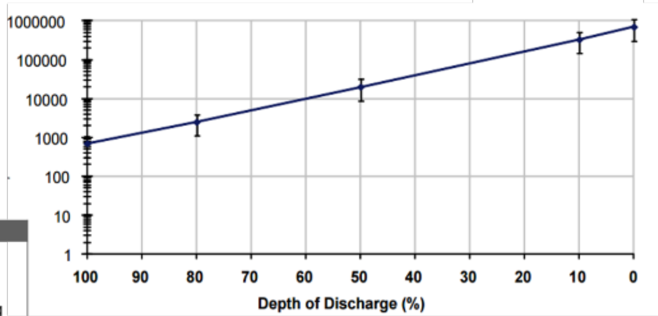
[6] Electricity Storage Technologies for Short Term Power System Services at Transmission Level. Report for ForkEl Project, 2010.

2.4 Nickel-metal hydride (NiMH) battery

NiMH batteries show higher cycling performance than NiCd batteries and they are free of toxic components. Traditionally, main drawbacks are their poor performance at low temperatures and high self-discharge rate.

- **Ni – MH batteries**
  - Performance

Specific energy	30 - 80 Wh.kg^{-1}
Energy density	80 - 435 Wh.L^{-1},
Specific power	70 - 1500 W.kg^{-1}
Energy efficiency	70 – 80 %
Cycling at 80 % DoD	500 – 2 000
Cost	600 - 1500 $.kWh^{-1}



Advantages	Drawbacks
- **Mature technology**	- Limited lifetime depending on the DoD
- **Abundance of raw materials**	- Highly exothermal reaction during discharge
- **Recyclability of Nickel**	- Self-discharge
- **High specific power**	
- **Safety**	

influence of the DoD on the cyclability of Ni-MH batteries (Zelinsky, M., Koch, J. & Fetcenko, M., HEAT TOLERANT NiMH BATTERIES FOR STATIONARY POWER, Rochester Hills, MI USA. Available at: http://www.battcon.com/PapersFinal2010/ZelinskyPaper2010Final_12.pdf)

↳ High power ↳ Expensive

↳ Safety ↳ Relevant for high power / low discharge

Figure 3- Main characteristic indicators of NiMH batteries

However, VHT modules from Arts Energy currently show exceptional operational robustness in extreme climates (from -40 ºC to 85 ºC) and low self-discharge rates. Their main drawback is their cost, higher than 1,000€/kWh.

2.5 Nickel zinc (NiZn) battery

NiZn battery is similar to NiMH batteries, but with a higher voltage of 1.6V. Although this rechargeable battery technology has been known for over 100 years, a stabilized zinc electrode system was not achieved until the beginning of this century. As a result, NiZn is viable and competitive in some applications, like digital cameras or electric tools. However, they require particular charging procedure, since trickle charging is not recommended. This requirement makes them unsuitable for PV self-consumption application.

- **Ni – Zn batteries**
  - Performance

Specific energy	60 - 80 Wh.kg^{-1}
Energy density	200 - 300 Wh.L^{-1},
Specific power	500 - 1000 W.kg^{-1}
Energy efficiency	60 – 70 %
Cycling at 80 % DoD	200 – 1 000
Cost	400 - 800 \$.kWh^{-1}

Advantages	Drawbacks
- **High voltage (↗ energy)** - **Abundance of raw materials** - **Recyclability of Nickel** - **High specific power** - **Safety**	- Limited lifetime depending on the DoD - Formation of Zn dendrites during charge - High sensibility to over-discharge

Parameter	NiMH	NiZn
Form Factor	Prismatic	Cylindrical
Number of Cells	168	128
Nominal Voltage	201.6 V	204.8 V
Nominal Capacity	6.5 Ah	6.5 Ah
Pack Energy	1,338 Wh	1,357 Wh
Pack Peak Power	20 kW	26 kW
Gravimetric Energy Density	46 Wh/kg	69 Wh/kg
Bare Pack Weight	29.1 kg	19.2 kg

Comparison of batteries Ni-MH and Ni-Zn for use in an hybride vehicle (Toyota Prius), according to Soman, S., 2014. Driving Fuel Economy Improvements with Low Voltage Systems in a Dynamic Regulatory Environment. In Batteries 2014. PowerGenix.

↳ High power
↳ Energy density
↳ Safety

↳ Compromise between Pb-acid and Ni - MH ?

↳ Development still needed

Figure 4- Main characteristic indicators of NiZn batteries

2.6 Aqueous hybrid ion batteries (AHI)

Aqueous sodium-ion batteries are composed of abundant and cheap materials. They offer high cycling with environmental friendly and inherently safe chemistry, but low energy density (15 – 30 Wh/kg, 12 - 30 Wh/L) and efficiency (60 - 85 %).

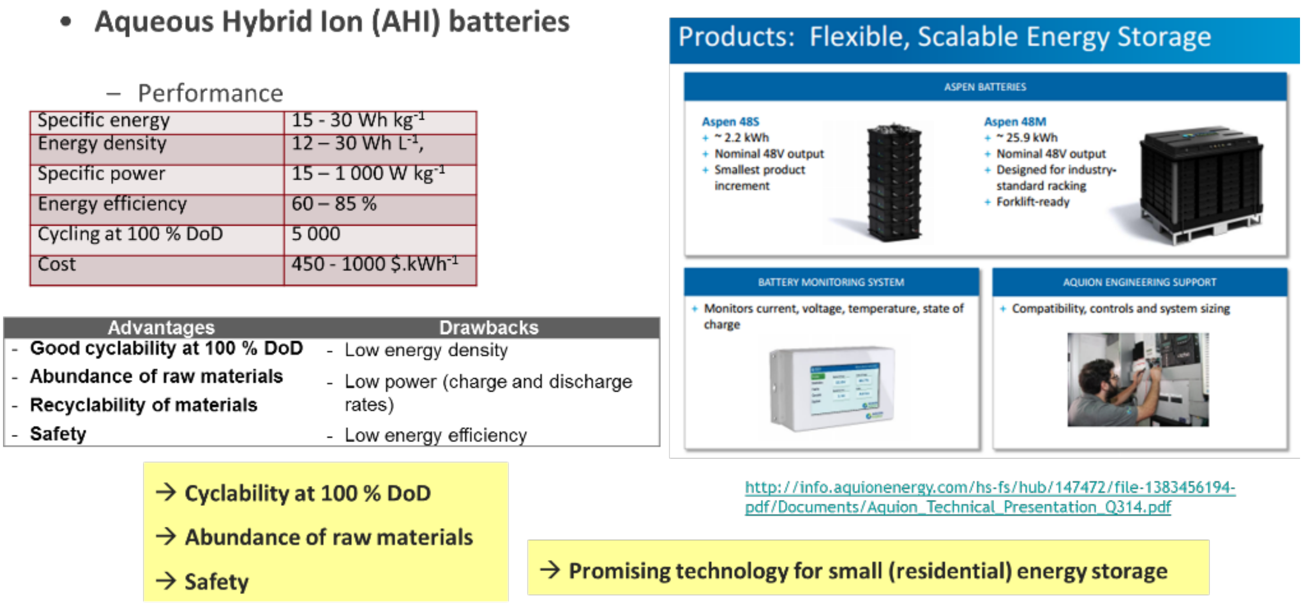


Figure 5- Main characteristic indicators of AHI batteries

This technology has been developed by Aquion, which has recently filed a voluntary petition under Chapter 11 of the United States Bankruptcy Code[7].

[7] http://blog.aquionenergy.com/aquion-energy-inc.-files-voluntary-petition-under-chapter-11-to-target-a-sale-of-assets

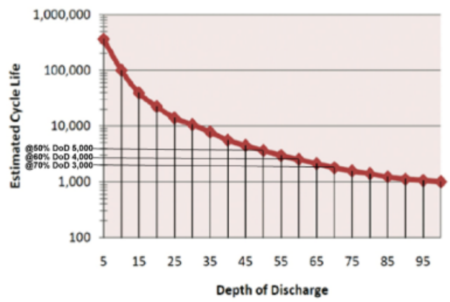
2.7 Lithium-ion battery

The Lithium is a very interesting component for battery manufacturing due to its lightness and high electrochemical potential, offering high energy densities. There are a great number of alternatives with different chemistries and resulting in different performance, safety and cost. In all the cases, the system must include a Battery Management System (BMS) increasing its cost. In general, they offer great energy density and power capacities, while self-discharge rate is extremely low. The cycling is quite good, particularly in the case of Lithium Titanate (LTO).

- **Lithium – ion batteries**
  - Performance

Specific energy	70 - 250 Wh.kg^{-1}
Energy density	50 – 500 Wh.L^{-1},
Specific power	180 – 3 000 W.kg^{-1}
Energy efficiency	75 – 90 %
Cycling at 80 % DoD	300 - 3 000
Costs	300 – 600 $.kWh^{-1}

Advantages	Drawbacks
- **Mature technology** - **High specific energy and power** - **High Efficiency** - **Costs are reducing dramatically**	- Safety (fire, explosion, toxicity) - Recyclability -Toxicity of electrolytes



Relationship of battery cycle life as a function of Depth of Discharge for the considered ~~LifePo4~~ battery

$LiFePO_4$ / G

→ **High specific energy**

→ **High specific power**

Figure 6- Main characteristic indicators of Li-ion batteries

	Cathode	Anode	Electrolyte	Energy density	Cycle life	2014 price per kWh	Prominent manufacturers
Lithium iron phosphate	LFP	Graphite	Lithium carbonate	85-105 Wh/kg	200-2000	USD550-USD850	A123 Systems, BYD, Amperex, Lishen
Lithium manganese spinel	LMO	Graphite	Lithium carbonate	140-180 Wh/kg	800-2000	USD450-USD700	LG Chem, AESC, Samsung SDI
Lithium titanate	LMO	LTO	Lithium carbonate	80-95 Wh/kg	2000-25000	USD900-USD2,200	ATL, Toshiba, Le-clanché, Microvast
Lithium cobalt oxide	LCO	Graphite	Lithium polymer	140-200 Wh/kg	300-800	USD250-USD500	Samsung SDI, BYD, LG Chem, Panasonic, ATL, Lishen
Lithium nickel cobalt aluminum	NCA	Graphite	Lithium carbonate	120-160 Wh/kg	800-5000	USD240-USD380	Panasonic, Samsung SDI
Lithium nickel manganese cobalt	NMC	Graph-ite, silicon	Lithium carbonate	120-140 Wh/kg	800-2000	USD550-USD750	Johnson Controls, Saft

Table 2- Comparative analysis of different lithium ion alternatives[8]

[8] (IRENA), 2015b. BATTERY STORAGE FOR RENEWABLES: MARKET STATUS AND TECHNOLOGY OUTLOOK case studies : battery storage, Available at: http://www.irena.org/DocumentDownloads/Publications/IRENA_Battery_Storage_case_studies_2015.pdf).

Lithium-ion batteries can be dangerous under some conditions and can pose a safety hazard since they contain a flammable electrolyte and are oxygen-sensitive materials. Thus, lithium cobalt oxide ($LiCoO_2$) offers high energy density, but also presents higher safety risks, especially when damaged or misused. New chemistries, like lithium iron phosphate ($LiFePO_4$), lithium ion manganese oxide (LMO) or lithium nickel manganese cobalt oxide (NMC), present lower energy density but higher lifetime and safety. LTO is specially designed for very high performance (cycling and power capacity) aiming at particular roles, where its high cost can be justified.
According to a report published by Australian Renewable Energy Agency (ARENA) in 2015, lithium-ion is the technology with greater expectations of cost reduction in the short-term, as shown in the following figure. The main reason is that lithium ion is extensively used in EV market, favoring economies of scale.

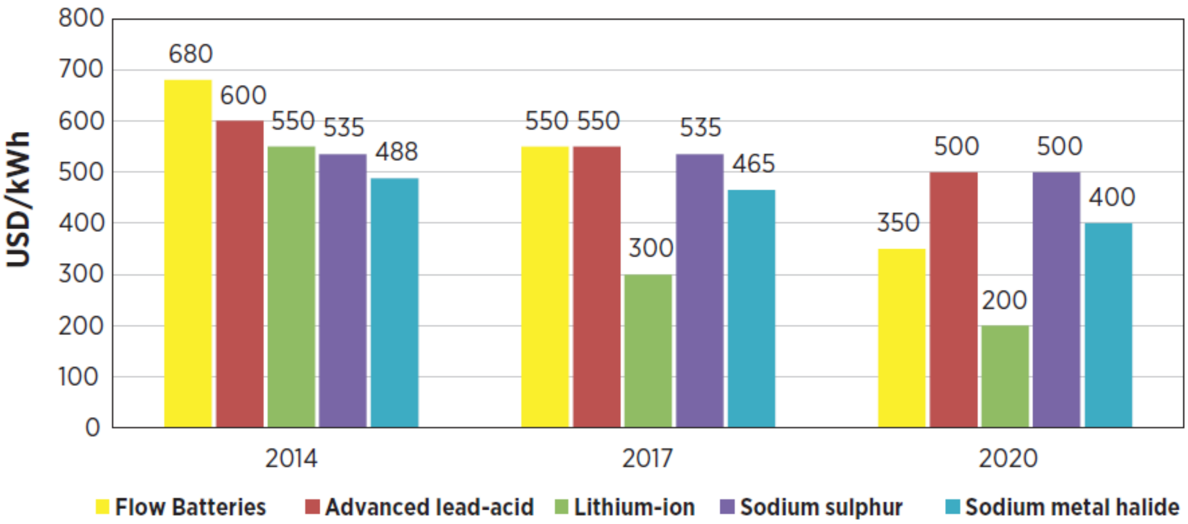


Figure 7- Lowest current and projected battery cell price by type for utility-scale applications. Source: ARENA.

2.8 Sodium-sulfur (NaS) batteries

NaS batteries were developed in 1960s for automation sector by Ford, but nowadays their great market is stationary applications, due to the progress of the technology in Japan.
They offer high energy density and cycling (4,500 cycles). Furthermore, they can offer 600 % of their nominal power for 30 seconds. However, NaS batteries work at high temperature (300-350 ºC) in order to maintain their active elements in liquid state. This means that NaS batteries are only convenient for high-scale applications (>1 MW), where the required thermal management is affordable.

- **Na – S batteries**

  - Performance

Specific energy	100 - 150 $Wh.kg^{-1}$
Energy density	100 -150 $Wh.L^{-1}$,
Specific power	50 - 200 $W.kg^{-1}$
Energy efficiency	75 - 90 %
Cycling at 80 % DoD	2500 - 4500 cycles
Costs	300 – 500 $\$.kWh^{-1}$

Advantages	Drawbacks
- **High specific energy** - **Abundant and low cost materials** - **Mature technology**	- High temperature (compensate thermal losses) - Danger of liquid Na (fire) - Only one producer: NGK (https://www.ngk.co.jp/nas/)

→ **High specific energy**

→ **Performance and costs very close to present Li-ion batteries**

Figure 8- Main characteristic indicators of NaS batteries

2.9 Sodium metal halide or Zebra batteries

Zebra batteries are also high-temperature devices (around 300 ºC). If the battery is not used, in order to maintain this temperature for a day, energy equivalent to 12 % of their nominal capacity is needed. If the battery is switched off, solidification of molten salts will occur and several days will be necessary to re-heating. On the other hand, they present higher price and lower energy density in comparison to NaS batteries.

- **Na – $NiCl_2$ batteries (ZEBRA)**
  - Performance

Specific energy	100 -120 Wh.kg^{-1}
Energy density	100 - 150 Wh.L^{-1},
Specific power	100 - 400 W.kg^{-1}
Energy efficiency	85 - 90 %
Cycling at 80 % DoD	2500 - 3500 cycles
Costs	400 – 600 \$.kWh^{-1}

Advantages	Drawbacks
- **High specific energy**	- High temperature (compensate thermal losses)
- **Mature technology**	- High cost of Ni
- **Recyclability**	

FIAMM (I) storage system: 75 kW/270 kWh
http://www.fiamm.com/en/emea/energy-storage/prodotti/spring,-mod-312.aspx

→ **High specific energy**

→ **Safety**

→ **Less difficult to produce than Na-S (filled with NaCl)**

Figure 9- Main characteristic indicators of Na-$NiCl_2$ batteries

Medium and large-scale energy storage systems using Zebra-type batteries are commercially available [9,10].

[9] http://www.gridedge.com.au/assets/gridedge-quantum-20160302.pdf
[10] http://www.off-grid-europe.com/batteries/sodium-nickel-chloride

2.10 Flow batteries

2.10.1 Vanadium redox batteries (VRB)

In VRB batteries, chemical energy is stored in liquid electrolytes containing electroactive species. These liquids are stored in separated tanks and are pumped through a stack where chemical reactions produce electricity. The process is reversible in order to recharge the battery.

As the reaction only affects the electrolytes, electrodes are maintained inalterable and, consequently, they present a great number of cycles (>10,000). Another main feature of VRB batteries is the independence between energy and power capacities. Energy capacity only depends on electrolyte tank volume and concentration, while power capacity is determined by the stack specifications. This way, VRB systems are very flexible, allowing resizing energy capacity according to application requirements. However, they are particularly worthwhile for high-scale applications (>1 MW) and with a high relation energy/power. For PV self-consumption application, VRB is not an economic solution, since VRB batteries require pumping, monitoring and control systems. Another drawback is the reduced temperature range (0-40 ºC). As a result, VRB batteries also require refrigeration and heating systems.

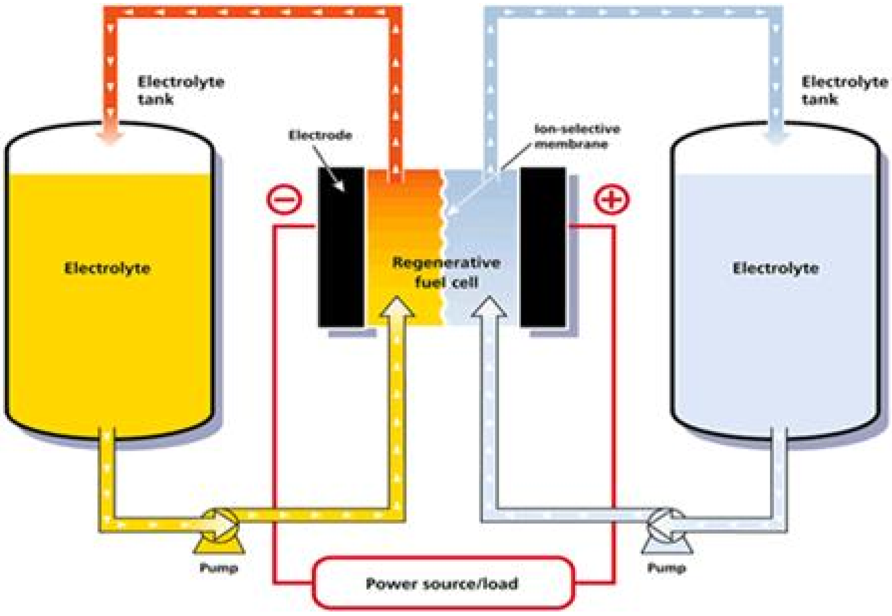


Figure 10- Flow battery architecture (Source: Prudent Energy)

- **Vanadium Redox Flow Batteries (VRB)**
  - Performance

Specific energy	10 - 30 $Wh.kg^{-1}$
Energy density	10 - 25 $Wh.L^{-1}$,
Specific power	1 - 4 $W.kg^{-1}$
Energy efficiency	65 - 80 %
Cycling at 80 % DoD	> 10 000 cycles
Costs	500 – 750 $\$.kWh^{-1}$

Gildemeister energy solution CellCube®
http://energy.gildemeister.com/en/store/cellcube-fb-10-20-30

Advantages	Drawbacks
- **Possibility to decouple energy and power** - **100 % of the capacity to be used**	- High operation costs - Complex systems (auxiliaries) - Self discharge

→ Decouple energy (tanks volume) to power (electrochemical cell size)

Figure 11- Main characteristic indicators of vanadium redox flow batteries

2.10.2 Zinc bromine (Zn-Br_2) redox batteries

Zn-Br_2 batteries are hybrid batteries, because one of their electrodes modifies its state during charging and discharging process. They offer higher energy and power densities than VRB. The efficiency depends on operating conditions (temperature and power rates) but it is around 75 % for the whole system. The response time is lower than 20 ms.

Their main drawback is the degradation due to the corrosive nature of bromine, limiting their cycling to 2,000 cycles. In contrast to VRB, Zn/Br batteries show dependence between energy and power. Since electrodes are active elements, their energy capacity depends not only on electrolyte tank capacity but also on electrode area in the stack.

Finally, special safety aspects must be considered due to potential bromine inhalation in case of electrolyte leakage.

- **Zn – Br_2 batteries**
  - Performance

Specific energy	34 – 75 Wh.kg^{-1}
Energy density	15 - 70 Wh.L^{-1},
Specific power	50 – 175 W.kg^{-1}
Energy efficiency	65 - 75 %
Cycling at 80 % DoD	>2 000 cycles
Costs	300 – 1000 \$.kWh^{-1}

Advantages	Drawbacks
- **Possibility to decouple energy and power**	- Environmental impact (Br_2)
- **High durability / cyclability**	- Complex systems (auxiliaries)
- **Tolerant to overcharge**	- Self discharge

Redflow Zn-Br_2 system (300 kW / 660 kWh; container de 20 feet, 25 t) http://www.impress.com.au/newsroom/redflow/1933-redflow-powers-up-for-battery-battleground.html

Figure 12- Main characteristic indicators of Zn-Br_2 redox flow batteries

2.11 Metal-air batteries

Metal-air batteries consist on a metallic anode (Mg, Fe, Al, Zn, Li), while the cathode is air. As the cathode is not necessary to be stored, metal-air batteries offer great theoretical energy densities and cost reduction potential. A common drawback is the degradation of the battery due to the deposition of the metallic oxides produced during the reactions.

They must be improved, as they are still in an early development stage and there is no metal-air batteries electrically rechargeable commercially available presently. In this sense, the most advanced technologies are those employing Zn negative electrodes [11].

[11] Energy Storage for the Power Grids and Electric Transportation. CRS (EE.UU.), 2012.

2.12 Battery technology selection

2.12.1 Application requirements

The first step when it comes to select the most suitable battery technology for a particular application is to determine its main requirements. This specification should be as precise as possible. In PVSITES project, the application is grid-connected BIPV self-consumption. Although detailed information about electrical consumption profile of every single demo site is not available yet and consequently energy management strategies are not completely defined for the moment, some general requirements can be specified:

1. Energy/power ratio. The energy/power ratio is the relationship between required energy and power capacities. As stated in the beginning of this chapter, electrochemical batteries present the most suitable energy/power ratio for grid-connected BIPV self-consumption applications (in the range of 1 to 4), since energy capacity of power-type technologies (supercapacitors, SMES, flywheels) is quite low and energy-type technologies (pumped hydroelectric systems, compressed air energy storage or hydrogen) are not competitive enough in terms of cost and efficiency. Similarly, electrochemical battery technologies can be also classified according to their capacity to deliver power and energy. Thus, each battery technology offers particular energy/power ratios. Even for a given technology, diverse battery packs can be manufactured to offer varied energy/power ratios. On the other hand, in some particular battery technologies, like flow batteries, these two concepts can be clearly separated, since energy capacity only depends on tanks volume and power capacity on stack configuration. In general, most of battery technologies can cope with BIPV self-consumption energy/power ratios. However, battery technologies with very high power capacities tend to be too expensive and uncompetitive for this application.
2. Energy storage costs. The main question regarding energy storage in PV self-consumption applications is if it is economically worthwhile. In order to analyse the economic performance of the battery, it is necessary to know the cost per served energy unit. However, energy storage costs are usually expressed as the cost of energy (€/kWh) and power (€/kW). These parameters show the required initial investment, but not the cost per served kWh along the lifetime of the battery. For this purpose, it is necessary to know the amount of delivered energy along its lifetime. This depends on the lowest figure of the following ones: the maximum number of cycles that can deliver the battery and the maximum number of cycles required by the application during its calendar life. Thus, a battery could reach its end of life without having delivered its maximum number of cycles. In a grid-connected PV self-consumption application, 200-300 cycles are annually expected. This means that battery technologies with more than 5,000 cycles and a calendar life lower than 15 years will not be completely used. It is important to note that the number of cycles usually given by battery manufacturers is for 1C charge/discharge rate, 80 %DoD and 25 ºC. Unfortunately, operating conditions in real applications are quite different from these. As a result, a particular battery characterization for the estimated operating conditions in each use case should be carried out, since extrapolations are not always feasible. For example, some battery technologies show a significant degradation at partial loads, that it is a common operating condition in PV self-consumption applications.
3. Overall efficiency. Cycle efficiency also impacts on economic performance of the battery. Cycle efficiency is the relationship between the energy delivered by a battery and the energy previously introduced into it. This parameter is more or less significant depending on the primary energy cost. In BIPV self-consumption applications, this cost depends on the

potential usages of BIPV excess. In addition to battery cycle efficiency, power electronics efficiency is also quite important because energy flows through it twice. In this sense, a high-efficiency DC-coupled PV storage inverter is proposed in PVSITES project, though this requires battery packs with high output voltages (400-600 V). This means serious inconvenience because current commercial solutions are generally designed for conventional residential inverters working at 48 V. Finally, battery capacity degradation along its lifetime and self-discharge should be also taken into account to better analyse its economic performance.

4. Operating temperature. Operating temperature is a key parameter since it determines efficiency and number of cycles of a battery. In general, most of technologies underperform under 10 ºC and over 40 ºC. Fortunately, in BIPV self-consumption applications, temperature can be easily delimited within these limits by means of suitable indoor location and forced ventilation, if necessary. It is important to note that some particular technologies, like NaS and Zebra batteries, only work at high temperatures (>300 ºC), requiring additional installation and maintenance conditions.
5. Safety. This aspect is particularly relevant in residential applications, where safety measures are more difficult to take. As a consequence, it is essential to identify potential dangers for each battery technology, since different chemistries mean different hazards.
6. Installation and maintenance requirements. Apart from potentially required auxiliary systems (power electronics, BMS, heating and/or refrigeration systems, safety systems like ventilation or fire protections), the most restrictive factor is energy density, normally expressed in L/kWh and kg/kWh. Once more, this kind of questions is more pertinent in residential applications, where available space tends to be more limited.

2.12.2 Comparative analysis of alternatives

In the following table, a qualitative comparison of previously listed battery technologies is shown. Green, yellow and red colours mean suitable, intermediate, and inadequate battery technology, respectively. Columns represent the different requirements explained before, excluding energy/power ratio because all considered technologies are supposed to fit. Some comments and general data are given to justify selected colours.

Some battery technologies have been directly excluded due to their immaturity or other clear limitations explained above.

Battery technology	Energy cost	Cycle efficiency	Operating temperature	Safety	Installation requirements
Lead acid	Low initial investment Limited cycling Degradation under low charge levels	Low	-40ºC…50ºC	Required ventilation	Low energy density
NiMH	High initial investment High cycling	Moderate	-40ºC..85ºC	Required fire protection	Moderate energy density Required BMS
Li-ion LFP	Moderate initial investment High cycling	High	0ºC..50ºC	Required fire protection	High energy density Required BMS
Li-ion LTO	High initial investment High cycling	High	-30ºC..55ºC	Required fire protection	High energy density Required BMS
Li-ion NMC	Moderate initial investment High cycling	High	-10..45ºC	Required fire protection	Moderate energy density Required BMS
AHI	High initial investment High cycling	Moderate	-5ºC..40ºC	Inherently safe	Low energy density

Table 3- Comparative analysis of battery technology alternatives.

As a result, two technologies (Li-ion LFP and AHI) have been selected for a deeper characterization through laboratory tests representative of grid-connected BIPV self-consumption application. On the one hand, among lithium ion alternatives, LFP represents the most economic one maintaining high energy density, high cycling and efficiency. On the other hand, AHI is a very promising technology, particularly for residential applications due to its inherent safety.

More quantitative results and more detailed recommendations will be given for each demo site, once a more precise specification of uses cases is provided and a better characterization of these most promising battery technologies is performed.

3 BATTERY CHARACTERIZATION TEST PLAN

3.1 Purpose and objectives

Due to the high cost of batteries and wide-ranging performance, a wrong selection can severely impact on the economic feasibility of the whole system. As a consequence, most of PV storage systems in the market are still far from being worthwhile. Thus, the objective is to find the storage technology with the best lifetime throughput in terms of cost per unit of energy served. However, this is not a straightforward question. On the one hand, technology forecasting is necessary since storage technology is being rapidly upgraded. On the other hand, battery performance is a function of working conditions (number of daily cycles, depth of discharge, discharge current…). Furthermore, not all batteries are created equal, even batteries of the same chemistry. The main trade-off in battery development is between power and energy, but the chemistry can be also modified to provide higher battery lifetime at the expense of power and energy. Taking into account the lack of standardization of battery manufacturer specifications, characterization tests will be carried out in CEA's facilities for the assessment of preselected batteries performance. These tests will consist of measurement of battery efficiency and testing of cycling degradation.

3.2 Review of existing standards

The table below gives a synthesis of the main standards applicable to test batteries. These standards are organized per application and/or technology.

Standard	Date	Applications	Technologies	BIPV?
IEC 61427-1	2013	Renewable energy storage off-grid	Pb, Ni-Cd, Ni-MH, Li-ion	Yes
IEC/EN 62660-1	2012	BEV / HEV	Li-ion	No
IEC 61982	2013	BEV / HEV	Pb, Ni-Cd, Ni-MH, sodium	No
IEC/EN 60254-1	2005	Traction (road vehicles, locomotives, industrial vehicles and trucks)	Pb	No
IEC/EN 60896-11	2003	Stationary (UPS)	Flooded Pb	Yes
IEC/EN 60896-21	2004	Stationary (UPS)	Sealed Pb	Yes
IEC/EN 61056-1	2013	General use (applications either cyclic or floating ; batteries included in portable equipment, or in central sources for lighting of safety or UPS)	Sealed Pb	Yes
IEC 61960	2004	Portable	Li-ion	No
IEC/EN 61951-1	2003	Portable	Ni-Cd	No
IEC/EN 61951-2	2011	Portable	Ni-MH	No
IEC 62620	2014	Stationary application : Telecom, Uninterruptible power supplies (UPS), Utility switching, Emergency power and similar applications Mobile applications :	Li-ion	Yes-

		Forklift truck, Golf cart, AGV, railway, and marine, excluding road vehicles.		
IEC 62675	2015	Industrial	Ni-MH	No
IEC 61427-2	2016	Renewable energy storage on-grid		Yes

Table 4- Synthesis of the main standards applicable to test batteries

The main methods of tests from the standards useful for BIPV application are summarized below.

IEC 61427-1 : Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1 : photovoltaic off-grid application

- Capacity: C/5 for Ni-Cd, Ni-MH and Li-ion, C/10 for Pb and other batteries + C/120 for all
- Endurance: according to standards per technology
- Charge preservation: according to standards per technology
- Endurance application PV: 40 °C with two steps :
    - Step A : discharge until SOC = 10% followed by 50 partial cycles between10 % and 40%
    - Step B : charge until SOC = 100% followed by 10 cycles between 100% and 75%

IEC 60896-11: Stationary lead-acid batteries - Part 11: vented types - General requirements and methods of tests.

- Capacity measurement at chosen C-rates (2C - C/240)
- Ability to function in floating: 20 °C, at least 6 elements, CU each six months
- Endurance in cycling: 20 °C, discharge 3 h C/5, without rest, charge 21 h C/5 limited to 2.4 V per cell, CU each 50 cycles
- Endurance in overcharge: charge 720 h C/50 after recharge
- Preservation of charge: 90 h at 20 °C
- Method of measurement of short-circuit current and internal resistance: 20 s of discharge at 0.4-0.6C, rest 2-5 min, 5 s of discharge at 2 – 4C

NF EN 60896-21: Stationary lead-acid batteries - Part 21: valve regulated types - Methods of test.

- Capacity measurement: 5 rates to be tested (4C – C/10)
- Charge preservation: 180 days at 25 °C
- Floating with daily discharges: 20 °C, cycling discharge 2 h C/5, without rest, charge 22 h C/5 limited at Umax) until reaching minimal threshold in less than 2 h, recharge 168 h then capacity measurement.
- Behavior during recharge (capacity recovery after power supply interruption) : comparison 24 h / 168 h
- Calendar: SoC 100 % at 40 °C, CU 118 days with cooling under floating
- Impact of thermal stress at 55 °C or 60 °C (idem except CU 42 days for 55°C/ 30days for 60°C)
- Abusive over discharge
- Sensitivity to thermal runaway
- Sensitivity to cold temperatures (-18 °C)

IEC EN 61056-1: General purpose lead-acid batteries (valve-regulated types) – Part 1: General requirements, functional characteristics – Methods of test

- Capacity measurement: C/20 and C
- Cycling: discharge 2 h C/4, without rest, charge 6 h IU C/10 at C/5, CU 50 cycles
- Floating: 40 °C CU 2 months

IEC 61427-2: Secondary cells and batteries for **renewable energy storage** - General requirements and methods of test - Part 2 **on-grid applications**
Comparing to other standards, this one addresses the whole battery including BMS but without DC/AC conversion:

- Performance: Energy at 25 °C, efficiency, thermal losses, standby energy consumption
- Endurance : 5 types of cycles : clause 6.1 to 6.5

For BIPV self-consumption application, the standard IEC 61427-2 clause 6.5 is the most suitable standard clause. This standard clause concerning time-shift duty for renewable energy storage is useful to test storage systems in the case of self-consumption. It will be described in § 3.3.4.

3.3 Battery characterization test plan

For the characterization of the batteries and the comparison of their performance, the following tests are planned:

- Reception test procedure enabling a cell evaluation at reception state realized at room temperature.
- Initial characterization procedure used to evaluate cell performances such as capacity and energy for different charge and discharge C-rates. This procedure is applied at 3 test temperatures: 0 °C, 25 °C, and 45 °C.
- Cycle life testing at 45 °C and 1 or more charge/discharge rate conditions.

For Lithium-ion battery:

- Thermal stability test enabling to determine the thermal runaway behavior for the selected cell.

This test plan is completed by a test following the standard IEC 61427-2 clause 6.5 described above.

These tests are detailed in the following sub-sections.

3.3.1 Reception tests

Reception tests protocol includes cell weight measurement and standard electrical performances measurements. Its target is not to measure all the characteristics of the cell but only to check some of the supplier specifications and their reproducibility by analyzing the dispersion of each parameter.

Test procedure is:

- Cell weight measurement;
- Open Circuit Voltage at reception;
- Shipping State-of-Charge (SoC) determination by first residual discharge at C/2 discharging rate;
- 3 cycles at C/2 (means half of the nominal capacity of the cell), with recording of the last cycle's capacity and energy;
- Set capacity at SoC 50% at C/2 rate;
- Internal impedance by AC method at 1 kHz at SoC 50%;
- Storage of cells at 12 °C until next tests.

All reception tests are done at 25 °C room temperature. Three cycles are performed to ensure that capacity measurement is repeatable (low variation between each cycle).

As an example, the next figure shows the current and voltage profiles during the reception test.

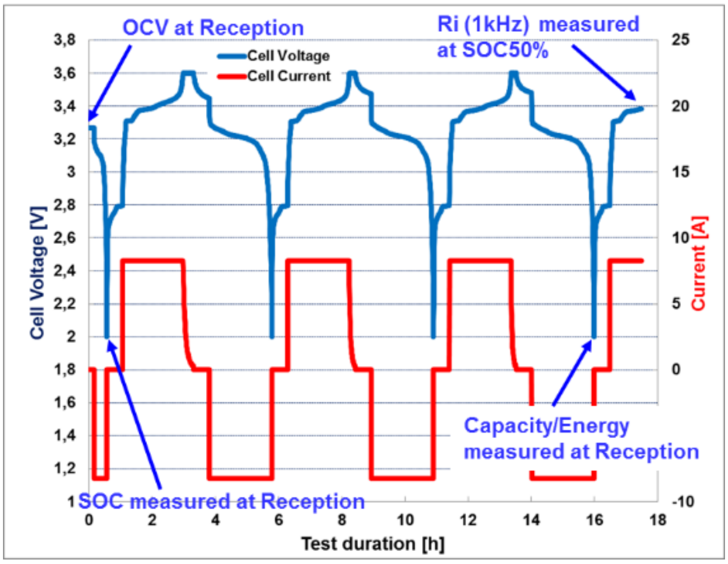


Figure 13- Current and voltage profiles during the electrical reception test

3.3.2 Initial characterization

The aim of the initial characterization is to deeply evaluate the cell performance in term of capacity/energy capability at different charge and discharge C-rates. Two cells will be tested in this part. In case of 5 % loss of capacity is observed during the test, then two new cells have to be considered in order to continue the test. Furthermore, if the skin temperature of the cell rises above 60 °C, then the test is stopped for safety reason. The thermal stability is also characterized.

3.3.2.1 Discharge behaviour study

In order to evaluate cell performances in discharge phase, the charge will be done with a *reference charge procedure* described in the datasheet of the cell.
The different discharge C-rates to be applied are: Id = 0.5C, 1C, 2C and IMAX.
3 test temperatures are planned with the following order: 25 °C, 45 °C and 0 °C.
The test procedure is described as below:

- Thermalization at 25 °C, 5 hours;
- Residual discharge at C/2 until Umin;
- Rest period of 1 hour;
- Complete charge with the *reference charge procedure*;
- Set in test temperature if different of 25 °C, thermalization rest of 5 hours (if the test temperature is 25 °C, pause of 1 hour);
- Complete discharge for each discharge C-rate Id until Umin.

Note that the voltage, current and the skin temperature of cell will be recorded during the test.

3.3.2.2 Charging behaviour study

As mentioned in the previous paragraph, in order to evaluate cell performances in charge phase, the discharge will be done with a *reference discharge procedure*:
The different charge C-rates to be applied are with respecting cell specifications and supplier recommendations for 3 temperatures: 25 °C, 45 °C, 0 °C.
The test procedure is described as below:

- Residual charge at C/2 at 25 °C;
- Set in Test temperature T°C, thermalization of 5 hours;
- Residual discharge at C/2 until Umin;
- Pause of 1 hour;
- Complete charge for each charging rate Ic given;
- Set in temperature at 25 °C, thermalization of 5 hours;
- Complete discharge with the reference discharge procedure.

Note that the voltage and the skin temperature of cell will be recorded during the test.

3.3.2.3 Thermal stability

At cell level, a thermal runaway test is performed. This test is done in a pseudo adiabatic calorimeter with the “Heat-Wait-Seek” protocol for all tests: from an ambient temperature set at 30 °C, the temperature is raised by 5 °C, then stabilized until an exothermal reaction of the cell is detected in less than 30 minutes. If not, a new 5 °C step is done. An exothermal reaction is considered when self-heating rate is higher than 0.02 °C/min at skin level. When detected, this temperature level is recorded and is called the onset temperature. Then, the temperature keeps on rising until one of the end criteria is reached, namely 180 °C or 1 °C/min (for equipment safety reason).

The Figure 18 below is an illustration of the process with higher temperature ranges.

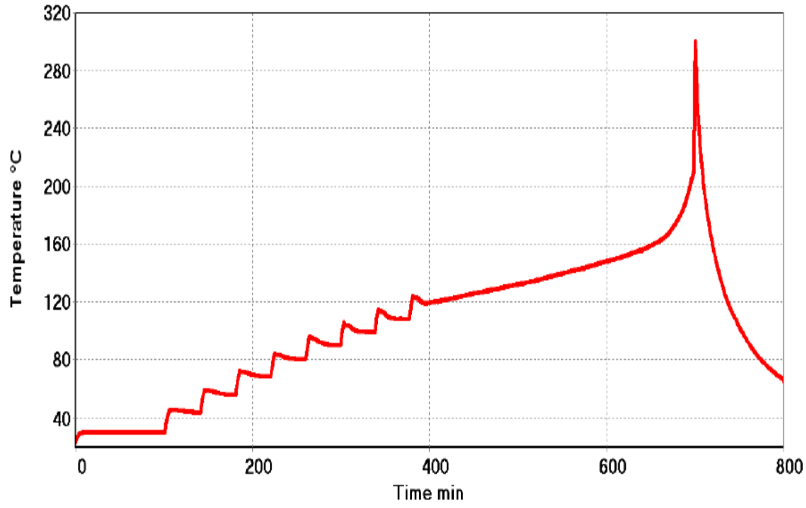


Figure 14- Heat-Wait-Seek process

During this test, the monitored parameters are:

- Cell voltage;
- Cell temperature measurement: one on cell surface (middle position) and another one at the middle between positive and negative poles.

3.3.3 Cycle ageing characterization

The cycle ageing of batteries depends on many conditions. Below some of them:

- The temperature;
- The C-rates of charge/discharge;
- The charge and discharge voltage thresholds;
- The depth of discharge and the SoC range;
- The relaxation duration between charge and discharge;
- The compression on cells in case of pouch cells.

The usual cycling conditions for some battery technologies comparison are given below:

	Li-ion	Lead acid	Nickel
Nominal temperature (°C)	25	25	25
Ageing temperature (°C)	45	40	25
End of charge criteria	floating current < C/20	24 h (floating included) or floating current < C/100 to C/500	12 h at C/10 or 125 % or dV/dt or dT/dt
End of discharge criteria	Minimal voltage	Minimal voltage	Minimal voltage
C-rate of charge during cycling	1C	C/10	C/2
C-rate of discharge during cycling	1C	C/10	1C
Rest between steps during cycling	0 min.	1 h	30 min.

Table 5- Usual conditions for cycle ageing for some batteries

We can notice here that the intrinsic differences between batteries technologies (lithium, lead acid and Nickel) lead to different evaluation criteria. Thus we can compare batteries inside one technology. Different battery technologies can be compared using complementary tests for example using endurance cycling from standards.

The C-rate of charge/discharge is defined here using the nominal capacity of the battery without adjustment at the actual capacity during ageing and with respect to battery manufacturer limitations.

Some cycling ageing tests can also be done with repetition of specific profiles representing the application for example from standards.

The duration of cycling phases between two periodic check-up tests is:

- Established using a number of cycles: default value 200 equivalent cycles at DoD=100 %
- Adjusted in such a way that the irreversible losses between two period check-up tests remain lower than some percent of capacity: default value is 5 %

3.3.4 Test according to IEC 61427-2 clause 6.5

In order to test the energy efficiency with a power set point according to the standard IEC 61427-2 clause 6.5, the following test plan in two steps is used.

- The first test at 25 °C allows to determine the available energy with discharge at a given power Pi. It consists in a reference charge procedure recommended by the battery manufacturer, then a pause of 1 h then a discharge at Pi until minimum discharge voltage Umin and finally a pause of 1 h.
- The second test allows to calculate the energy efficiency. It is carried out at three temperatures: 25 °C, minimal and maximal ambient temperatures allowed by the battery manufacturer.
    - At each temperature, the battery temperature is stabilized during a sufficient duration (typically 5 h for Lithium-ion cells and 24 hours for the Aquion battery).
- Reset the cycle duration (tcycle=0).
- Charge at Pi during 4 h and then at Pi/2 during 2 h, voltage limitation to Umax
- Pause during 1 h
- Discharge at –Pi until Umin
- Pause until tcycle=24 h

3.4 Test equipment description

Four test benches have been used to test the batteries:

- PEC © test bench to test Aquion battery electrical characteristics
- ARBIN © and VMP Biologic © to test lithium-ion cells electrical characteristics
- ARC (Accelerating Rate Calorimeter) equipment to test lithium-ion cells thermal stability

In order to control temperature during testing and ageing, batteries are put in a climatic chamber and battery skin temperature is recorded.

The testing equipment records also voltage and current and some calculations, such as charge throughput and power, are done by the equipment software.

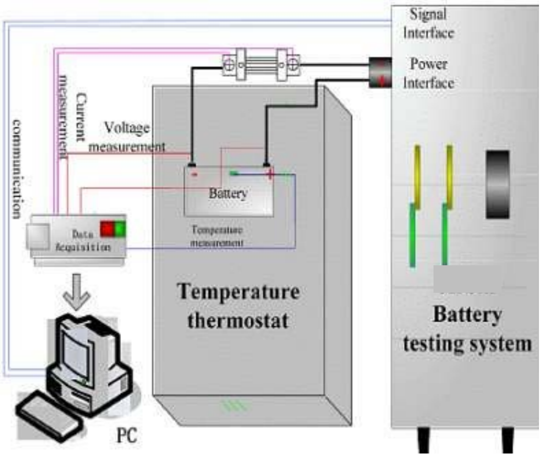


Figure 15-Testing instrumentation of batteries

The following table gives the main characteristics of the test equipment used during PVSites project.

Equipment	Main characteristics		Test Type	Calibration
PEC	Voltage range	8-100 V	Aquion Battery testing Reception, initial characterization and efficiency	done based on CEA quality procedure
	Error on Voltage Range	0.05% full scale		
	Current	+-50 A		
	Error on current Range	0.05% full scale		
	Power Set Point			
	tcycle Set			
Arbin	Voltage range	5 V	Lithium Ion battery testing, reception tests, initial characterization, ageing	done based on CEA quality procedure
	Error on Voltage Range	0.1% full scale		
	Current	+-20 A		
	Error on current Range	0.1% full scale		
	Power Set Point	Yes		
	tcycle Set	Yes		
VMP	Voltage range	+-20 V	Lithium Ion battery testing : efficiency	done based on CEA quality procedure
	Error on Voltage Range	0.1% full scale		
	Current	+- 20 A		
	Error on current Range	0.1% full scale		
	Power Set Point	Yes		
	tcycle Set	Yes		
ARC	Voltage range	0- 7 V	Thermal Stability	Internal Calibration and check before test
	Temperature range	25°C -250°C		
	Thermal run away resolution	0.02 °C/min		
Climatic chamber	CLIMA	-30°C -->80°C, +/-1°C	Thermalization	done based on CEA quality procedure
	SERVATIN			
	CTS			
	VOETCH			
	WEISS			
Temperature	TCK+equipment	-200 °C --> 200 °C,+/-1°C	Temperature measurement	Check

Table 6- Test equipment description and characteristics

4 TEST RESULTS

4.1 Tested batteries

The tests have been carried out on 3 lithium-ion references (3 LFP/G and one LFP/LTO) and on an Aquion ASPEN 24S battery. The table below gives the main characteristics on the tested cells.

Battery reference	Technology	Nominal capacity	Nominal energy	Minimum voltage	Maximum voltage
Aquion Aspen 24S -83	aqueous Na-ion	83 Ah	1992 Wh	20 V	29.7 V
Li-ion LFP/LTO	Li-ion LFP/LTO	1 Ah	1.8 Wh	1.1 V	2.4 V
Li-ion LFP/G (A)	Li-ion LFP/C	3.3 Ah	10.56 Wh	2.5 V	3.65 V
Li-ion LFP/G (B)	Li-ion LFP/C	3.2 Ah	10.24 Wh	2.5 V	3.65 V

Table 7- Tested batteries characteristics

Supplier (B) is a battery pack and system manufacturer. They don't produce battery cells. The cells supplied by supplier B are very similar to other cells tested by CEA, called reference (C).

4.2 Testing results on Aquion Aspen© 24Sbattery

4.2.1 Reception and initial performance

The reception test allow determining the energy density of the Aquion ASPEN 24S battery at C/10 rate: 18 Wh/kg and 22.41 Wh/L.

The initial performance tests give the following results.

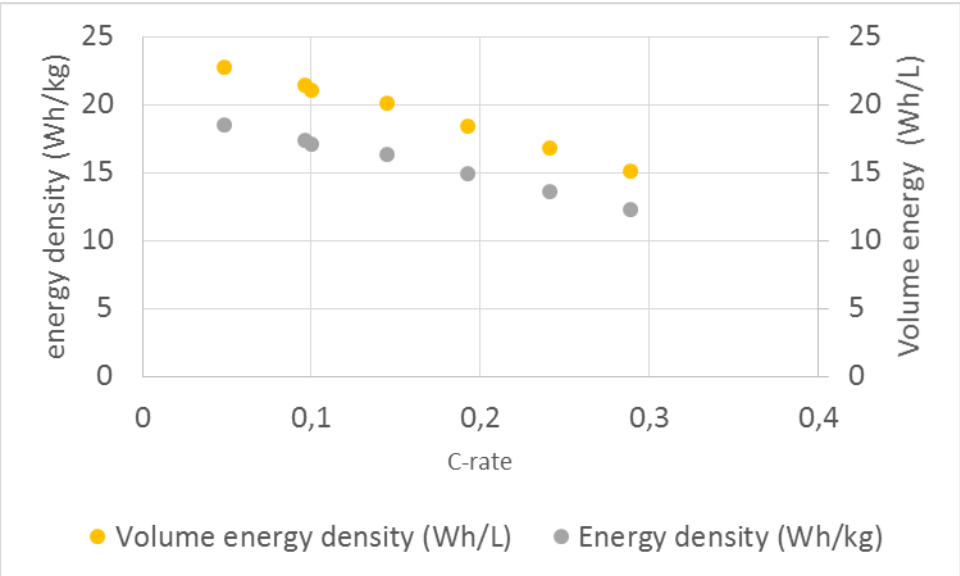


Figure 16- Energy density at 25 °C for Aquion Aspen 24S battery

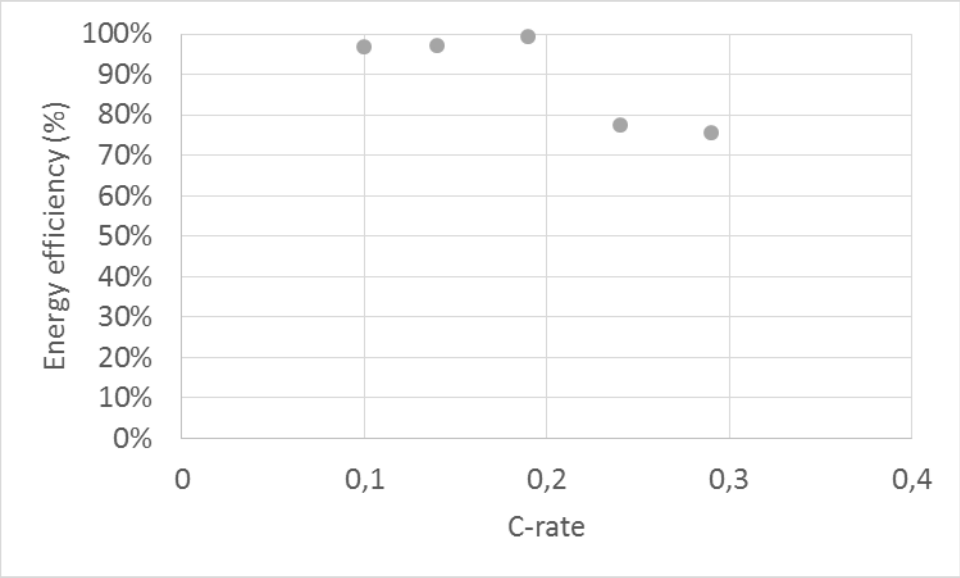


Figure 17- Symmetric round trip energy efficiency measured at different C-rates

These graphs indicate that C-rates higher than C/5 lead to parasitic reactions that reduce the energy efficiency (overcharge).

4.2.2 IEC 61427-2 clause 6.5

The power set point Pi of the Aquion battery is 300 W. The first test according to this standard allows to calculate the available energy in the battery at this power set point in discharge. Charge is the standard one.

The figure below shows the voltage evolution during this test. The available energy is calculated at phase 5. It is 1299 Wh which gives 11 Wh/kg and 13.58 Wh/L.

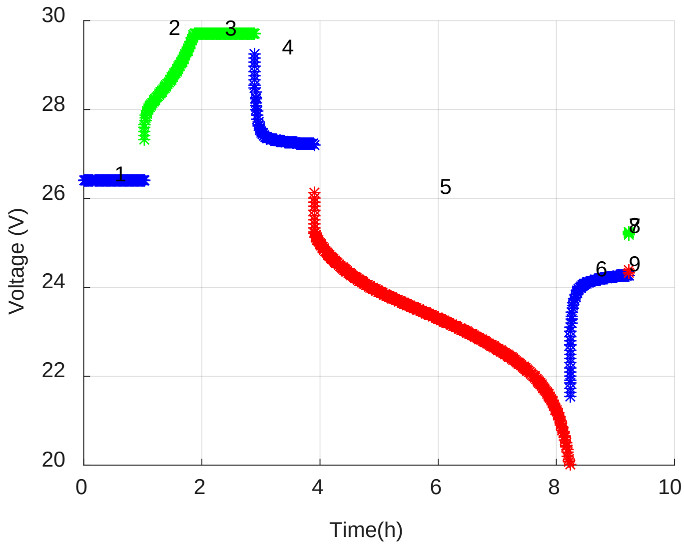


Figure 18- Voltage evolution during available energy test according to IEC 61427-2 clause 6.5

The second test according to the standard is the calculation of the energy efficiency with a power set point.

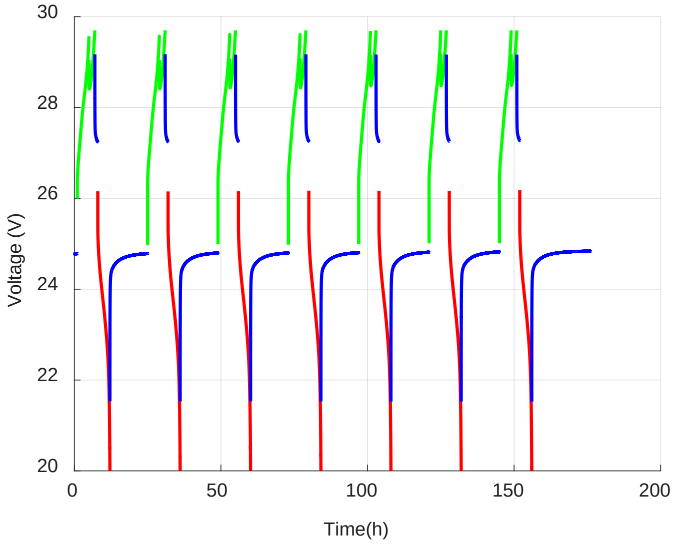


Figure 19- Voltage evolution during energy efficiency test according to IEC 61427-2 clause 6.5

The average energy efficiency is 83 % and is shown in the graph below.

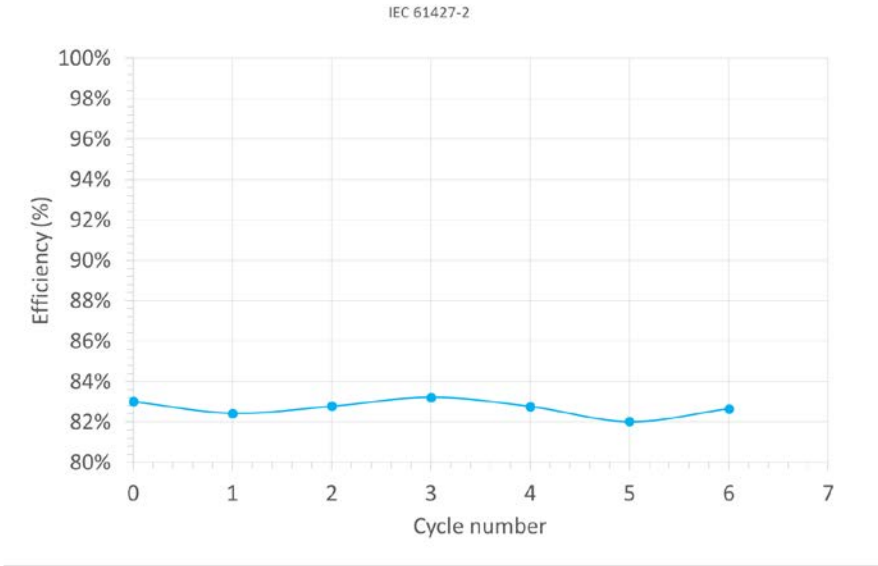


Figure 20- Energy efficiency according to IEC 61427-2 clause 6.5

4.3 Testing results on lithium-ion cells

4.3.1 Reception and initial performance

Reception tests give mainly the energy density for lithium-ion cells.

Battery reference	Energy density (W	Volume energy de
Li-ion LFP/LTO	49,6	111,6
Li-ion LFP/G (A)	123,9	295,5
Li-ion LFP/G (B)	119,0	301,7
Li-ion LFP/G (C)	119,9	298,3

Table 8- Lithium ion batteries energy density

The cells supplied by SUPPLIER (B) show the same characteristics and reception test results as reference (C) cells already tested in CEA facilities. Since reference (B) cells have been received only by middle of March, we report below the results for reference (C) cells in comparison with LFP/G reference (A) and LFP/LTO reference.

The graphs below show the initial performance of lithium-ion cells in terms of volume L/kWh.

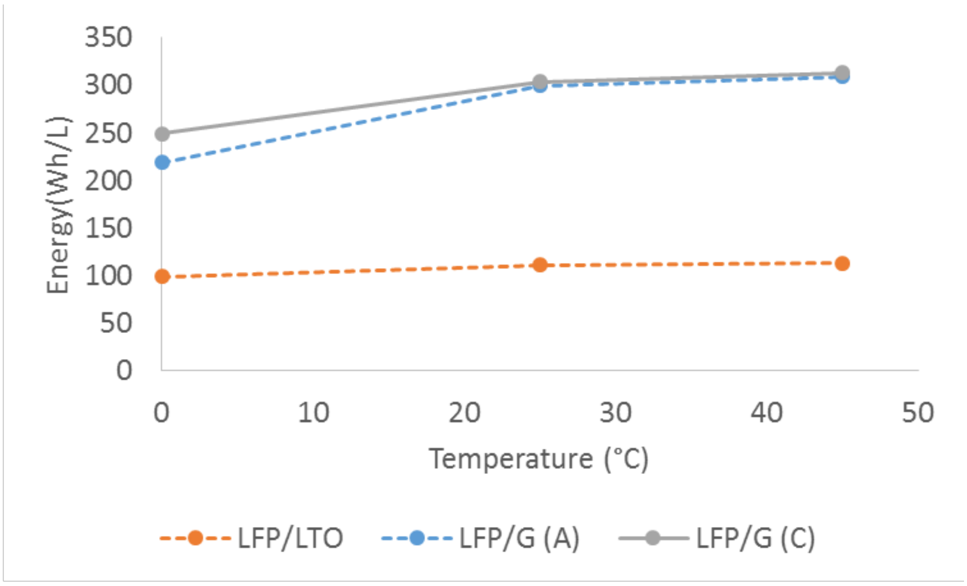


Figure 21- Performance at C/2 in [0 °C - 45 °C] temperature range

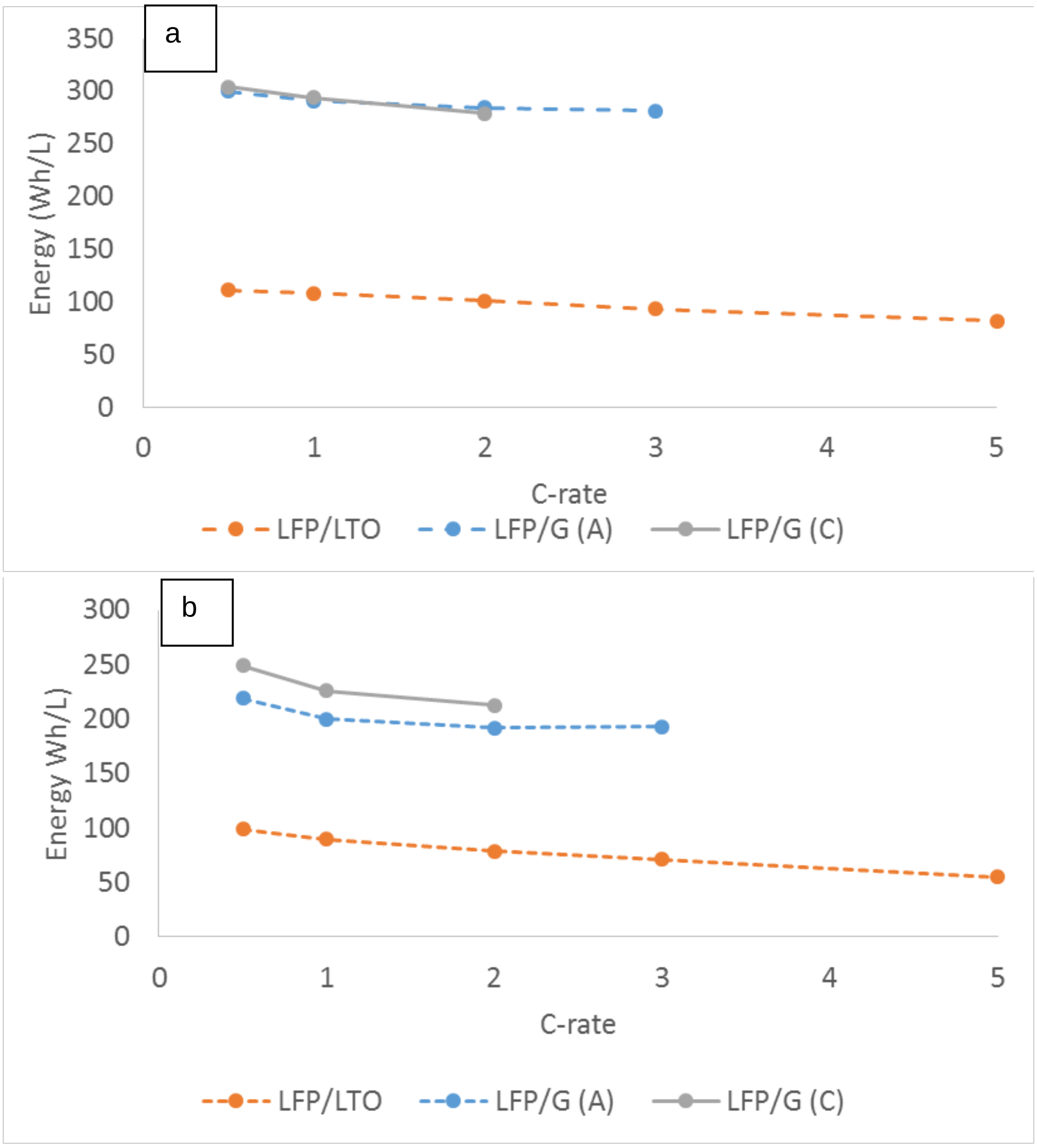


Figure 22- Performance at different C-rates, a: at 25°C, b: at 0°C

These graph shows that the energy density is more than two times lower for LFP/LTO. It is almost the same for both LFP/G references.

4.3.2 Thermal stability

Lithium-ion cells thermal stability has been tested in order to check their behavior for thermal runaway. The state of charge of the cell at the beginning of the test was 100 %.
The temperature and the speed of thermal runaway have been measured. The results are summarized in the following table for three lithium ion references. The LTO/LFP cell shows the best performance in terms of thermal stability.

Element	Capacity	Onset Temperature (°C)	Speed 10°C after onset (°C/min)	max Speed (°	Temp at Smax (°C)
LFP/LTO	1 Ah	142	0,042	0,33	200°C
LFP/G (A)	3.3Ah	91	0,046	1,79	187
LFP/G (C)	3,2 Ah	89	0,04	1,455	154,18
LFP/G (B)	3,2 Ah	109	0,03	0,08	154,35

Table 9- Lithium ion batteries thermal stability results

The graph below shows the temperature evolution of SUPPLIER (B) and LFP/LTO reference cells during thermal runaway test.

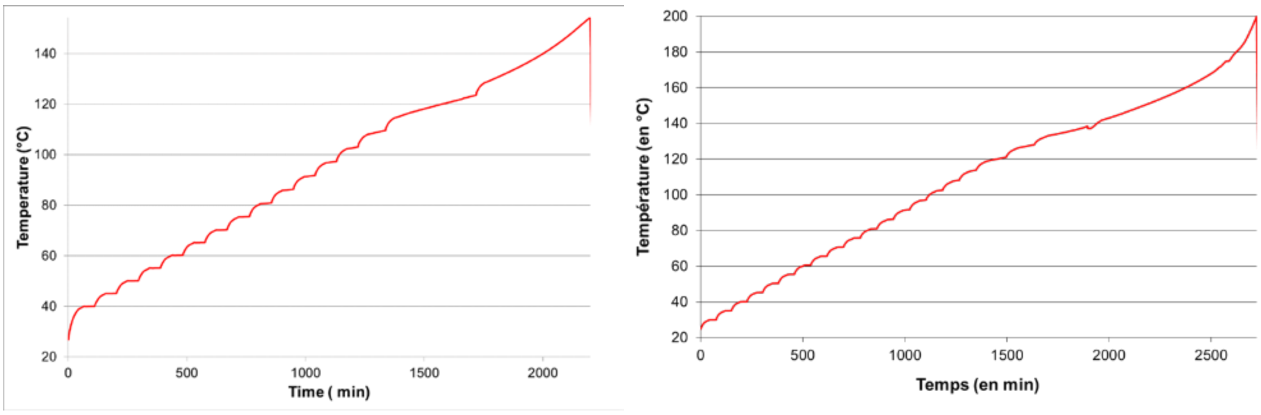


Figure 23- Thermal stability test of SUPPLIER (B) 3200 mAh (top) and LFP/LTO 1000 mAh (bottom)

In the case of SUPPLIER (B) cell the maximal speed is low showing a good safety of this reference. This good safety is confirmed for other LFP technologies.

4.3.3 Ageing

Since we received SUPPLIER (B) cells late in the project, cycling ageing tests have been done only on LFP/LTO reference and REFERENCE (A) (LFP/G) references. Their results are shown in the graph below.

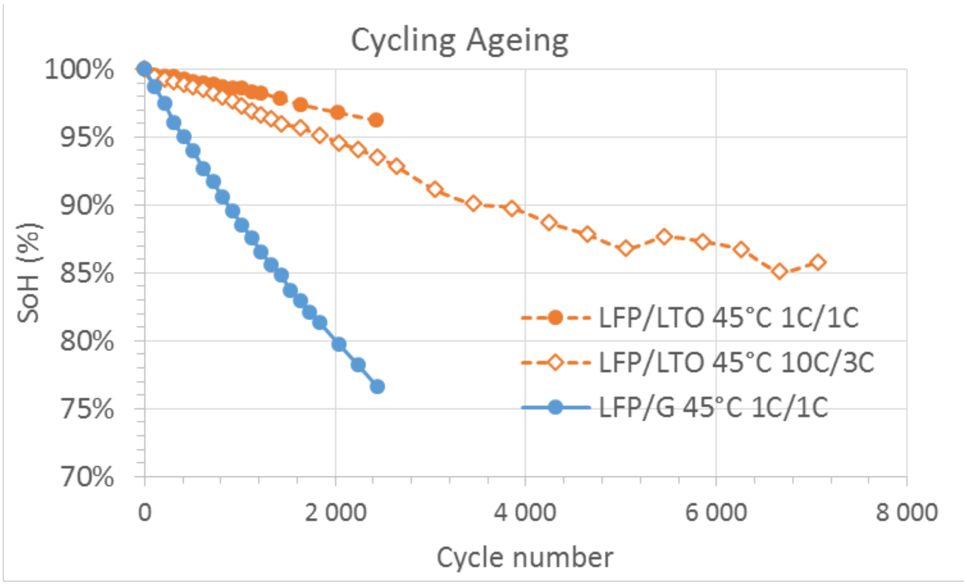


Figure 24- Cycling ageing test for LFP/LTO and LFP/G batteries

This figure shows a very good performance during ageing of the LFP/LTO batteries. As explained before, for a grid-connected PV self-consumption application, 200-300 full cycles are expected annually. This means that if the expected lifetime of the energy storage system is higher than 15 years [12], the system is supposed to perform at least 4500 cycles.

- In the worst case of operation (high temperature and high C-rate), we can expect that after 4500 cycles of operation, the LFP/G battery would have more than 50 % of its initial energy capacity. Then, a slight oversize (~ 20 %) of the battery size is recommended to guarantee the performance and the life span of the energy storage system.
- For LFP/LTO batteries, even after 4500 cycles, an energy storage capacity higher than 90 % of the initial value is expected.

The choice of the best solution depends on the total cost of the energy stored. The cost of the two types of batteries is really different (price of cells ordered for 100 units: 2055 €/kWh for LFP/LTO, compared to 370 €/kWh for LFP/G).

Even though LFP/LTO batteries are safer and present a higher performance, the cost is currently much greater than LFP/G batteries and not competitive for BIPV installation.

[12] There is currently no commercial energy storage system proposing a warranty longer than 10 years (https://www.solarquotes.com.au/battery-storage/comparison-table/)

4.3.4 61427-2 clause 6.5

Two Lithium-ion references have been tested according to this standard. The power set point Pi is 0.36 W for LFP/LTO and 2 W for SUPPLIER (B) cells.

The followings figures show the available energy according to this standard in terms of mass energy density and volume energy density.

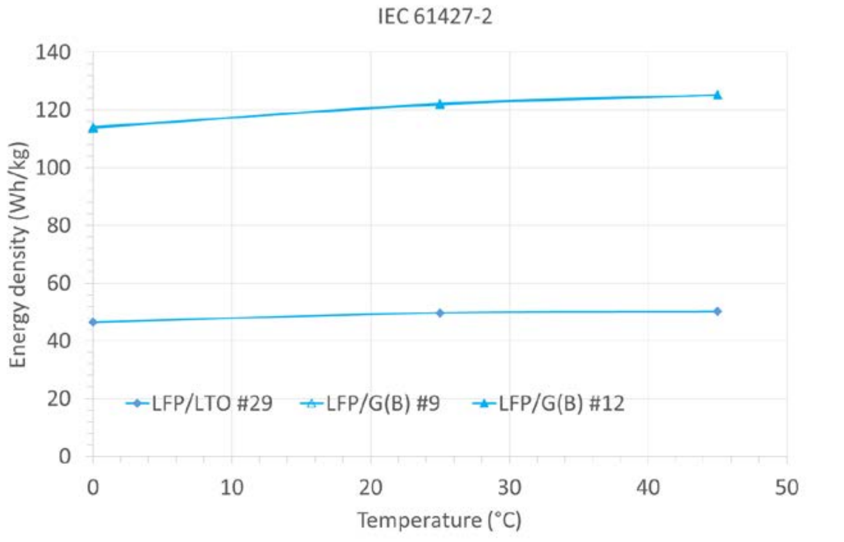


Figure 25- Mass energy density for Li-ion cells (IEC 61427-2, clause 6.5)

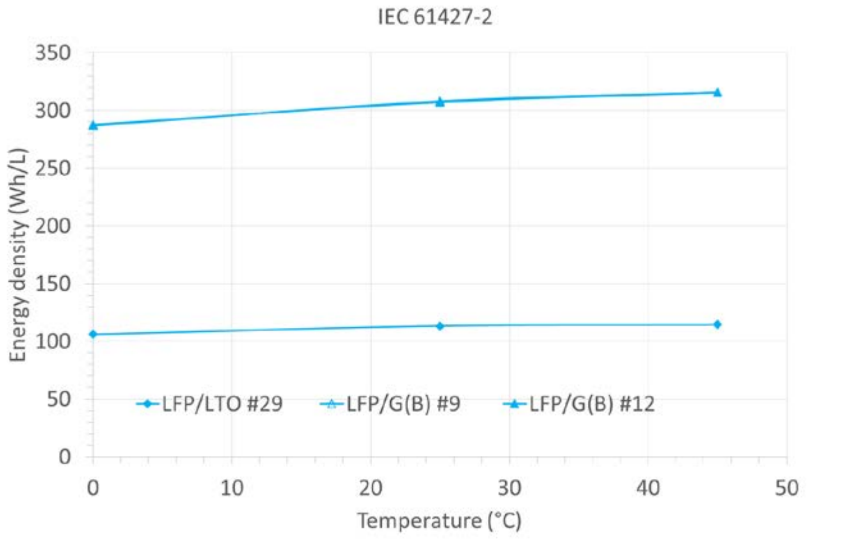


Figure 26- Volume energy density for Li-ion cells (IEC 61427-2, clause 6.5)

Mass and volume energy densities are almost three times lower for LFP/LTO cells than for LFP/G cells.

The following figure shows the energy efficiency at three temperatures calculated from the second test according to the standard.

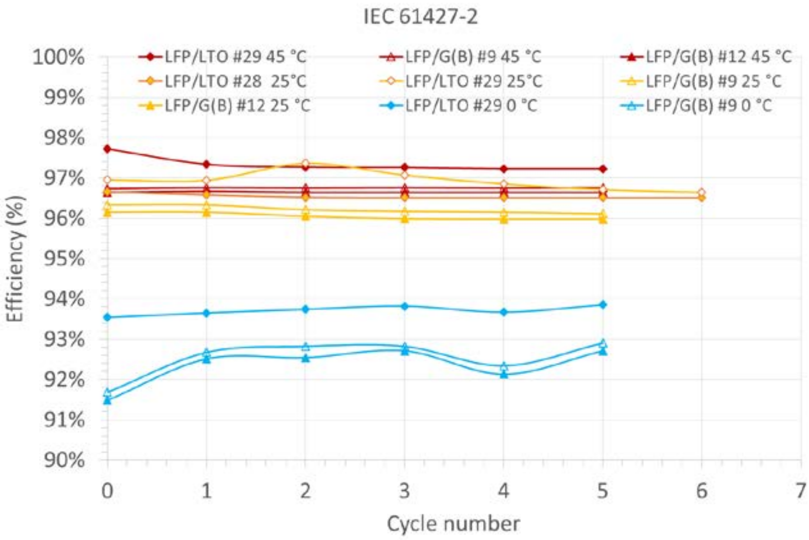


Figure 27- Energy efficiencies at 0, 25 and 45 °C for Li-ion cells (IEC 61427-2, clause 6.5)

At 25 and 45 °C, the energy efficiency of Lithium ion cells is higher than 98 %. At 0 °C, the energy efficiency is between 91 and 94 %.

4.4 Battery choice and use recommendations

According to the battery pre-selection and battery testing, the lithium ion batteries have been selected compared to Aquion batteries which have very low energy density and discharge rate. Also after the recent bankruptcy of Aquion batteries manufacturer, we can't guarantee the supply of BIPV installations with this technology.

Among Lithium-ion batteries, LFP/G are selected for the BIPV application since they have three times higher energy densities than LFP/LTO and also lower cost (2055 €/kWh for LFP/LTO, compared to 370 €/kWh for LFP/G).

TECNALIA selected SUPPLIER (B) battery manufacturer to supply lithium ion LFP/G batteries packs for the BIPV systems. SUPPLIER (B) portable energy is a manufacturer of industrial batteries (lithium – ion battery packs and primary zinc-air alkaline industrial batteries) and energy storage systems for mobile and stationary applications. The tests of SUPPLIER (B) cells show good performance in terms of thermal stability, energy density and efficiency.

In general Lithium ion batteries should operate at moderate temperature and state of charge in order to decrease ageing. Thus; a thermal management of the battery pack is necessary.

5 Conclusions

This report of the WP 5.1 of PVSites project describes the main electrical storage technologies, compares them taking into account the application in order to pre-select the battery types for testing. Finally, battery pre-selection and testing reveal that C/LFP batteries are probably the best compromise between cost and performance to be used in the BIPV systems.