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Battery Storage for Multi-megawatt Plants

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BATTERY STORAGE FOR MULTIMEGAWATT PLANTS

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ABSTRACT

To reduce pollution, move towards sustainability and maximise the introduction of renewable energy, the introduction of battery powered energy storage systems (BESS) into the grid is essential. A BESS consists of a battery module, a power conversion module and a controller.

This work reviews and compares the characteristics of batteries and discusses their possible application, listing the advantages and disadvantages of the different types, noting that the performance and capacity of the large-scale battery power storage system is dependent on the battery and the power status system. Finally, it presents the prospects for the application of electrochemical devices and concludes with the dominant technology in the market.

Depending on the type of technology and the environmental conditions, the given application can affect battery performance in addition to other factors such as life span, and therefore, the final cost.

The capacity of a battery to store energy depends directly on the speed of discharge: the longer the discharge time, the more energy the solar battery can generate. Other factor to be considered is the depth of discharge (DOD): the greater the DOD, the shorter the life cycles (charge/discharge cycles).

The capacity of a battery is normally measured in ampere hours (Ah) or by life cycles, and usually sized according to a series of criteria such as the type of use, daily consumption, days of autonomy or maximum power of the installation, among others.

Another factor to be considered is the temperature: high temperatures accelerate the aging of the battery but, on the contrary, very low temperatures can cause the freezing of batteries with liquid electrolyte. So, thermal management of the batteries is an important consideration in the design of the BESS.

After the present research, it can be stated that Lithium-Ion batteries have enormous global potential for energy sustainability and substantial reduction in greenhouse gas emissions.

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Keywords: *Battery, Storage, Lithium-ion batteries, Large scale storage, Power condition system*

1. INTRODUCTION

Many efforts are being made to integrate renewable energies into the electricity grid because of the new demand for clean and safe energy and with the aim of making energy generation sustainable. Solar energy is of great importance for reducing air pollution in the production of electricity and heat. In the coming years, solar energy systems will continue to be installed around the world. For this reason, it is important to find methods of continuous improvement of the photovoltaic generation processes.

With the current generation and consumption model, electricity is produced to be used almost instantly. Then, any unforeseen can unbalance the process. To avoid this, the integration of energy storage elements would make possible a more flexible relationship between demand and production, while at the same time improving the interaction between the consumer and the generator.

1.1. Objective

This work will focus on the storage of energy in battery banks for photovoltaic generation plants. The aim is to illustrate how batteries have become increasingly popular both in electrical systems and anywhere else in the world outside the network. A technical/economic comparative analysis will show the current status of electrochemical accumulation as well as future trends in the dominant battery technology in large-scale installations.

1.2. Background

Although photovoltaic solar energy accounts for one percent of the world's total electricity capacity (Figure 1), the percentage of each country's energy mix is much higher. In recent years investment costs have been reduced. Thus, in 2014 the generation of electricity from photovoltaic installations had a capacity of over 150 gigawatts (GW) worldwide [1], while in 2015, 51 GW of photovoltaic power were installed. China and Japan with 15 GW and 10 GW respectively, have placed Asia as the region with the most photovoltaic systems installed in 2015. The United States installed 9.8 GW in 2015 and grew by 56% compared to 2014. Europe also continues to invest in photovoltaics with 8.5 GW, mainly in the UK market with 4 GW installed and 1.4 GW in Germany [2]. The global solar PV generation capacity was 227GW in 2015, 21.12% of the production is generated with renewable energy and, within these, solar energy amounts to 8.53%.

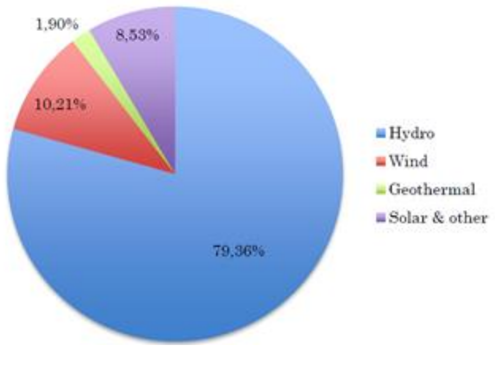

Figure 1. Percentage of renewable energies used globally in 2015 [2].

With the aim of favouring the integration of this technology and giving stability to the grid, it can be said that accumulation goes hand in hand with photovoltaic energy. Overall storage capacity is 176 GW and more than three quarters of all energy storage was installed in only 10 countries, while only 3 (China (32.1 GW), Japan (28.5 GW) and the United States (24.2 GW)), accounted for almost half (48%) of world capacity (Table 1).

Table 1. Capacity for stationary energy storage by type of technology and country, operational by mid-2017[3].

	Electro-mechanical	Electro-chemical	Thermal storage	Pumped hydro storage	Grand total (GW)
China		0.1	0.1	32.0	32.1
Japan		0.3		28.3	28.5
United States	0.2	0.7	0.8	22.6	24.2
Spain	0.0	0.0	1.1	8.0	9.1
Germany	0.9	0.1	0.0	6.5	7.6
Italy		0.1	0.0	7.1	7.1
India		0.0	0.2	6.8	7.0
Switzerland	0.0	0.0		6.4	6.4
France	0.0	0.0	0.0	5.8	5.8
Republic of Korea		0.4		4.7	5.1

Pumped hydroelectric storage represents the world's largest electrical storage capacity, with 169 GW of power in operation by mid-2017 representing 96 % of global installed capacity, whereas thermal, electrochemical and electromechanical energy storage technologies contribute a total of 6.8 GW of energy storage.

Focusing on electrochemical storage it is observed that it is one of the fastest growing market segments, representing the energy storage technology with the largest number of operational projects, followed by Pumped Hydroelectric Energy Storage (PHES) and then the thermal systems, as shown in Figure 3 [3].

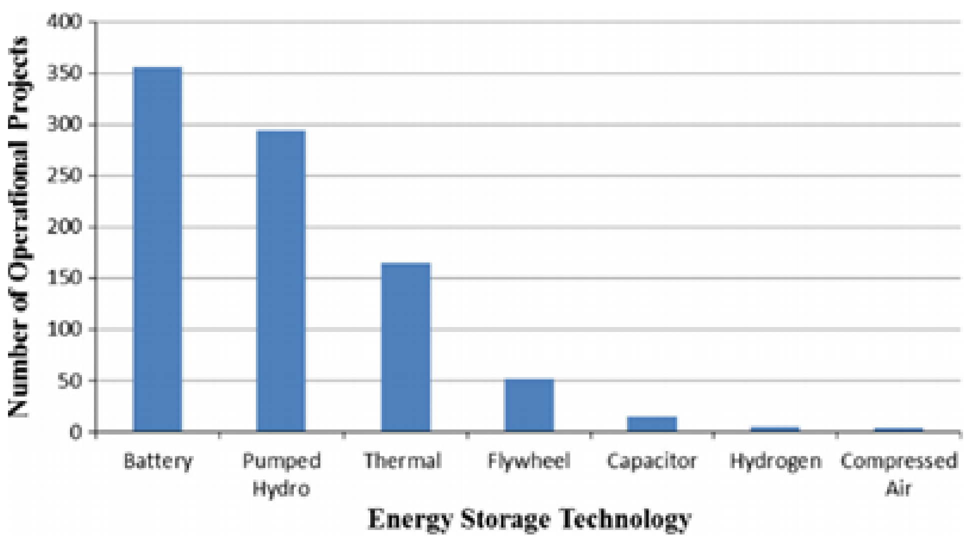

Figure 2. Projects in operation of the different storage technologies [4].

Over the past 20 years, global electrochemical storage facilities have grown exponentially as rapidly declining costs and improved performance have stimulated investment. The United States, with 680 megawatts (MW), the Republic of Korea (432 MW), Japan (255 MW) and Germany (132 MW), are the main markets, accounting for 78 % of total deployment in mid-2017 [3]. Within this, the lithium-ion batteries account for most (59 %) of the installed operating capacity by mid-2017 (Figure 3). However, there are small but important contributions of high temperature sodium sulphur batteries, capacitors and flow batteries.

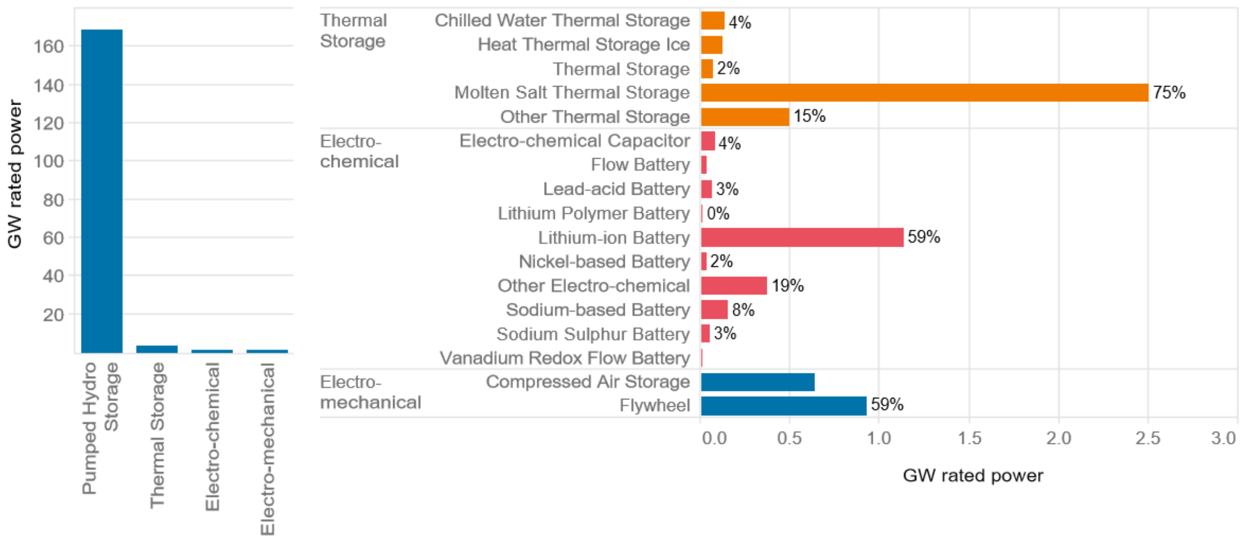

Figure 3. Global operational capacity for electricity storage by technology by mid-2017 [3].

1.3. On-grid and off-grid storage applications

Traditionally, the electricity network has been made up of four key interconnected elements: generation, transmission, distribution and final consumption. By integrating storage systems into the network as the fifth element, power could be delivered when and where necessary, creating a network with greater adaptability to consumption needs. This will lead to a move towards "smart grids" capable of managing a much more complex electricity system than at present, in which many distributed generation and consumption points would need to be integrated, due to the proliferation of small generation plants of renewable origin.

1.3.1. Applications of main integrated storage systems

- *Generation with renewable energies.* The intermittent nature of these energies and their increasing integration into the electricity grid make storage systems indispensable to be able to have enough energy available for periods that can vary from hours to even weeks [5].

- *At the generation level.* They would have the function of storing the exceeding energy to be able to supply it at peak demand or in the event of a power drop in the network. They would also serve as frequency regulators. They would keep the energy demand curve in balance [5].

- *At the level of transmission and distribution.* In this case, they would have the function of giving stability to the network, keeping all the components of the transmission system operating in a synchronized manner, thus avoiding a collapse in the transmission of energy. In addition to regulating the voltage, keeping it stable and avoiding possible voltage drops [5].

- *At the level of consumption.* Storage systems would provide power to consumers in the event of power outages [5].

1.3.2. Battery storage – islands and off-grid applications

Knowing beforehand that electricity generation in rural areas and islands is carried out with Diesel groups (generation that is unsustainable, has very high CO_2 emissions and will also be increasingly expensive). Consequently, the latent push to electrify these areas increases the integration of renewable energies.

According to the International Renewable Energy Agency (IRENA), including the initial investment, the operation of diesel generators can cost more than 0.352 USD/kWh, while the generation of renewable energy can cost as much as 0.05-0.25 USD/kWh [3].

In this way, it can be stated that energy storage systems in batteries can contribute significantly to the fight against electricity generation with fossil fuels, favouring distributed energy production anywhere in the world and even reduce the costs of generation facilities [3].

Table 2 obtained from the Lazard report [11] groups the most commonly used battery technologies according to their uses and application scales [6].

Table 2. Commonly employed energy storage technologies for different applications [6].

		Use Case Description	Technologies Assessed[2]
In-Front-of-the-Meter	1 Peaker Replacement	• Large-scale energy storage system designed to replace peaking gas turbine facilities; brought online quickly to meet rapidly increasing demand for power at peak; can be quickly taken offline as power demand diminishes[1]	• Lithium-Ion • Vanadium Flow Battery • Zinc Bromide Flow Batteries
	2 Distribution	• Energy storage system designed to defer distribution upgrades, typically placed at substations or distribution feeder controlled by utilities to provide flexible peaking capacity while also mitigating stability problems (typically integrated into utility distribution management systems)	• Lithium-Ion • Vanadium Flow Battery
	3 Microgrid	• Energy storage system designed to support small power systems that can "island" or otherwise disconnect from the broader power grid (e.g., military bases, universities, etc.) – Provides ramping support to enhance system stability and increase reliability of service (emphasis is on short-term power output vs. load shifting, etc.)	• Lithium-Ion • Vanadium Flow Battery
Behind-the-Meter	4 Commercial	• Energy storage system designed for behind-the-meter peak shaving and demand charge reduction services for commercial energy users – Units typically sized to have sufficient power/energy to support multiple Commercial energy management strategies and provide option of the system providing grid services to utility or wholesale market	• Lithium-Ion • Lead-Acid • Advanced Lead (Lead Carbon)
	5 Residential	• Energy storage system designed for behind-the-meter residential home use—provides backup power, power quality improvements and extends usefulness of self-generation (e.g., "solar plus storage") – Regulates the power supply and smooths the quantity of electricity sold back to the grid from distributed PV applications	• Lithium-Ion • Lead-Acid • Advanced Lead (Lead Carbon)

2. METODOLOGY

After careful research and a general overview of the main uses of off-grid and on-network energy storage, it is now possible to identify the main uses of off-grid and on-network energy storage.

The present work will proceed as follows: in section three, the different components of a photovoltaic energy plant will briefly described. Subsequently, in section four a description of the main types of batteries used for energy storage and their main characteristics will be given.

In the fifth section, a technical-economic comparison will be made, in addition to presenting the projects installed and to be installed throughout the world.

With the results obtained, it will be able to conclude which electrochemical technology will dominate the market for large photovoltaic plants in the next years.

3. MAIN ELEMENTS OF A PHOTOVOLTAIC PLANT WITH BESS

3.1. Photovoltaic Panel

A PV panel is composed of a set of semiconductor cells electrically connected in series, encapsulated and mounted on a support structure or frame. First cells were based on a few materials such as crystalline silicon or gallium arsenide, but nowadays they use many other materials.

The photovoltaic modules provide a DC voltage at their connection output and are designed for specific voltage values (6 V, 12 V, 24 V....), which will define the voltage at which the photovoltaic system will work.

A typical solar cell has a surface area of 243 cm^2 and produces approximately 4 W of power, with a voltage of 0.5 V and a current of between 7 and 8 A. The low voltage and power values make it necessary to connect several cells in series. Most solar panels or photovoltaic solar modules have between 36 and 96 cells connected in series. Typical standard for solar power plants is 60-72 cells.

The types of solar panels are given by the manufacturing technology of the cells, and are fundamentally [7]:

- Crystalline silicon:
  - Mono-crystalline: continuous structure.
  - Multi-crystalline: composed of small crystals.
- Amorphous silicon: amorphous and crystalline form.

3.1.1. Main producers / installers of PV modules

Market instruments have been developed to support the advancement of solar technology. With better prices, solar technology has entered the power generation market.

Tier 1 module manufacturers (Table 3) are those which have provided own-brand, own-manufacture products to six different projects higher of 1.5 MW, which have been financed non-recourse by six different (undeveloped) banks, in the past two years.

Table 3. Module manufacturers meeting Bloomberg New Energy Finance´s tier 1 2018 [8].

Firm/brand	Annual in-house module capacity (MW/year)	Firm/brand	Annual in-house module capacity (MW/year)
Canadian Solar*	8,110	SunPower*	1,900
Trina Solar*	8,000	BYD*	1,700
Jinko Solar*	8,000	Changzhou Almaden	1,500
Hanwha Q Cells*	8,000	China Sunergy	1,450
JA Solar*	7,000	REC Group*	1,400
Risen	6,600	Adani/ Mundra*	1,200
Longi*	6,500	Akcome	1,000
GCL Systems*	5,400	ET Solar	1,000
Suntech/ Shunfeng*	3,300	Boviet*	700
Seraphim	3,000	Lightway Solar	660
Chint/ Astronergy*	2,500	Tata Solar Power	500
Znshine Solar	2,300	Waaree	500
First Solar*	2,200	Hansol Technics	480
Talesun	2,200	Heliene	250
Renesola	2,000	Sharp	210
Eging	2,000	Shinsung Solar	200
Phono Solar*	2,000	Swelect	110
		Total	93,870

3.2. Battery Storage Systems

A battery is an electrochemical device that delivers electrical energy using the chemical energy generated in different reactions. There are different types of technologies that are characterized by different capacities ranging from less than 100 W to several MW and discharge rates from a few seconds to several hours (Figure 4). Batteries have a wide range of energy storage efficiency ranging from 60-95 % depending on the operating cycle and the type of electrochemical technology [9].

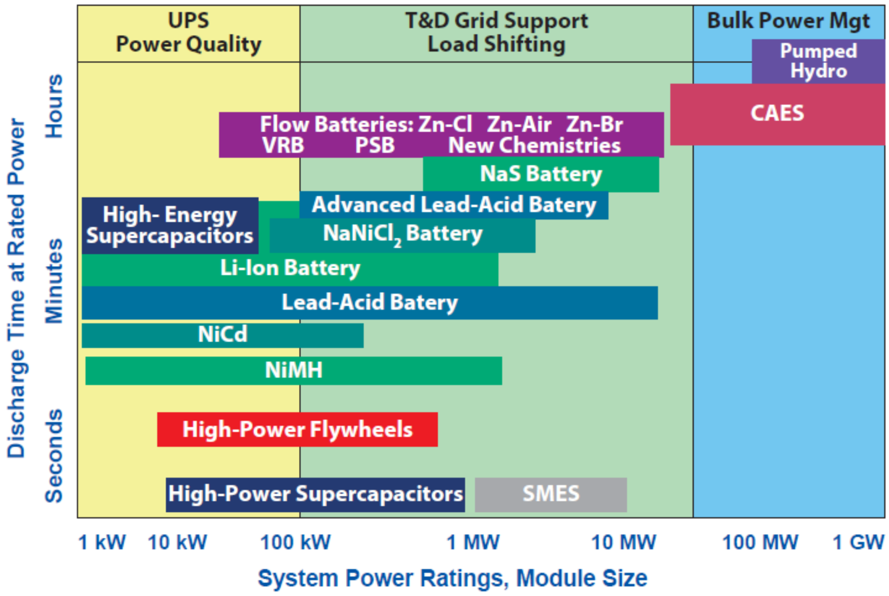

Figure 4. Positioning of Energy Storage Technologies [9].

Figure 5 shows a common scheme of the interface of a battery storage system. In general, a battery storage system includes the battery itself (battery cells assembled into modules and optional module configurations), a Thermal Management System (TMS) (which can be subdivided into Battery-TMS (B-TMS) and System-TMS (S-TMS)), which is also known as a Battery Management System (BMS), as well as an Energy Management System (EMS) [10].

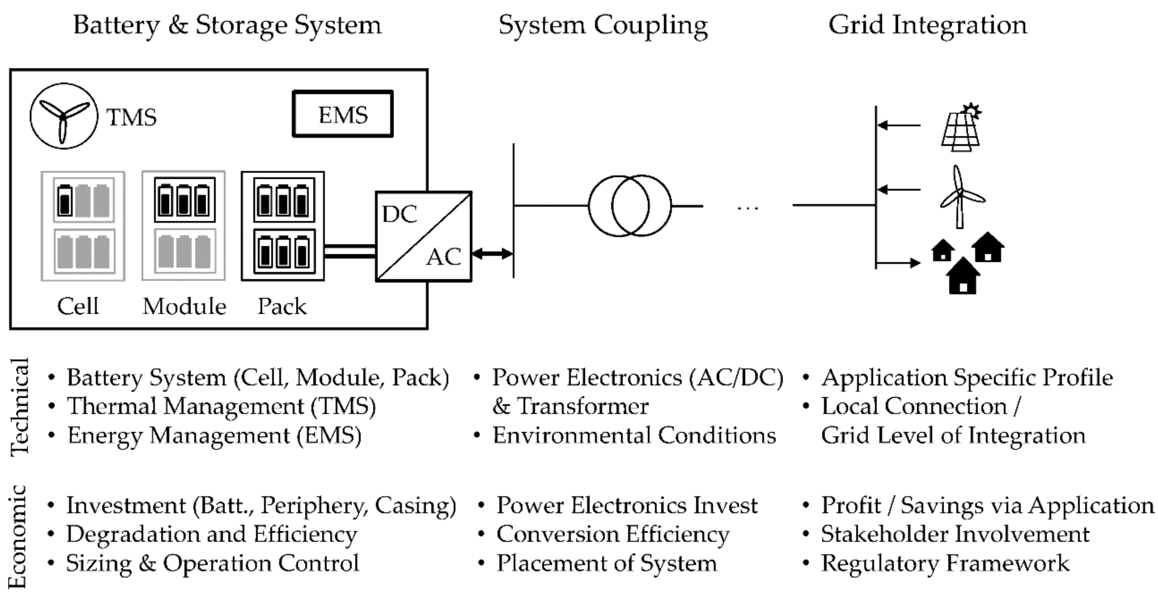

Figure 5. Scheme of battery-based electricity storage system [4].

Any storage system is characterized by a series of parameters or properties that will be now explain for the different battery technologies [10]:

- *Energy density:* it is defined as the ratio of the real stored energy to the volume of the storage device (W h/kg or W h/l).

- *Power density:* it is defined as the nominal output power between the volume of the device and is expressed in W/Kg or W/L. Energy storage systems with high power density are suitable for applications requiring high power quality at high discharge currents and fast response times.

- *Life time:* this is the operating time that the manufacturer forecasts if the specified conditions are maintained. Battery-based systems often have a short lifetime due to chemical deterioration, although this may improve with technological advances.

- *Investment and operating costs:* they are important factors for the commercial development of each technology. To perform a detailed analysis, the cost of any energy storage technology must include both capital and operating costs. In turn, operating costs include operating, maintenance, disposal and replacement costs. Battery investment costs are continuously decreasing due to technological advances [4].

- *Storage capacity:* this is the total energy stored in the system given in Wh. Due to the problem of self-discharge, duration of storage is one of the main characteristics to be considered when choosing one or another type of technology for energy storage. In the case of batteries, there are short, medium and long-time ranges [4].

- *Efficiency:* it is the ratio between the electricity production from the storage device and the electricity input from the device during a charge/unload cycle. Most batteries have an efficiency of between 50 and 90 %.

- *Response time:* it is a parameter that measures how fast a system is able to release stored energy. Some applications require a very fast release of stored energy to meet the energy demand of the system.

3.2.1. Main producers / installers of batteries

The leaders in medium- and large-scale storage are mostly Chinese companies or companies from the United States or Germany that are also based in China. So, the analysis will be focussed on this country.

The top ten manufacturers in the Chinese energy storage market according to "Global Energy Storage Database" [11] are: Sungrow-Samsung, Sacred Sun Power Co. (Sanyo Power), Shenzhen Clou Electronics Co., CATL (Ningde Times), Sunwoda Electric Co., Narada Power Source Co., ZTT (ZTT), China Aviation Lithium Battery Co. (AVIC), Guoxuan High-Tech Power Energy Co. and Shuangdeng Group (Shuangdeng). These ten companies accounted for 98 % of total new capacity in China in 2016.

Table 4 details several companies that are competitive in the manufacture/sale of solar batteries. The table shows the name of the company and the region of operating (China, although it has offices all over the world) and the technology it works with.

Table 4. Manufacture/sale of solar batteries in China. [12]

Company	Technology	Scalability
SAMSUNG SDI	Lithium.ion, lead-acid	Short-large scale
SIEMENS	Lithium.ion, lead-acid	Short-large scale
FLUENCE (SIEMENS & AES)	Lithium.ion	Large scale
BYD	Lithium.ion, niquel, hierro	Short-large scale
ABB	Lithium.ion	Short-large scale
LGCHEM	Lithium.ion	Short-large scale
PANASONIC	Lithium.ion	Short scale
SHOTO / SHUANGDENG GROUP COMPANY LIMITED	Lithium.ion, lead-acid	Short-large scale
ENERSYS	Lithium.ion, lead-acid	Short-large scale
SUMITOMO	Lithium.ion, lead-acid	Short-large scale
NGK	sodium bateries	Short-large scale
YUASA	Lithium.ion, lead-acid	Short-large scale
HOPPECKE BATTERY SYSTEMS	Lead-acid, niquel cadmio	Short-large scale
CSPOWER BATTERY	VLA, GEL, AGM, lithium ion	Short-large scale
ROLLS BATTERY ENGINEERING	VLA, GEL, AGM	Short-large scale
SUNGROW POWER SUPPLY	Lithium.ion	Medium-large scale
NARADAPOWER	Lithium.ion, lead-acid, high temperature	Short-large scale
SACRED SUN	Lithium.ion, lead-acid	Short-large scale

3.3. Power Conversion System (PCS)

3.3.1. Inverters

Wave inverters are the best choice for supplying alternating current loads, as they do not present problems due to harmonic distortion or voltage stability. In photovoltaic plants, the way of using them is in a string or central inverter and always accompanied by a charge regulator if this is not included. The schematic configuration of the inverters together with the three-phase transformer is shown in Figure 6.

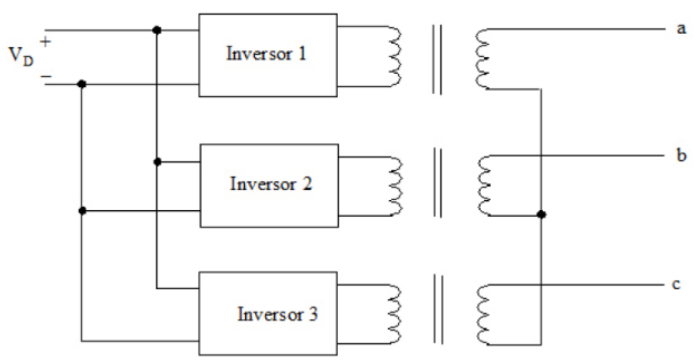

Figure 6. Schematic configuration of the inverters together with the three-phase transformer [13].

Solar inverters can cause major system disruptions if they fail. The investor will therefore play a key role in the overall profitability of the system [13]. Thanks to the development of power electronics, new products have been developed, such as maximum power point tracking and anti-islanding protection, to increase the efficiency and safety of the system.

The maximum point of the power transfer corresponds to the tangent point between the I-V curve for a given value of solar radiation and the hyperbola described by equation V * I = const. (Figure 7).

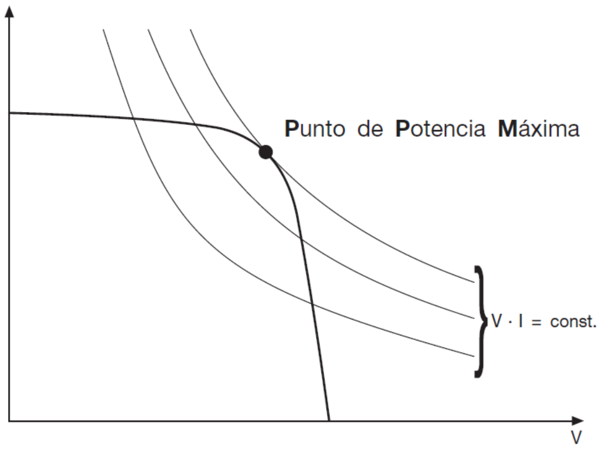

Figure 7. The maximum point of the power transfer [14].

Due to the characteristics of the required yields, inverters for isolated plants and for plants connected to the network have different needs:

- In isolated plants, investors must be able to provide a voltage on the AC side as constant as possible within the variability of the generator output and load demand [14].

- On grid-connected plants, inverters must reproduce, as faithfully as possible, the tension of the network and at the same time must try to optimize and maximize the output energy of the PV panels [14].

Inverter performance is the ratio of the output power to the power of the solar panels or battery at the input, also known as the DC/AC ratio. Working at full load and optimum conditions, 90-98 % efficiency can be obtained.

Focusing on large scale plants, the trend is to use container with the accumulation and the integrated converter. The usual scheme will be defined next.

3.3.2. Power Condition System (PCS) and Battery Management System (BMS)

The batteries are characterized by their modularization, fast response and great marketing potential. Technical innovations and development of new battery types will ensure a continuous improvement of efficiency, power and energy density and service life [10]. Battery-operated systems are associated with flexible installation and short construction cycles and can be applied to grid energy storage systems [15].

In a basic battery power storage system (Figure 6), different components can be distinguished:

- *Battery pack* which presents a modular design that facilitates integration, installation and expansion

- *A battery management system (BMS)* that oversees controlling the parameters of the battery, so it estimates its current capacity [10].

- *A power condition system (PCS)* that takes care of the necessary rectification and inversion when converting between AC and DC electric power [10].

- *An energy management system (EMS)* responsible for the proper programming and management of the power storage system having to meet, without any problems, the connection requirements between the communication and the programming of the main engine of the station [4]. One widely used software application is Supervisory Control and Data Acquisition (SCADA), which is a supervisory, control and data acquisition system that helps improve remote decision making from a cockpit.

3.3.2.1. Power Condition System (PCS)

The PCS system is the electronic interface between the DC batteries and the AC electrical network. This system not only acts as an interconnecting device of the storage system but also manages the charging and discharging of the battery [10]. When determining the capacity of the PCS system, not only the battery power is considered, but also the reactive power compensation must be considered [16].

Depending on the capacity of the battery system it will affect the topology of the PCS in one way or another. For low voltage batteries in parallel two conversion structures can be find: one of one stage and two of two stages. In a single stage conversion the battery system is directly connected to the mains via the DC/AC converter, so that several converters can be connected in parallel increasing the power rate. In contrast, when the conversion is in two stages, the DC/DC converter will increase the battery system voltage to a high level and will be connected to the network through the DC/AC converter which can use multilevel topology. This type of two-stage converter optimizes the operating range of the battery but reduces both the efficiency and reliability of the system. The single-stage converter has higher efficiency but is limited by a low cut-off voltage level of the battery system when completely discharged [16].

At present, its use is limited to high power battery storage systems, but it is still an immature technology. Research into this type of system would allow the development of high energy battery storage and reduce costs [10].

3.3.2.2. Battery Management System (BMS)

Due to the high specific energy density and application requirements, the batteries must be protected with a system that continuously and periodically checks the voltage and current of the battery cells during the charging and discharging process [17]. The main differences between batteries are their capacities and attenuation rates. Therefore, it is crucial to be able to balance the electrical energy quantity of each battery pack to ensure long-term operation and efficiency [10]. In the case of industrial demands, it is necessary to be capable of connecting batteries in parallel, making evident the need for a control system to correctly manage the components of the battery and guarantee the proper functioning of each one during charging and discharging.

The BMS will be able to provide the batteries with protection and balance against high or low voltage overloads, control current, overcurrent protection and protection against short circuits and high temperatures. The presence of a BMS system has gradually become essential especially in applications where lithium-ion batteries are used [10].

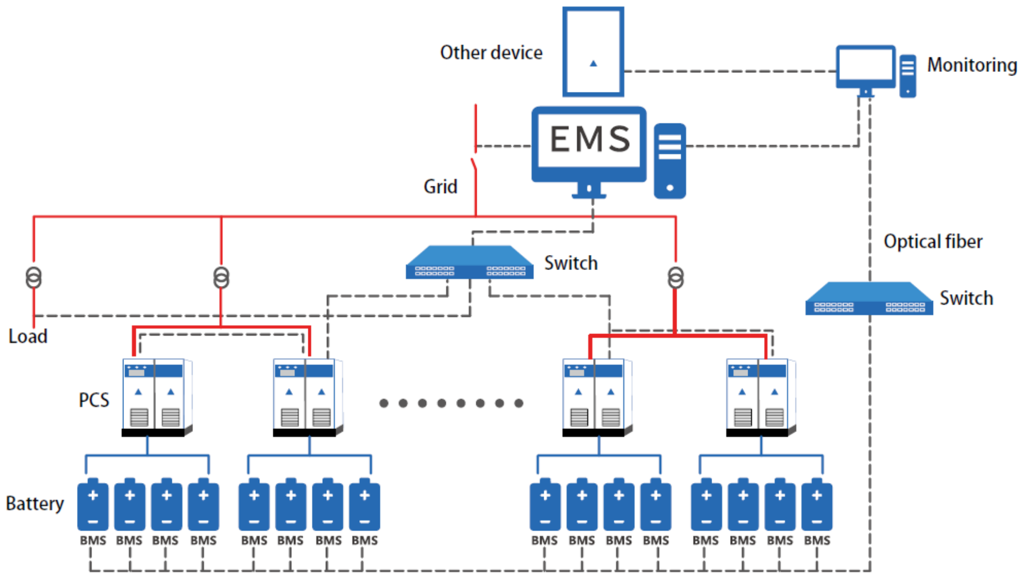

Figure 8. Kehua scheme of battery-based electricity storage. [Anexo 9.1.3]

There are single stage converters (AC-DC) whose advantages are to have a simple and high efficiency structure; or two stages (AC-DC and DC-DC) being this more suitable for large scale connections. When the charge current is too high, life cycle degradation and even explosion hazards may occur.

The characteristics of the different types of batteries can affect the system. For example, the charging of lithium-ion batteries is very different from that of lead-acid batteries, requiring a much lower current. Thus, in case the current is too high it could cause a degradation of the life cycle or even an explosion, which is why a BMS has to be installed as it can limit and regulate the required current [17].

Table 5 shows the manufacturers of inverters and PCS from China found in the market.

Table 5. Competitive companies in PCS sales [12].

Company	Country

ABB	United States
HUAWEI	China
SIEMENS	Germany
SMA	Germany
SUNGROW	China
KEHUA TECH	China
KOSTAL	Germany
VICTRON	Netherlands
JEMA	Spain
SAJ	China

3.4. Grounding and Transformers

A PV system can only be earthed if it is galvanically separated from the mains by a transformer. A transformer is a static alternating current machine responsible for converting the voltage of the generator into the voltage of the network where the energy produced will be delivered.

This is achieved by varying the voltage, maintaining the frequency and power. The voltage variation is made by the input winding that transforms the current into magnetism and then transforms it back into electricity in the secondary winding. So, it is a critical point to be where all the electrical energy comes out [18].

3.4.1. Plants with transformer

In transformer plants, in addition to the analysis of the PV system, both isolated and earthed, for protection against indirect contacts, it is necessary to differentiate between the upstream and downstream masses of the transformer by referring to the direction of the electrical power produced by the PV plant. The most commonly used typical IT (isolated or impedance-earthed neutral system, Figure 9) and TN (exposed conductive parts connected to the neutral system, Figure 10) diagrams [14].

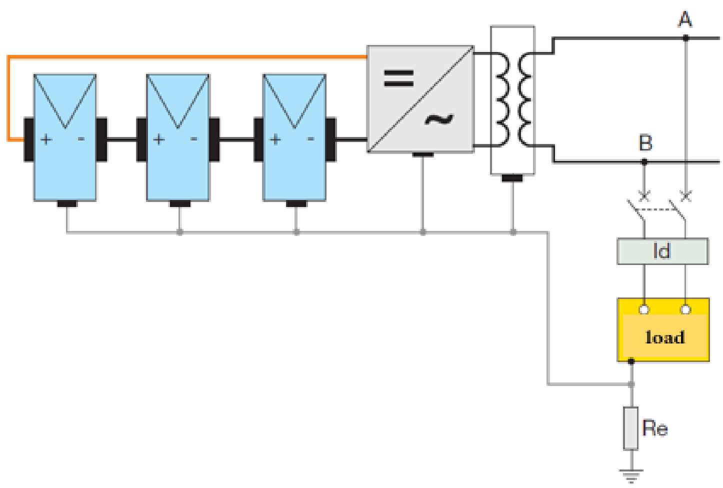

Figure 9. Scheme of IT active parts are insulated from earth, while exposed conductive parts are earthed. [14].

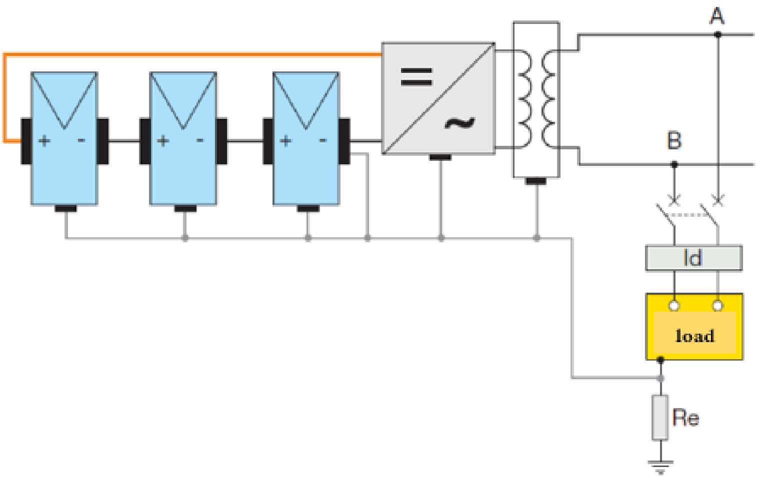

Figure 10. Scheme of TN active parts and exposed conductive parts are connected to the same grounding system [14].

In a TT-type user-network system. The masses belonging to the user's installation - protected by residual current circuit-breakers fitted at the start of the installation (Figure 11) - are protected both with respect to the grid and to the PV generator.

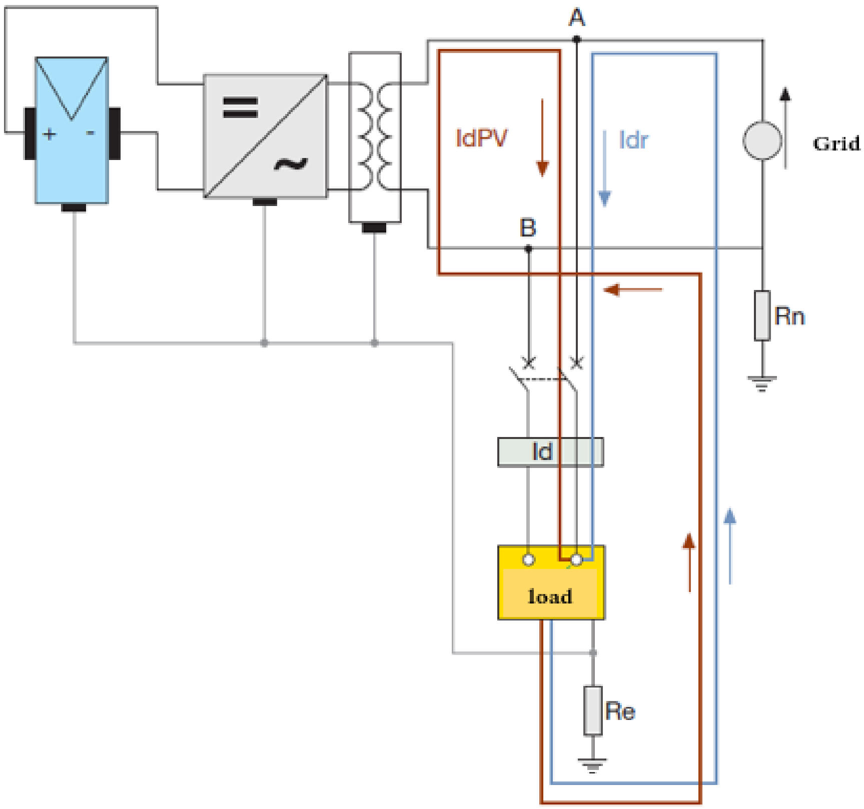

Figure 11. Masses downstream of the transformer [14].

3.4.2. Plants without transformers

In the absence of an isolating transformer (Figure 12) between the PV system and the grid, the PV system itself must be isolated from earth in its active parts, thus becoming an extension of the grid, usually with a grounded point (TT or TN system) [14].

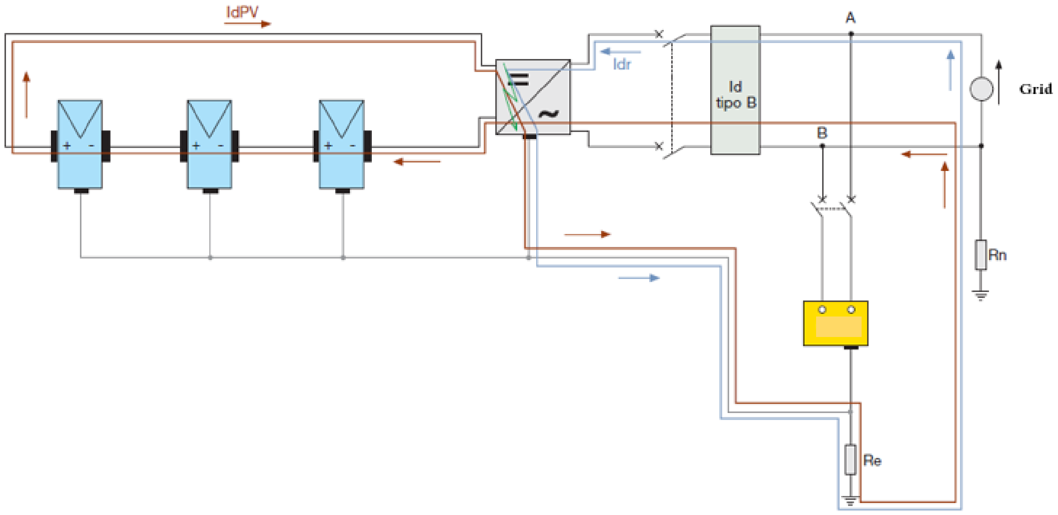

Figure 12. Scheme of plant without transformer. On the DC side, a ground fault of the masses involves the tripping of the differential switch installed in the water below the inverter [14].

3.4.3. Transformer efficiency

The transformer, like other elements, will cause the energy to suffer losses, which is why it is necessary to consider it when calculating the energy generation performance. The transformers have high efficiency and require little maintenance. Also, the closer the work gets to the rated power, the more efficient they are. The most known losses in a transformer are:

- Iron or magnetic losses: among these are hysteresis losses and eddy current losses.

- Copper or ohmic losses.

Manufacturers of transformers in the market are given in Table 6.

Table 6. Some transformer manufacturers [19].

Company	Country
SIEMENS	United States
ABB	Germany
SEA	Italy
TIANAN	China
Schneider electric	France

4. BATTERY TECHNOLOGIES

One of the oldest methods of electricity storage is based on the use of chemical energy in batteries. Within the batteries there are have different categories ranging from mature, proven and reliable technologies (lead-acid battery, invented in 1859) to technologies under development such as NiCd, NaS, Li-ion and flow batteries [20].

4.1. Nickel-Cadmium Batteries (Ni-Cd)

It was the dominant rechargeable battery in the 1990s [10]. The positive electrode material is nickel hydroxide ($Ni(OH)_2$) while the negative electrode is cadmium (Cd), and an alkaline solution KOH (potassium hydroxide) acts as the electrolyte. The interaction of these substances results in a characteristic electromotive force of 1.3 V [21].

It is a battery with a very fast recharge time, although its useful life depends mainly on the discharge levels in each cycle, reaching up to 50,000 cycles with 10 % discharge [22]. It has deep download speeds that do not produce damage or loss of capacity [4]. However, one of the main disadvantages is its low energy density, as well as its limitation with respect to electrical memory, which is a phenomenon of reduction in storage capacity that occurs when it is charged without having been completely discharged in advance [21]. It also has a cost 10 times higher than that of lead-acid [23] and poses serious environmental problems as a result of its toxicity due to the presence of cadmium.

Finally, it is worth mentioning that batteries of this type have been losing ground in recent years, compared to other technologies, such as nickel metal hydride and lithium ion [24]. They are not very advisable in renewable energy systems.

4.2. Nickel-Hydrogen Batteries

During the 1980s Nickel-Hydrogen batteries were used in aerospace applications. One of the characteristics of this type of battery is the good hermetic seal that allows it to have a high life cycle. It is for this reason that in many applications Nickel-Cadmium batteries are replaced by Nickel-Hydrogen batteries [25].

Among its features are long life cycles (more than 7000) with discharge depths of up to 80%, a service life of about 20 years due to the hermetic seal that also makes no maintenance exhaustive. The Nickel-Hydrogen batteries can have applications in the field of photovoltaics for energy storage. However, this type of battery has a fast self-discharge and high costs, therefore its use is limited [25].

4.3. Nickel-Metal Hydride Batteries (Ni-MH)

This type of battery is similar in construction and chemistry to a Nickel-Cadmium battery with the only difference in the negative electrode, which consists of a metal hydride alloy [26] being the positive a cadmium electrode. The main materials used at the negative and positive electrodes of Ni-MH batteries are metal hydrides, type AB_5 ($LaNi_5$) and type AB_2 (ZrV_2), and $Ni(OH)_2/NiOOH$, respectively [27].

Continuous efforts in the development of this technology have led to the production of small-scale batteries with comparable kinetic consumption, but with up to twice the energy content per unit volume as the Nickel-Cadmium cells [28]. Nickel-Metal Hydride (Ni-MH) batteries have been effectively applied in power tool storage systems, hybrid electric vehicles, light rail vehicles and industrial energy storage.

However, their use in renewable energies is limited because of relatively low high-speed discharge performance and cycle stability requiring improvements in both the chemical composition and the manufacturing process [29], although they are less problematic from an environmental point of view than the Ni-Cd batteries.

4.4. Nickel-Zinc Batteries (Ni-Zn)

Ni-Zn batteries have attractive advantages, such as high energy and power density or low cost [21]. These Nickel/Zinc batteries are a promising candidate for alkaline storage systems, not only because of the features mentioned above, but also because of their good performance, high open circuit voltage and low self-discharge rate. It is also important to remark that the active materials of the electrodes used are not very toxic and economic, existing in abundance in nature. This makes Ni-Zn batteries an ideal replacement for as Lead-Acid and Nickel-Hydrogen storage in renewable energy systems [30].

However, its commercialization has not been carried out due to serious problems as the dendritic growth (crystalline growth), shape change and high dissolution of the Zn electrode [29].

4.5. Lead-Acid Batteries

The Lead-Acid battery was invented in 1859 by the French electrochemist Gaston Planté [21]. Since its invention to date, this battery is still in use and is still the most manufactured in the world [32].

Lead-acid batteries have been used for many years as backup in power plants and transformer substations, playing a key role in the reliable operation of power systems [33]. Pb-Acid batteries are the most mature and cost-effective battery system of the different battery power storage technologies [10]. One of the problems with this type of battery is that, in the case of deep and/or fast discharges, its storage capacity decreases. On the other hand, there are inconveniences due to low energy density, low power density, long recharge times, low life cycle and high self-discharge rates. As a result of the more than likely environmental pollution that this type of battery can produce, its use in the energy storage market around the world has been low despite its low cost [10].

According to data obtained from the review by Energy for Sustainable Development [34], the cycle life of these batteries is low, around 500 to 1000 cycles, and an energy density of 30 to 50 Wh/kg. Its efficiency is between 75-80 % with a service life of 5-15 years, depending on the operating temperature. It has a low self-discharge rate of less than 0.1 % [22].

The service life of this type of battery can be increased by adding activated carbon to the negative battery plate [35]. There is no difference between the usual lead acid bathtub and this one improved with carbon (advanced Lead-Acid battery), but it is true that the latter has substantially increased the specific power, besides increasing the cycle life in the case of small discharge depths.

The entry into the market of new storage technologies means that stationary Lead-Acid batteries face tough competition. Lithium-Ion batteries have been steadily gaining market share, replacing traditional Lead-Acid batteries in many applications due to improved service life, greater efficiency and higher energy density.

The Valve-Regulated Lead-Acid battery, also known as the "sealed" Lead-Acid battery (VRLA), reflects a breakthrough in the development of traditional flooded batteries. The VRLA battery is usually more expensive than the Lead-Acid flooded battery but has the advantage of being maintenance-free for more than ten years due to its self-regulating nature. VRLA batteries are commonly further classified as:

- *Absorbed glass mat battery (AGM):* Filled with liquid electrolyte.
- *GEL battery:* Filled with so-called gel electrolyte.

The advantages include low maintenance and the high recycling rate of its materials. However, they are more sensitive to high temperatures, overloads and underloads.

A summary of the properties of Lead-Acid batteries can be seen in Figure 13.

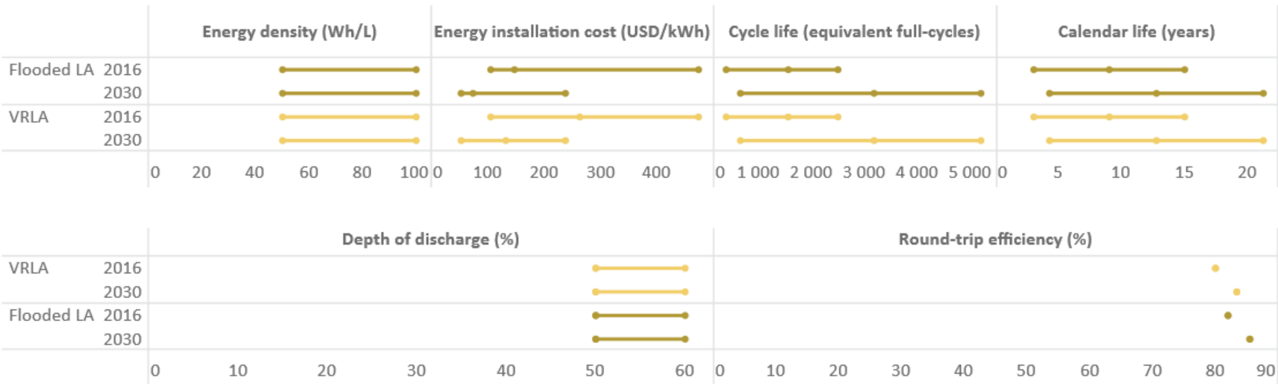

Figure 13. Properties of lead-acid battery energy storage systems, 2016 and prevision 2030 [3].

4.6. High Temperature Batteries

4.6.1. Na-S Batteries

Sodium-Sulphur (Na-S) batteries have their origin in vehicle applications in the 1960s, with further developments in the 1970s, finally developed jointly by NGK Insulators Ltd. and TEPCO in 1984 [36].

In Na-S batteries the positive electrode consists of sulphur (S), while the active material of the negative electrode corresponds to sodium (Na). The ceramic β-alumina (β-Al_2O_3, isomorphic form of the aluminium oxide, Al_2O_3) acts as separator and electrolyte at the same time. In NaS batteries, the operating temperatures are between 270 and 350 ºC, and at these temperatures electrode materials are melted, which makes possible to take advantage of the conductivity of β-alumina [22].

The efficiency of this technology is in a high range, between 75 and 100 %, with low self-discharge (0.01% per month). Its useful life is around 3000 cycles and it can reach between 10 and 15 years [22].

Compared to other similar systems, Na-S batteries have an extremely fast response time. Additionally, these batteries can inject up to 600 % of their power per pulse (Rated Power Pulse, RPS) reaching up to 30 seconds of duration, which is limited by the temperature rises in the cells and the depth of discharge [34]. This allows this technology to be used in storage applications, reducing rapid peaks in demand or production of a wind farm, with a long service life since the electrodes are liquid, eliminating the corrosion that affects all other solid electrode technologies. They require low maintenance (every 3 years) and have no environmental impacts, since these batteries are sealed and have no emissions during operation [38]. These batteries work at high temperatures due to exothermic reactions, and consequently, there are pressure changes with resulting risks of explosion or fire.

The state of this technology is commercial, but there is only one supplier, the Japanese NGK, which is the world's leading manufacturer. Japan has invested heavily in the development of this technology, in which NGK is the pioneer, reaching 20 MW of capacity to supply peak demand cuts in around 30 cities [23].

4.6.2. Na-NiCl₂ Batteries

As Na-S batteries, Sodium-Nickel Chloride batteries are high temperature devices. Under normal conditions, its operational temperature range varies between 270 and 350ºC [31]. The material used as electrolyte by the NaS battery is ceramic, sodium-nickel-chlorine (NaNiCl) crushed, this helps to separate the electrodes. The negative electrode is crushed sodium. The positive electrode is nickel, when the battery is discharged, and nickel chloride when it is charged. Since nickel and nickel chloride are practically insoluble in neutral and basic solutions, intimate contact between electrolyte and electrodes is possible, which results in very low resistance to charge transfer.

The electrolyte only conducts Na+ but isolates the electrons, so the reaction can only occur when an external circuit allows the electrodes to pass through in the same proportion as Na+ [23].

This type of batteries is suitable for bulk storage in large renewable energy plants due to its long discharge time, long service life and fast response time. The disadvantage is that molten sodium reacts dangerously with water and related incidents have been reported.

Figure 14 shows a summary chart with the properties of the high temperature batteries.

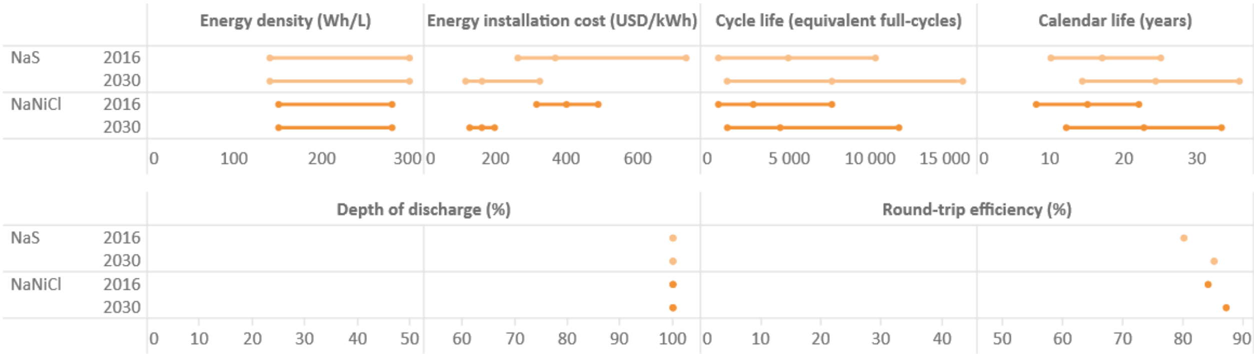

Figure 14. Properties of high temperature battery electricity storage systems, 2016 and provision 2030 [3].

4.7. Aluminium-Ion Batteries

In 2015, a group of researchers at Stanford University revealed a new Aluminium-Ion battery (Al-Ion) to the scientific community. It has excellent charging speed properties that make it fully chargeable in one minute and charge/discharge cycles can be up to 7500 [31]. This Aluminium-Ion battery uses metallic aluminium as a negative electrode (anode), while as a positive electrode (cathode) it uses three-dimensional graphic foam and an ionic liquid as electrolyte.

The Aluminium-Ion battery produces an energy density of 40 W h/kg and a power density of up to 3000 W/kg, reaching Lead-Acid batteries in these terms and usually designed in a cylindrical configuration [21].

Different studies have addressed the potential of this type of Aluminium-Ion battery in order to be applied in energy storage systems in the electricity grid [41].

4.8. Lithium-Ion Batteries

The origin of this accumulator technology is based on the discovery made in the late 1970s by researchers at the University of Oxford [21]. Exxon developed the first rechargeable Lithium-Ion battery, which was based on a titanium disulphide cathode (TiS_2) and a aluminium-lithium anode (Al-Li) [42].

All Lithium-Ion batteries work in the same way. During battery charging, the positive electrode removes some of its ions, which move through the electrolyte to reach the negative electrode and remain there. The battery stores energy during this process. When the battery is discharged, the ions return through the electrolyte to the positive electrode, feeding the charge [43].

Lithium-Ion batteries have advantages that make them more attractive than other types of these devices, such as being lighter, smaller and more powerful [44]. Lithium-Ion batteries have a power and energy density range of 90 to 190 Wh/kg and 500 to 2000 W/kg [45] [46]. Another feature is the fast load/discharge capacity (reaching 90 % of their rated power in 200 ms) and high efficiency (about 78 % with more than 3500 cycles) [22], making them a suitable solution for electric vehicle (EV) [4].

One of the biggest drawbacks of Lithium-Ion batteries is the life cycle dependence on temperature making them brittle. To achieve better performance, it is better to work at temperatures between 20 and 30 ºC. This means that in hot climates it is necessary to cool the storage place of the battery. However, at very low temperatures severe power losses can occur. These batteries need a protection circuit to avoid overloads. Currently, its high capital cost (900-1300$/kW h) limits the use of this technology for high capacity applications [4].

Lithium-Ion batteries have had a great technological development in the promotion of electric vehicles. As an energy source, it is a perfect storage technology for small-scale electronics. Nowadays, these batteries are used in the renewable energy grid on both a large and small scale [10].

4.8.1. Lithium-Polymer Batteries (Li-Po)

In a study carried out at the University of Grenoble, the ionic conduction in polymers was investigated, and it was found that they have a relatively high dielectric constant and are capable of dissolving large amounts of lithium salts [21].

This technology is very similar to the Lithium-Ion technology in relation to the electrochemical reactions that take place inside them [47]. The substantial difference is in the electrolyte, which is a polymer gel for Li-Po, and a lithium salt dissolved in a non-aqueous Li-Ion solvent [32]. The technology has a relatively high-power capacity, the environmental advantage of an economical, non-toxic cathodic material and a long service life. In terms of construction they do not differ physically from other cell technologies. They consist of two layers of electrodes and an electrolyte layer that varies according to the type of battery in between, separated by a layer of a porous polyethylene or polypropylene material, the positive electrode is made of cobalt oxide LCO(LiCoO2) or lithium iron phosphate LFP (LiFePO4). The negative electrode is made of carbon (graphite). These features, as well as the relatively low download rate, make the LFP BES system a very attractive technology for stationary applications.

4.8.2. Lithium-Titanium Batteries (LTO)

The Battery uses Lithium Titanium Oxide (LTO) at its anode to achieve excellent features including safety, long life, low temperature performance, fast charging, high input/output power, thermal stability in the charge/discharge states and high effective capacity.

One of the characteristics that is affected is the maximum energy density, which is reduced due to the voltage drop of the cell.

Graphite has less potential than titanium and this causes the voltage to drop between 2-2.5V. Although the energy density is lower than that of other lithium batteries, it always remains above the PB-acid and Ni-Cd values. These are characteristics for their safety, the high potential of the LTO anode prevents electrolyte decomposition problems.

The cost of this type of battery is still high, although a continuous decrease is expected, it can be said that the LTO technology is the lithium battery with the longest life of more than 20,000 cycles (Figure 15).

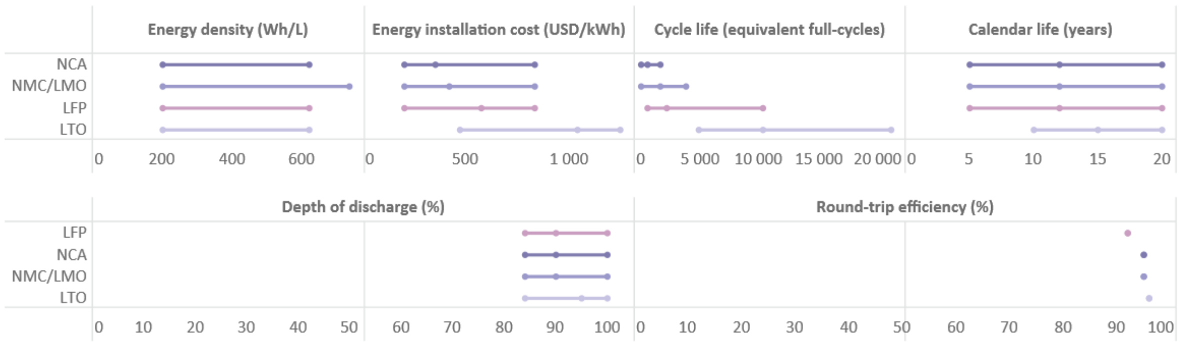

Figure 15. Properties of certain chemicals in lithium-ion battery electricity storage systems, 2016 and prevision 2030 [3].

4.9. Redox-Flow Batteries (RF)

The principle of RF battery operation was introduced by NASA24 in the early 1970s and finally developed in 1974. Since 1970, V (Vanadium Redox Battery, VRB) and Zn-Br (Zinc Bromine Redox Battery, ZBRB) based types are the most advanced and have reached the demonstration stage for storage applications.

In a RF battery, energy is stored chemically in liquid electrolyte containing dissolved electro-active materials. Electrolytes are stored in external tanks, which when pumped through separate circuits to the cells, one undergoes oxidation while the other undergoes reduction, converting chemical energy into electrical energy [23].

RF batteries are characterized by high capacity, high power, high efficiency, long life and high safety. There properties have allowed it to develop more quickly. However, due to problems with certain materials (electrolytes, electrodes or ion exchange membranes), their industrialization has not exploded and present a high construction capital [48].

4.9.1. Vanadium-Redox Batteries (VR)

The electrical energy of a VRB is stored in the sulphuric acid electrolyte as chemical energy [49]. These devices have efficiency between 75and 85 % and with proper maintenance can achieve a service life of 12,000 cycles at 100 % depth of discharge. However, its energy density only reaches 13-33 Wh/m^3 [50]. The installation costs in 2016 for the flow batteries are between USD 315 and USD 1000/kWh. costs of this technology are [3].

4.9.2. Zinc-Bromine-Flow Battery (ZBF)

They basically work by the oxidation/reduction reaction that occurs when an electric current is applied or demanded to two chemically active species that are oxidized and reduced, respectively, forming the redox (reductionoxidation) system in a flow cell. A porous membrane divides this battery in two parts, with one electrode on the zinc side and one on the bromine side.

Zn-Br flow batteries are characterized by high storage capacity and overall efficiency, with efficiencies of between 70% and 80% and energy densities around 75-85 Wh/kg with a minimum capacity of 2,000 cycles and a 100 % discharge capacity [51].

It consists of carbon plastic electrodes to prevent oxidation in bromine-rich environments and is a highly reliable battery with a flexible design, since its power and capacity are partially decoupled.

In addition, they have the great advantage of being able to operate at full discharge if necessary, without deteriorating the state of the battery or accelerating the degradation processes. The maintenance cost is really low.

The costs are 500 US$/kW and 1680 US$/kWh in 2016 [3]. Cycle life is often shorter than for VRB. Auxiliary systems are required for circulation and temperature control.

In large systems, increases the size of the temperature control device, increased containment of electrolyte loss, impact and leak detectors and controls can increase battery weight and reduce specific energy.

Figure 16 displays the properties of electricity storage systems with flow batteries.

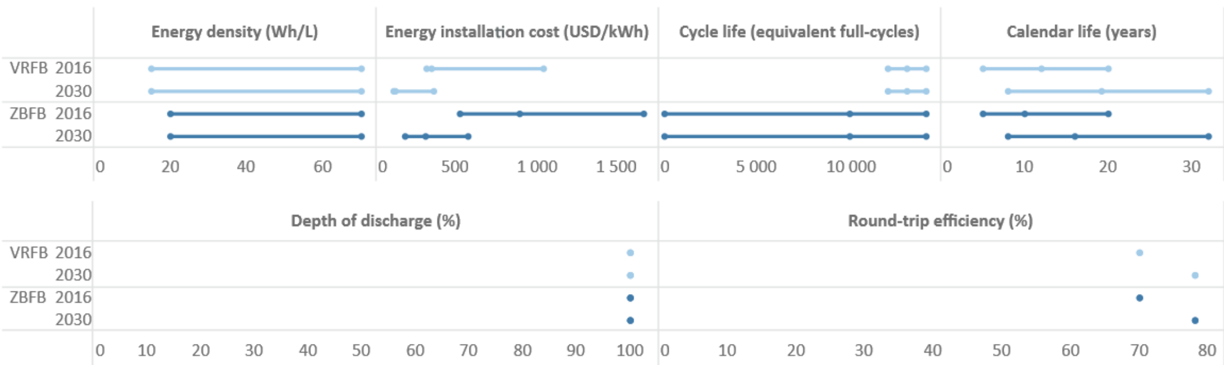

Figure 16. Properties of certain chemicals in flow battery electricity storage systems, 2016 and prevision 2030 [3].

5. RESULT AND DISCUSSION

5.1. Comparative overview of electrochemical technologies

After discussion and analysis of the characteristics of the exposed batteries, it can be concluded that typical lead-acid batteries have a negative effect on the environment and have an imitated service life, so that their application in storage systems is increasingly restricted. The trend is to replace them with Pb-C batteries or advanced Lead-acid batteries [10].

Na-S batteries present high power, high energy density and high efficiency, although their costs are too high [50].

Although the energy storage cost of the Li-Ion battery is high, it appears that it has been decreasing over time, with high performance, high energy density and high efficiency, but it is highly dependent on temperature and control for safe operation is needed. Moreover, this technology is increasingly being used for large-scale storage.

The safety of the flow batteries is high, and they can supply power to the electrical system quickly, being suitable for large-scale storage of power on the grid [53]. However, flow batteries require additional performance improvements and reduced energy storage costs.

Na-S battery has the features of high capacity, long service life and high efficiency. However, safety and reliability are lower compared to ambient batteries which restrict to some extent their popularity and application in energy storage [10].

The raw materials of the Al-Ion battery are low cost, so there is no price instability, its safety and reliability are high, but have not yet extended its marketing.

The performance of several batteries is compared in Table 7. It can be seen that the weak point so far of lithium batteries compared to other technologies could be in the duration of the discharge, something that is compensated by their high efficiency.

Table 7. Comparison of some features of different battery technologies [4].

Battery technology	Rated power (MW)	Energy density (W h/kg)	Discharge duration (h)	Energy efficiency (%)	Lifetime/Cycles
Lead-acid battery	< 36	< 50	< 8	75–85	3–12 years/500–1200
Lithium-ion battery	< 102	< 200	< 6	90–94	5–15 years/1000–10,000
Vanadium based flow battery	< 28	< 30	< 10	70–85	5–15 years/12,000–18,000
Sodium-sulfur battery	< 50	< 240	< 8	75–86	5–10 years/2500–4000
Aluminum-ion battery (Estimated)	N/A	< 60	< 6	90–94	5–15 years/1000–10,000

In addition, a summary of the advantages and disadvantages previously stated of the different battery technologies is presented in Table 8.

Table 8. Advantages and disadvantages of different technologies [4].

Battery technology	Advantages	Disadvantages	Energy storage applications
Lead-acid battery	Low capital cost	Limited life cycle, long charging time and high self-discharge rate Environmental pollution	Hot spare, frequency control and load adjustment
Lithium-ion battery	High energy densities, high efficiency, and long life cycle	High production cost, requires special charging circuit	Frequency control, load shifting and power quality
Vanadium based flow battery	High power, long life cycle, fast charge and discharge	High production cost, large area	Load shifting, emergency standby and power quality
Sodium-sulfur battery	High power and energy densities, high efficiency	Production cost and safety concerns	Load adjustment and standby power
Aluminum-ion battery (Estimated)	Low capital cost, fast charge and discharge, high efficiency	Under development Low energy densities	N/A

5.2. Executed projects and implementation of large-scale storage

According to the China Energy Storage Alliance (CNESA) database [55], by the end of 2016, the world's total operational energy storage capacity was 168.7 GW, 2.4 % higher than in 2015. Of this amount, 1,770 MW corresponds to electrochemical energy storage capacity, making it the third largest technology behind pumped hydro storage and molten salt thermal energy storage. Despite having grown by 56 % compared to the previous year, this capacity represents only 1.05 % of total capacity [56].

As shown in Figure 17, the most commonly used operating battery energy storage technology is the Lithium-Ion, followed by the Sodium Sulphur, Vanadium Flow and the Lead-Acid batteries [3]. The popularity of Li-Ion-based energy storage systems has been increasing as the capacity of large-scale installations has increased, thereby reducing market costs.

Analyzing by country, it is observed that the United States of America leads both in number of projects (95) and installed capacity in energy storage (357 MW), Japan would follow as second in installed capacity with 310 MW while China would be second in number of projects with 63. Within the United States, two-thirds of the storage capacity installed in the country is concentrated in the East (Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia), with Li-Ion battery technology accounting for 70 % of this installed capacity. Of the new installed energy storage capacity in China in 2014, 74 % was by Li-Ion batteries, followed by Pb-Acid and Na-S batteries with 14 and 10 %, respectively. In contrast, Japan is the world leader in energy storage systems based on Na-S batteries, with more than 300 MW installed [57].

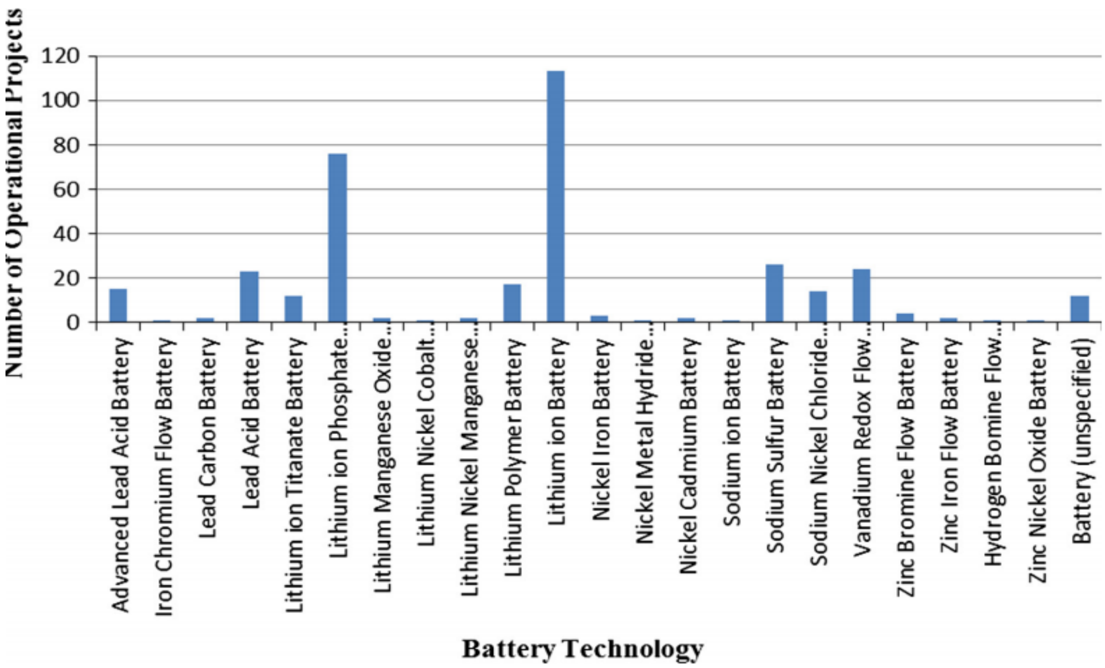

Figure 17. Number of operational projects in terms of battery technology [10].

This trend towards Lithium-Ion batteries can be seen in Figure 21, which shows how the installed capacity of this type of technology grew between 2013 and 2014, being much higher than for the other electrochemical storage technologies [11].

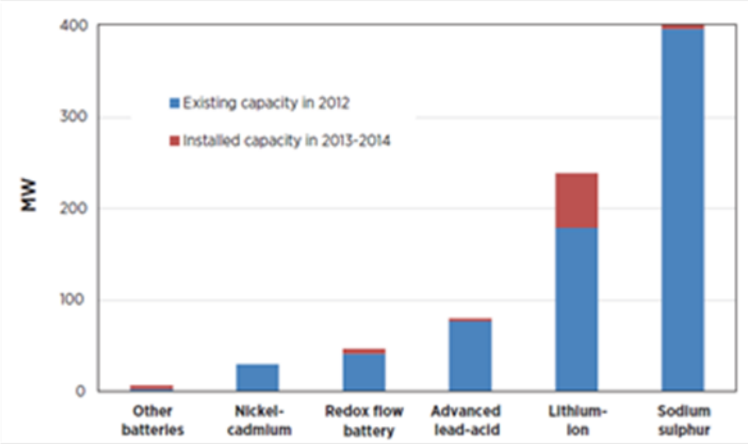

Figure 18. Installed capacity by battery technology.

According to the Global Energy Storage Database (DOE) [11], which provides information on updated grid-connected energy storage projects subject to third-party verification processes and analyses the number of projects for the three most commonly used energy storage technologies, there are currently 474 registered Li-Ion, 83 Lead-Acid and 68 Flow battery storage projects (Table 9).

Table 9. DOE. Total projects for Lithium-Ion, Lead Acid and Flow batteries [11].

TECHNOLOGY	SUB-TECHNOLOGY	TOTAL, PROJECTS
LITHIUM-ION	Lithium Iron Phosphate Battery	112
	Lithium Polymer Battery	20
	Lithium Ion Titanate Battery	17
	Lithium Nickel Manganese Cobalt Battery	7
	Unspecified	318
LEAD-ACID	Advanced Lead-acid Battery	19
	Valve Regulated Lead-acid Battery	13
	Hybrid Lead-acid Battery-Electro-chemical capacitor	12
	Unspecified	39
FLOW BATTERIES	Vanadium Redox Flow Battery	43
	Zinc Bromine Flow Battery	19
	Unspecified	6

5.3. Technical and cost comparison of the main technologies installed

5.3.1. Brief comparison of investment costs

As it can be seen, there is a range of values for each system in terms of energy and power costs because of the existence of different sizes of capacity of large-scale energy storage systems around the world. Specifically, both Pd-Acid and Na-S batteries have the lowest energy costs [50]. On the opposite side, the two types of Flow batteries, V and Zn-Br, present the highest values of power-related costs [55].

The Li-Ion chemicals of lithium nickel cobalt aluminum (NCA), lithium manganese oxide (LMO) and lithium iron phosphate (LFP) have relatively competitive installation costs, but are hampered by relatively poor life cycles, although always higher than Pb-Acid technology.

According to reports from the International Renewable Energy Agency (IRENA), high temperature batteries are among the most expensive lead-acid batteries and the lowest cost lithium-ion batteries.

Figure 19 shows the energy installation costs in 2016. In the case of lead-acid batteries, the costs are between 147 USD and 263 USD/kWh, the lowest. On the other hand, high temperature batteries, NCA, LMO and VRF, have higher costs, between 350 USD and 420 USD/kWh. In 2016, costs of 578, 900 and 1,050 USD/kWh were estimated for LFP, ZBF and LTO batteries, respectively [3].

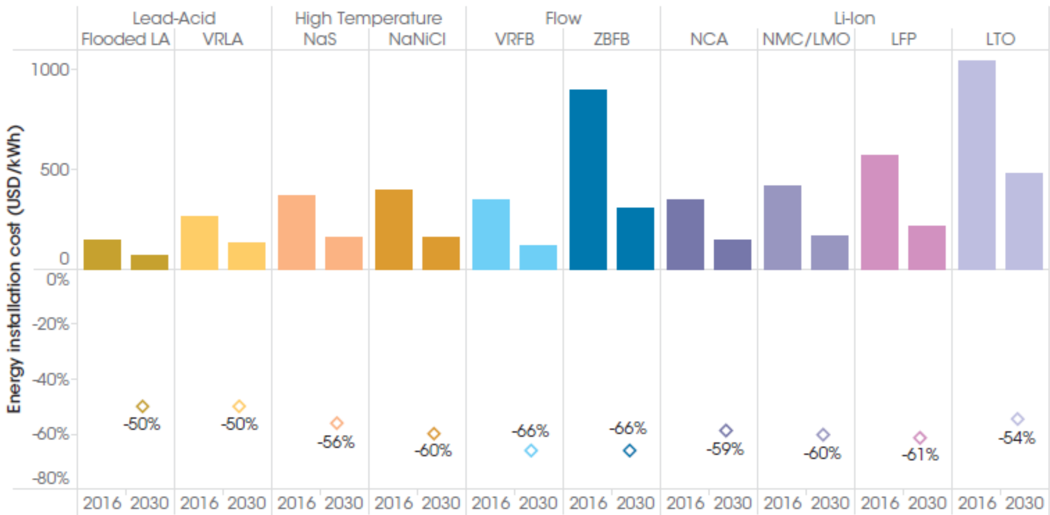

Figure 19. Central energy Installation costs estimated for battery technologies, 2016 and prevision 2030 [3].

5.4. Technical analysis

Considering that Flow batteries are the most expensive on the market and the installed capacity is not relevant, the present work will be focused on Lithium-Ion and Lead-Acid devices.

5.4.1. Useable energy

Looking at technical data sheets [59] [60], the depth of discharge (DOD) of a Valve-Regulated Lead-Acid (VRLA) or AGM batteries is 50-60 % whereas for lithium iron phosphate (LFP) a DOD of 80-90 % is observed.

Next, two examples of 24V batteries are considered:

- 1 x Lithium-Ion 24 V 180 Ah. The nominal voltage of the LFP cell is 3.3 V. This 26.4 V LFP battery consists of 8 cells connected in series with a 180 Ah load. The available energy is 26.4 x 180 = 4.75 kW. The usable energy is 26.4 x 180 x 0.8 = 3.8 kWh [59].

- 2 x VRLA 12 V 220 Ah. The nominal voltage of the Lead-Acid cell is 2.0 V/cell. Each 12 V battery consists of 6 cells connected in series with a 220 Ah charge. Connecting two 12 V 220 A batteries to provide 24 V and a 220 Ah load, the available energy is 24.0 x 220 = 5.28 kWh. The usable energy is 24 x 220 x 0.50 = 2.64 kWh [60].

Therefore, the charge of the VRLA batteries to produce 3.8 kWh will be approximately twice due to the 50 % DOD rule, i.e. 3.8 x 2 = 7.6 kWh. With 24 V this would mean 7600 kWh/24 h which gives a battery capacity of 316.66 Ah, twice the nominal capacity of the 24 V 180 Ah Li-ion battery.

It is necessary to clarify that this calculation does not take into account the aging of the batteries, the decrease in power due to temperature or the effect of higher charges.

For VRLA batteries, higher charges produce greater effects than for Li batteries, effecting the discharge capacity and voltage of different charges. Based on all this, it is reasonable to say that an VRLA battery will need twice as much Ah charge as a Lithium battery.

On the other hand, considering costs, the price of a VRLA 12 V 220 Ah battery is around 470 €, which means 2.136 €/Ah. For 316.66 Ah, that equals 676.50 € at 12 V or 1353 € at 24 V. A 24 V 180 Ah Li battery costs around 4600 € for the same amount of usable energy and is therefore 4600 €/1353 € = 3.39 times more expensive when comparing Ah charges. Based on this calculation, it can be tentatively established that the Li battery is not profitable. However, the comparison of usable energy versus price is only a part of it [61].

Based on the above, it has to be taken into account two factors: the useful capacity needed in a Pb-Acid battery compared to a Li battery is double; and in a Pb-Acid battery will be necessary to charge twice as much Ah to mitigate the effects on the capacity and discharge voltage. Then, the Lithium-Ion battery is 3.39/4 = 0.847 times cheaper than the Lead-Acid battery. But even more factors will make this difference in favor to lithium.

Although for large stationary systems it is not relevant, it should be mentioned that taking the previous batteries as a reference, acid lead would have a weight of 2x 65kg; while for a Li-Ion device a weight of 55kg is estimated for the same characteristics. Therefore, 130/55 = 2.36, i.e. Pb acid is approximately 2.5 times heavier than lithium-ion batteries.

5.4.2. Effects on discharge capacity and voltage at different loads

Considering that most of the battery charges are estimated with reference to a discharge time of 20 h, for a 100 Ah Lead-Acid battery with a discharge rate of 20 h, it is observed that for a discharge current of 0.05 C it would have a supply of 5 A for 20 h which would add up to the 100 Ah available until the battery is completely discharged. As long as only 50% of the battery has been used, it can be seen from Figure 21 that the voltage will remain at 24 V at 50% DOD for a discharge current of 0.5C for 10 h, and therefore 50 Ah will be consumed [59].

Increased current consumption can affect the available usable power and battery voltage. This effective decrease in power is known as the Peukert effect [62]. With a Pb-Acid battery, the higher the charge or consumption intensity, the greater the need to increase the battery's Ah capacity to mitigate this effect. With Li-Ion batteries, however, a charge even 10 times greater than 0.5 C can still provide a final voltage of 24 V at 80 % DOD (or 20 % Stade of charge (SOC)), without increasing the Ah capacity of the battery. This is what makes Li batteries especially suitable for high loads.

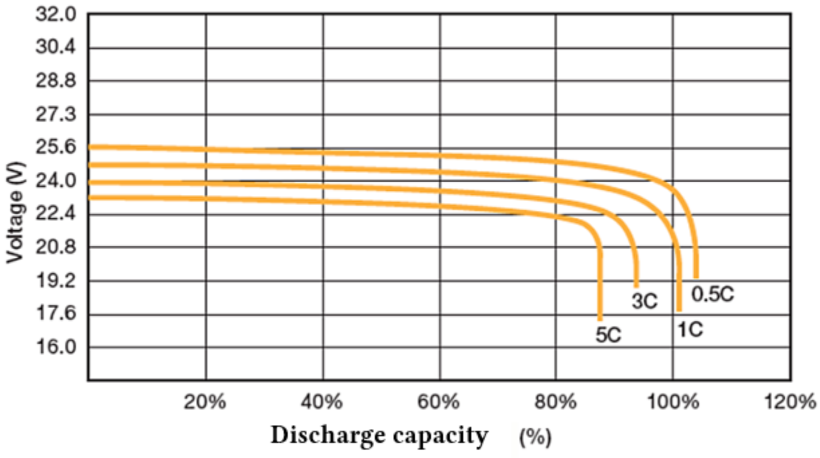

Figure 20. Voltage (V) vs discharge capacity (%). Lithium-Ion battery [58].

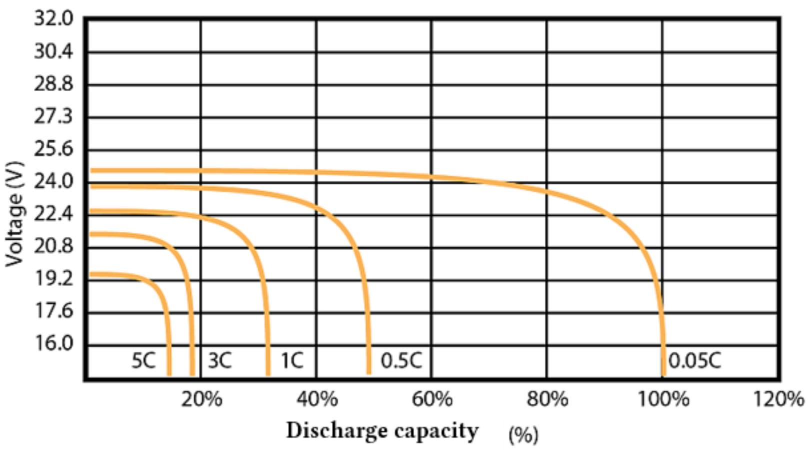

Figure 21. Voltage (V) vs discharge capacity (%). Lead-Acid battery [58].

Note: Lithium increases the usable energy at higher loads due to higher and more stable voltages.

5.4.3. Charging-discharging efficiency

Much of what was previously described for the discharge process is applicable also in the opposite process of charging. The process will be analysed for specific generator sizes, but the solutions are essentially scalable. First, a comparison of the efficiency of charging for Lead-Acid with Lithium-Ion batteries over a full charge cycle is shown. The charge of the last 20 % of a Pb-Acid battery is always slow and inefficient when compared to a Li-Ion battery. Having a 10 kVA diesel generator that consumes 3 L/h at low load and 8 L/h at full load, a Li-Ion battery will be charged in 1.4 h at full load consuming 8 L of fuel, while charging a Pb-Acid battery in two phases, one at full load and the second 20% at low load, involves a full battery charging time of 5.4 h and a consumption of 23 L of fuel [58].

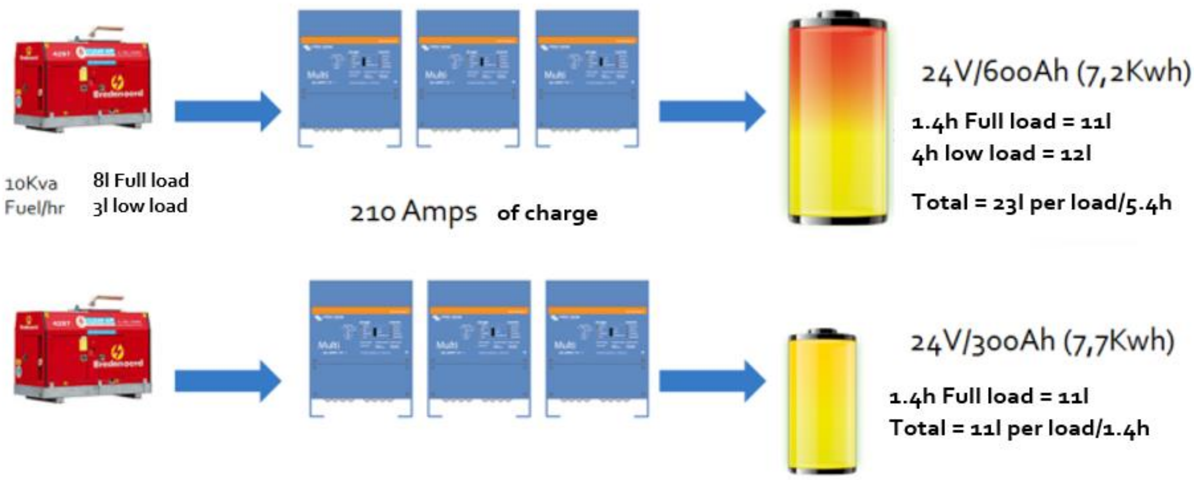

Figure 23. Efficiency of charging and discharging batteries with a diesel engine according to the charging percentages recommended by the manufacturer [58].

6. FUTURE SCENARIOS

From the analysis of DOE Global Energy Storage Database, it is noticed that most of the advertisements are the for Lithium-Ion technology [11].

According to the report “Electricity storage and renewables: costs and markets to 2030” [3], the next battery storage projects announced, contracted or under construction are expected to add another 1.2 GW in the coming years. While most of this new power capacity is classified as "electrochemical" (64.7 %), more than two-thirds of it is attributed to Lithium-Ion battery projects (27.5 %). Other types, such as advanced batteries (including redox ones, 5 %), Lead-Acid (1.8 %), metallurgical air (including Zinc-Air, 0.5%) and Sodium-Ion (0.4 %) batteries have their specific market niches, although they have no quantitative consequences. This clearly marks the future trend towards where battery storage is headed.

Table 10 shows large-scale battery power systems operational worldwide and Table 11 the storage capacity announced, contracted and under construction by type of technology.

Table 10. IRENA. large-scale battery power systems planned and operational worldwide [3].

	Electro-mechanical	Electro-chemical	Thermal Storage	Pumped hydro storage	Grand Total
China		0.1	0.1	32.0	**32.1**
Japan		0.3		28.3	**28.5**
United States	0.2	0.7	0.8	22.6	**24.2**
Spain	0.0	0.0	1.1	8.0	**9.1**
Germany	0.9	0.1	0.0	6.5	**7.6**
Italy		0.1	0.0	7.1	**7.1**
India		0.0	0.2	6.8	**7.0**
Switzerland	0.0	0.0		6.4	**6.4**
France	0.0	0.0	0.0	5.8	**5.8**
Republic ofKorea		0.4		4.7	**5.1**
Grand Total	**1.1**	**1.6**	**2.3**	**128.1**	**133.1**

Table 11. IRENA. Electrochemical storage capacity announced, contracted and under construction [3].

Country	Electro-chemical (unspecified)	Electro-chemical Capacitor	Lithium-ion Battery	Flow Battery	Vanadium Redox Flow Battery	Lead-acid Battery	Metal-Air Battery	Sodium-based Battery	Total (kW)
United States	500 398		61 959	3 030	20 250	21 500	14 250		621 397
Australia	122 010		9 400						131 410
Germany	30 000		92 000	210					122 210
India	110 000		125						110 125
Republic of Korea			48 500						48 500
Canada	12 150		12 010	4 000	5 000				33 160
Egypt			30 000						30 000
Italy		1 920	20 000	1 950				4 000	27 870
Kazakhstan				25 000					25 000
United Kingdom	1 000		20 300	140					21 440
Top 10	775 558	1 920	294 304	34 330	25 250	21 500	14 250	4 000	1 171 112
World	784 258	2 920	333 404	34 965	25 250	21 500	5 650	4 800	1 212 747

6.1. Prospects for reducing investment costs in energy storage

According to the LAZARD report [11], profitability and integrability are the main causes of the cost drop in lithium-ion batteries, in addition to lower cost inverters. Competition in the manufacture of this type of battery will result in further price declines.

With the entry into the energy storage market of new electronic equipment manufacturers will be reduced. This gives some hope for the costs of BES systems. The decrease in these costs from 2016 to 2030 is expected to be between USD 75 and USD 570 per kWh, leaving them at USD 75 and USD 480 per kWh in 2030[3].

With the reduction of the costs of the LTO batteries you will have linked an increase of up to 90% in their life cycle compared to real data, reaching values higher than 19.100 equivalent number of complete cycles by 2030. There are other types of lithium-ion battery technologies with higher cycles and lower costs that can be valid solutions in applications with very high life cycle rates.

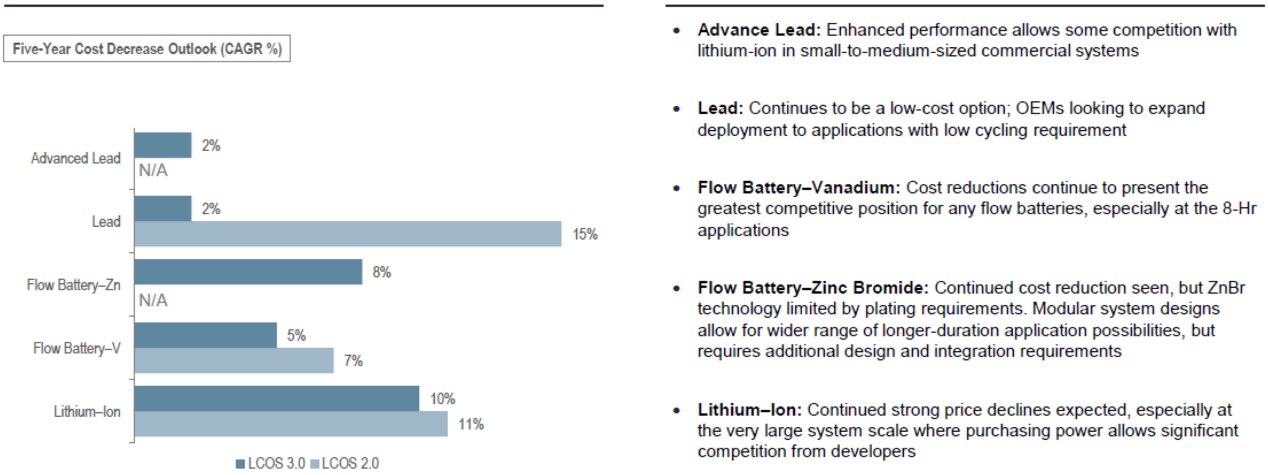

Figure 24. LAZARD. Expected energy storage capital cost declines [11].

7. CONCLUSIONS

Considering all the points analysed in the present work, it can be concluded that the technologies that stand out in large applications are Lithium-Ion, Redox-Flow and Lead-Acid batteries, with their corresponding sub-categories.

Redox-Flow batteries have high power, long life and are safe for large-scale use. However, they require additional performance improvements and reduction of energy storage costs that are higher than those for Lithium-Ion batteries.

The most mature technology is the Lead-Acid, which continues competing in the marketplace with its improved Advanced Lead-Acid version. This technology predominates on small and medium scales.

Comparison between Lithium-Ion and Lead-Acid in depth let to establish the necessity of replacing Lead-Acid batteries more frequently than Lithium-Ion ones, which means time, installation and transport costs, and therefore, this point is even more important in the final total cost which favours Lithium-Ion vs Lead-Acid technologies.

In addition, aspects such as life cycle and the fact that Lead-Acid batteries do suffer from ‘sudden death' and Lithium-Ion batteries do not, will have to be also considered, again in favour of Lithium-Ion devices.

Beyond the initial cost of Lithium (higher than Lead) batteries, it is found that Lithium-Ion batteries are more convenient and profitable over time, in addition to being able to face applications with that cannot and should not tackle with Lead-Acid batteries.

In conclusion, it is time to consider Lithium batteries as a cost-effective, reliable, versatile and high-performance solution for energy storage.

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9. ANEXOS

9.1. Real quotes requested from suppliers

9.1.1. Results achieved

9.1.2. Example of a request for proposals sent by the supplier

9.1.3. Catalogues

9.2. Proposed solutions for a large-scale installation (KEHUA)

9.2.1. Module used

9.2.2. Solution proposed by KEHUA

9.3. Examples of large-scale storage facilities around the world