ELY4OFF

PEM ELECTROLYSERS FOR OPERATION WITH OFFGRID RENEWABLE INSTALLATIONS

Benchmarking of energy storage technologies for RES off-grid installations

Deliverable 6.2

GRANT AGREEMENT
700359

D6.2 Benchmarking of energy storage technologies for RES off-grid installations

Grant agreement	Fuel Cells and Hydrogen 2 Joint Undertaking
Project no.	700359
Project full title	PEM ElectroLYsers FOR operation with OFFgrid renewable facilities
Project acronym	ELY4OFF
Deliverable no.	6.2.
Title of deliverable	Benchmarking or energy storage technologies for RES off-grid installations
Contractual date of delivery	M12 (March 2017)
Actual date of delivery	M18 (September 2017)
Author(s)	L. Gracia (FHA), A. Chabert (CEA), P. Casero (FHA)
Participant(s)	C. Bourasseau (CEA), G. Matute (INYCOM)
Work Package contributing to the deliverable (WPx)	WP6
Dissemination level (PU/CO/CI)	PU
Type (R/DEM/DEC/OTHER)	R
Version	1
Total number of pages	45

Executive summary

This report is part of the ELY4OFF project (http://ely4off.eu/). The strategic goal of ELY4OFF is the design and engineering of a robust, flexible, highly efficient and cost-competitive PEMWE. The system will be demonstrated at the premises of the Aragon Hydrogen Foundation, which will be modified to achieve the project outcomes of solar powered hydrogen generation and complete isolation from the mains, so that the results obtained are representative.

The goal of this report is to develop a cost survey of the most-promising and mature energy storage technologies. The analysis focuses in technologies in the range up to 100 kW and capable of discharge energy during hours, which are the criteria allowing the desired comparison with ELY4OFF system. The existing technologies fulfilling these criteria, besides hydrogen, are basically electrochemical batteries, and those currently commercial or that have the potential to be competitive in off-grid installations are screened, compiled and analysed. Characteristics, operating principle, advantages, limitations, current status and applications of each type of electrochemical batteries are obtained from literature and bibliography.

Afterwards an assessment of these technologies was done using the simulation software Odyssey based on scenarios defined by location and specific application. Two locations with different solar resources were used (Huesca and Edinburgh) and three specific applications covering a wide range of electrical consumption were considered (household, mountain hut, and hotel).

The assessment done shows that there are three technologies within the electrochemical batteries that appear to be the preferred alternatives in the most part of the cases: Pb-A, Li-Ion and Flow VRB. However, the basic cost data found are much more trustworthy for the first two than the last, so currently the technologies to consider for any application are basically Pb-A (the most used currently) and Li-Ion (their share of the market in stationary application is gradually increasing and their cost is reducing rapidly).

Final conclusions show how hydrogen can be suitable in certain locations compared to the rest of storage technologies. High current density, lack of self-discharge and achievable great storage capacity are the strongest points in favour.

The results obtained are expected to be used as a decision-making input to detect when water electrolysers can be more competitive than other technologies. The main PtP niche markets identified are: i) off-grid areas, where hydrogen competes with diesel generators and batteries, and ii) weak grid areas, to supply energy when the grid crashes.

TABLE OF CONTENTS

1. OBJECTIVES

The goal of this analysis is to develop a cost survey of the most-promising and/or mature energy storage technologies and compare them with a configuration employing hydrogen as the energy carrier, as it is described in the proposal of the project:

"In the EU and internationally, there is large variety of off-grid scenarios that may be addressed. Different climate areas, energy resources, cultures, etc., are possible. This task will give a general overview on the existing energy storage technologies that are suitable for integration with RES. The technologies considered will be, at least:

- *Electrochemical: lead acid, NiCd, Li-ion, NaS, ZEBRA, Redox-flow, metal air*
- *Electrostatic: capacitors, supercapacitors*
- *Electromagnetic: Superconducting Magnetic Energy Storage (SMES)*

These technologies will be benchmarked in detail in order to establish the most adequate ones for each type of off-grid RES installation.

The final deliverable will serve as a decision-making input to detect when water electrolysers are really more competitive than other technologies and, hence, they must be implemented."

Besides Ely4Off is focused on off grid hydrogen storage, it is also focused on a UPS Power Quality Load (low scale) scenario, hence existing technologies will be identified and benchmarked, according to their possible implementation on it.

The comparison has been limited to a few scenarios that are considered niches where the hydrogen can be a potential success. Data used for all the technologies are based on literature and bibliography information. This information will be the input for simulations and studies using the microgrid software Odyssey. For each of the scenarios and technologies established as suitable in the boundaries of Ely4Off, there will be a series of results that include technical parameters and economical valuation.

The conclusions of the assessment will be used as input for the Deliverable 6.5 Business Cases.

2. EUROPEAN POLICY AND CURRENT SITUATION OF ENERGY STORAGE

2.1 Energy storage context

From their home to their office, via their hobbies and means of transports, Humans are consuming huge amount of energy. For many years, coal and oil were used to produce energy and so satisfy Humans needs. These fossil fuel were burnt, releasing several types of gas in the atmosphere. Among them, some are greenhouse gases emissions, responsible of the global warming. Since the awareness of this phenomena, these ways of energy production are little by little replaced by energy production using renewable energies to produce “clean” energy.

Currently, main renewable energies used are the velocity of a river and the potential energy of high lakes thanks to dams, the velocity of wind thanks to wind turbines and solar radiations thanks to solar photovoltaic or thermal panels.

However, these renewable energies (especially wind and solar radiation) have the inconvenience of being unpredictable and variable. Even though weather forecasting can inform about sunshine and wind velocity, these data are available at about 1 week and their accuracy is not 100%. Furthermore, there are days without wind and sunshine, and solar radiation is obviously not available at night. This intermittency is a problem as a renewable energy production installation can produce a lot of energy while the demand is low, or not produce enough energy when there is high demand. The problem of intermittency is illustrated in figure below:

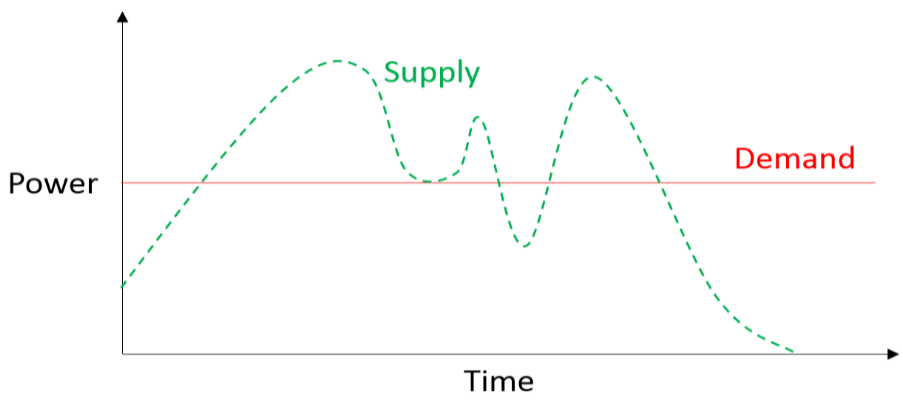

Figure 1. Intermittency and uncontrollable production lead to difference between power supply and demand.

In order to optimize the use of renewable energy for energy production, storage is needed. Indeed, storage allows the saving of energy when the supply is higher than the demand, and to provide energy when the supply is less i than the demand. This is illustrated on figure below:

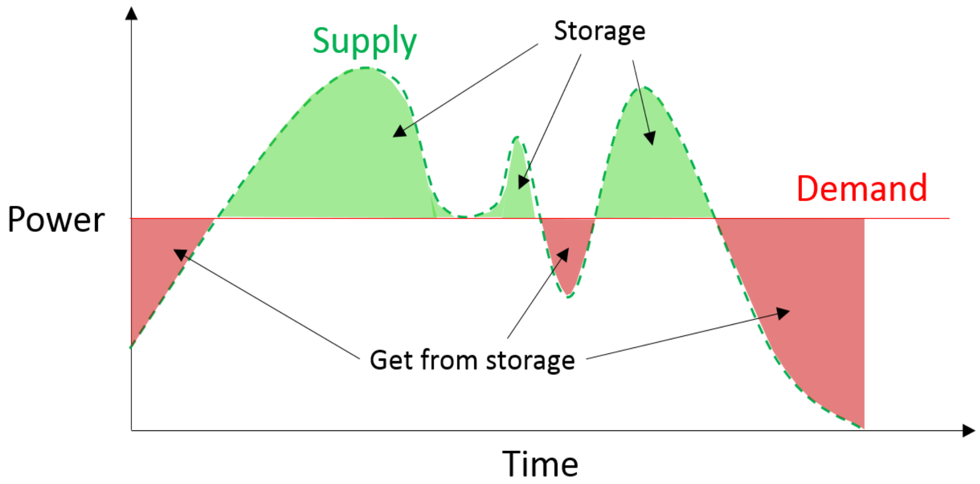

Figure 2. Storage benefits

The benefit of storage is then to **smooth the energy production**.

The importance of energy storage is highlighted below with the following reasons.

1) It helps the electrical grids to be more stable and flexible, so that any surge in peak demand can be addressed effectively and more efficiently, thereby allowing balance in supply and demand of energy.
2) It assists in managing excess energy generated for a later use.
3) It minimizes renewable energy curtailment, thereby increasing the return invested o renewable energy generation.
4) It reduces the use of fossil-fuels.
5) It facilitates in maintaining power quality.
6) It defers or eliminates the need for additional generation or transmission infrastructure.

Several types of energy storage exists. Principal ways of storage are electric (electrochemical and electrostatic storages), mechanic, thermal and chemical. Table below gives examples for each way of storage.

Energy	Way of storage
Electrochemical	Batteries
Electrostatic	Superconducting Magnetic Energy Storage (SMES)
Mechanic	Dam
	Flywheel
	Compressed Air Energy Storage (CAES)
Thermic	Sensible heat
	Latent heat
Chemical	Hydrogen

Table 1. Different technologies of storage

Furthermore, each way of storage has different characteristics, presented in the table below:

Characteristic	Meaning
Capacity [Wh]	Amount of energy that can be stored
Charging power [W]	Energy "flow" that can be absorbed by the storage
Discharging power [W]	Energy "flow" that can be provided by the storage

Table 2. Difference between capacity and power

Characteristics presented in the table above introduce the difference between "Power storage" and "Energy storage". Power storage are used to provide a lot of energy in a short time, whereas an energy storage has as principal function to save huge amount of energy.

Figure 3 below shows different kinds of energy storages options and their place between power and energy storage.

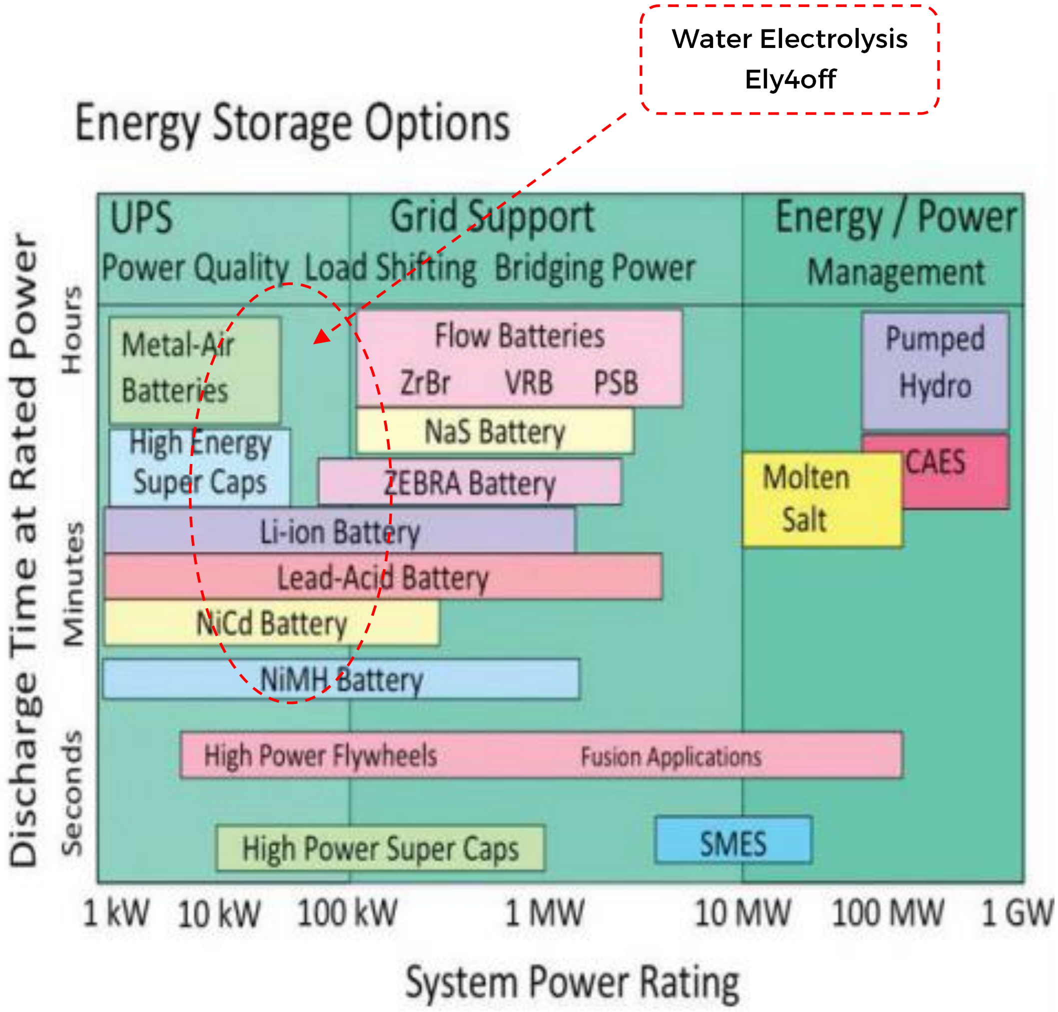

Figure 3. Energy Storage Options representation based on the discharge time and the power rating[1]

In this report, only different technologies of batteries are compared with hydrogen as these are the most relevant possibilities in the framework of ELY4OFF project as shown in figure above. Reasons are given in the following chapters.

2.2 Policy Framework

In early July 2016, at the G20, energy ministers agreed on a communique reaffirming their commitment to ensure access to affordable, reliable, sustainable and modern energy for all. They also adopted the G20 action plan on renewable energy and encourage cooperation on standards to accelerate smart grid deployment and interoperability.

At the European level, Member states agreed on a new 2030 Framework for climate and energy before the Paris Agreement aimed at sending a strong signal to the market and encouraging private investment.

There is currently only around 5% of total installed storage capacity in the European energy system. This is almost exclusive from pumped hydro and is mainly located in mountainous areas. Other forms of storage are either minimal or at a very early stage of development.

Nevertheless, the share of RES (Renewable Energy Sources) in the European electric power generation mix is expected to grow considerably. Significant amount of excess renewable energy will start to emerge in countries across the EU, characterized by periods of high power output far in excess of demand. In addition, the large intermittent power flows will put strain on the transmission and distribution network and make it more challenging to ensure that the electricity supply matches demand at all times. Energy storage is now required to provide flexibility to the power system.

The European Commission has mentioned several factors that slow down the development of energy storage, including administrative barriers, access to grids and excessive fees and charges.

Currently Europe does not have a common regulatory approach to energy storage, so potentially creating important differences between member states, like in Spain, with the approval of a self-consumption decree that prevents any possible deployment of energy storage systems.

This lack of a definition of energy storage in the current EU legislation leads to a series of barriers, creating an uncertain investment environment.[2]

Regarding Standards, the rapid growth and the new technologies involved in electrical battery storage in the near future as well as the expected installation of batteries by consumers will impose particular requirements for their characterisation and safety via the development of dedicated standards. For the new specific applications in grids, the industry started by significantly updating stationary battery standards and largely extending the newly developed standards for electric and hybrid vehicle applications. Experimental pre-normative research, aimed at defining and validating test procedures for electrical, thermal and safety characterisation of novel electrochemical storage systems for grid uses is strongly required over the first coming decade.

2.3 Market Trends and Evolution

As explained in section 2.1, energy storage capacity is supposed to increase, following increase of renewable intermittent energy production. This is illustrated in Figure 4. Total ESG Market, Installed Capacity by Region, World Markets below, from a study released by the Navigant Research. It projects that long-duration energy storage is expected to grow exponentially in the next 9 years; from trace amounts of value in 2012 to nearly $30 billion by 2022. The graph below was shared by Pike in its executive summary, showing that the greatest amounts of new storage capacity will occur in Europe, followed by North America and Asia Pacific.

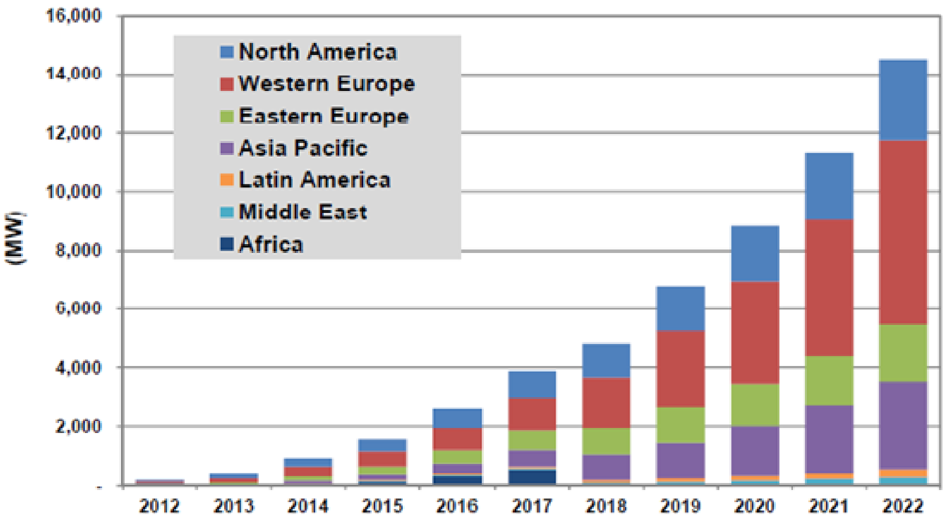

Figure 4. Total ESG Market, Installed Capacity by Region, World Markets [3]

Energy storages is required for several fields, as shown by Figure 5. Installed Distributed Energy Storage System power Capacity by Application, World Markets[3] below.

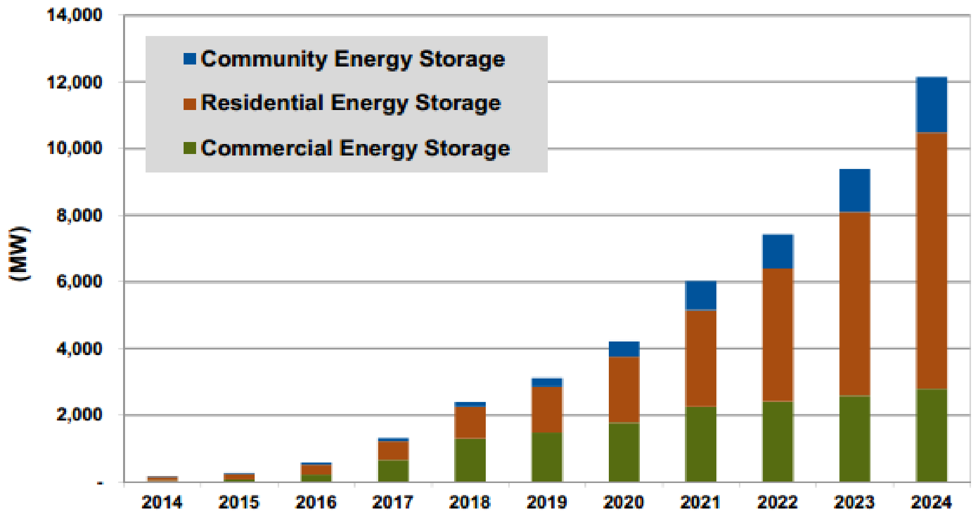

Figure 5. Installed Distributed Energy Storage System power Capacity by Application, World Markets[3]

Nowadays, to respond to national needs of energy storage, the main technology used is pumped hydro. However, this way of storage is limited by the typical geographic conditions it requires to be built. That is why other storage ways will be used to respond to these increasing storage needs.

According to Navigant Research's report, Energy Storage for the Grid and Ancillary Services, the market for energy storage, specifically for utility-scale wind and solar integration, is expected to grow from $31.88 million in 2015 to $2,917.76 million in 2024. The leading technology for wind and solar integration will be lithium ion (Li-ion) batteries representing 48.5% of the total market and $4.721 million in installed revenue. Flow batteries and power-to-gas will each account for 17.5% of the total market over the next 10 years, and the remainder of the market will be split between advanced batteries and CAES.

Figure 6. Installed Revenue, Energy storage for Wind and Solar Integration, World Markets [4] below agrees with these forecasts.

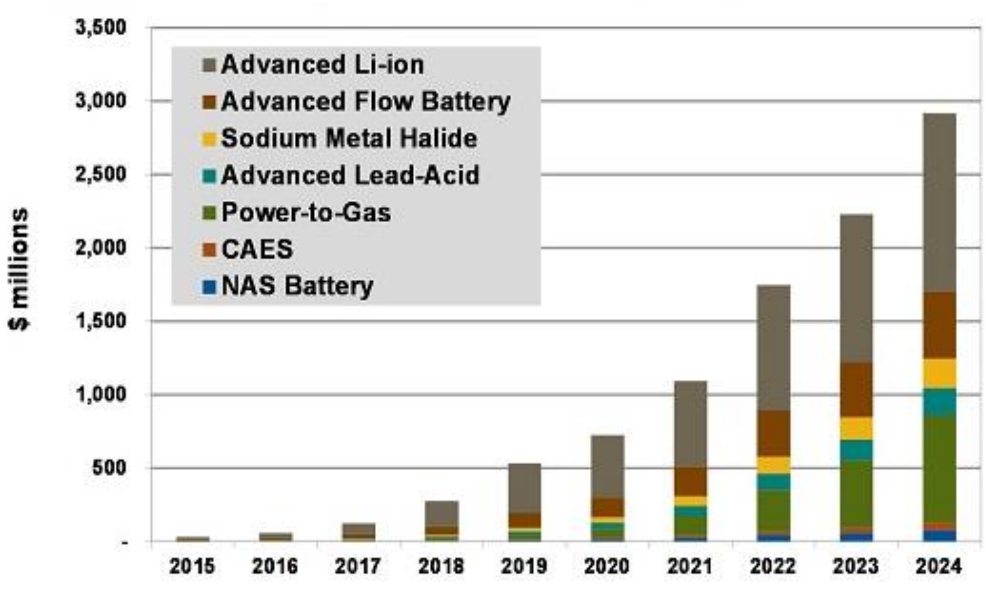

Figure 6. Installed Revenue, Energy storage for Wind and Solar Integration, World Markets [4]

Market for energy storage system for renewable energy integration will increase rapidly over the next decade, and see installed new capacity at a total of 45.1 GW between 2015 to 2025.

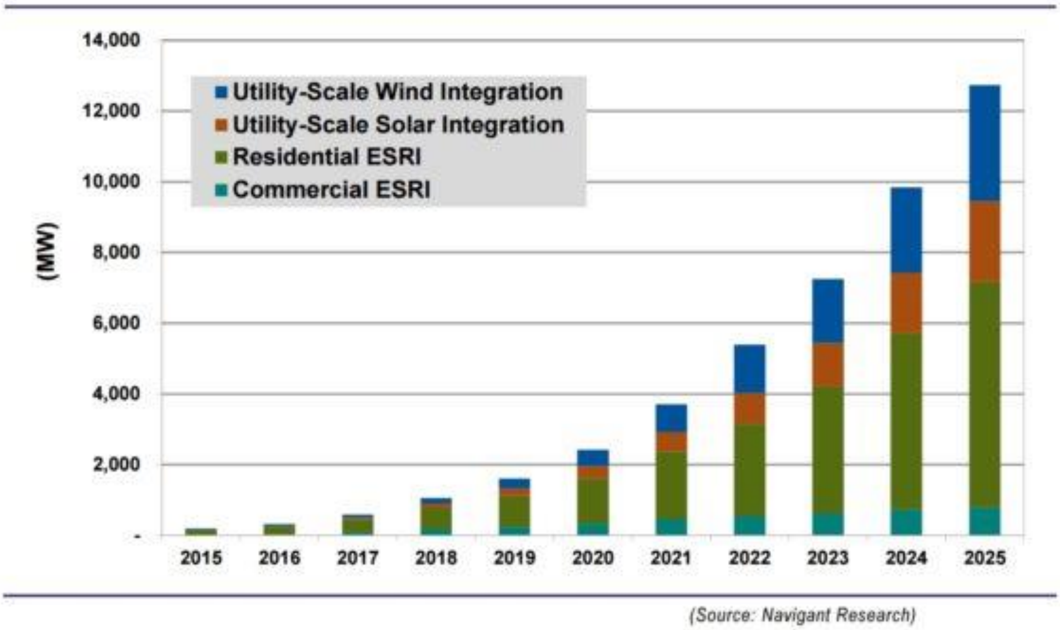

Figure 7. Integration of Energy Storage[3]

3. WATER ELECTROLYSIS AND HYDROGEN STORAGE SYSTEM

Hydrogen is an energy vector, meaning that it can be used as a portable fuel, and the point of production can be decoupled with the point of use.

The system to benchmark is divided in to water electrolysis for hydrogen production, a pressurized gas tank as energy storage and a fuel cell as hydrogen user (re-electrification or Power to Power). Characterization of the Power to Power system is as follows:

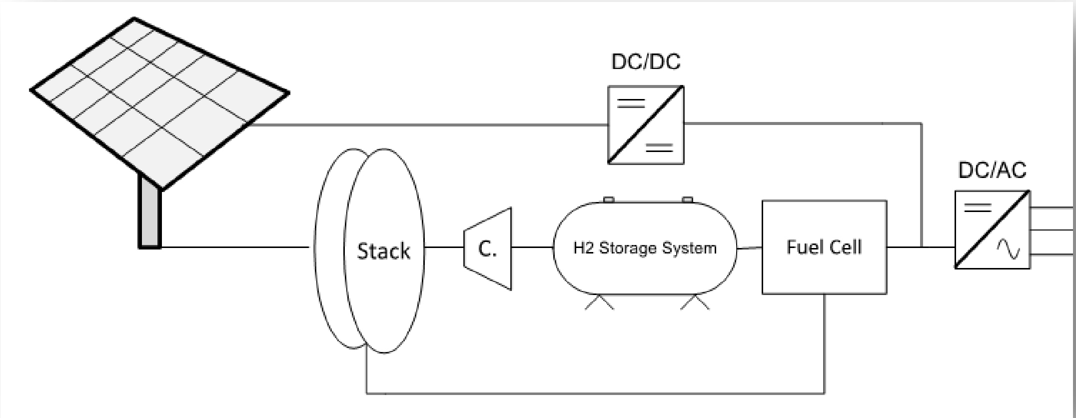

Figure 8. Hydrogen power to power characterization

The research of the characteristics of this storage technology will be taken from literature in order to detect when Water Electrolysis will be more competitive than the rest of technologies, being the technology used in Ely4Off.

Other uses for hydrogen such as the Power to Gas, automotive industry or chemical industry, the most promising markets, cannot be analysed because they are not energy storage methods. Therefore, in this report they are not going to be considered.

3.1 PEM Electrolysis

There are different types of electrolyser technology currently available as commercial products. Historically, alkaline electrolysis (liquid electrolyte) has been the most used technology. Proton Exchange Membrane (PEM) electrolysis is commercial for around a decade now. Recently a new technology (anion exchange membrane or AEM) appeared on the market. This report focuses on PEM technology as it is the one used in ELY4OFF.

The mechanism of hydrogen production from water and electricity follows the following steps:

1. Water is supplied to the anode side of the stack.
    a. Water reacts with at the surface of the catalyst and is divided in to oxygen, hydrogen ions (protons) and electrons.

2. Hydrogen ions move through the membrane to the cathode.
   a. Positively charged hydrogen ions collect at the cathode. Whereas oxygen collects at the anode.

   b. The electrons released the anode to the electricity generator, while oxygen is released to the atmosphere (or wherever)

3. The protons (hydrogen ions) with the supplied electrons from the electricity generator combined at the catalyst surface to create gaseous hydrogen in the cathode.

Reactions:

$H_2O \rightarrow 2H^+ + ½\, O_2 + 2e^-$	$2H_2O \rightarrow 4H^+ + O_2 + 4e^-$	Anode Reaction
$2H^+ + 2e^- \rightarrow H_2$	$4H^+ + 4e^- \rightarrow 2H_2$	Cathode Reaction
$H_2O \rightarrow H_2 + ½\, O_2$	$2H_2O \rightarrow 2\, H_2 + O_2$	Total Reaction

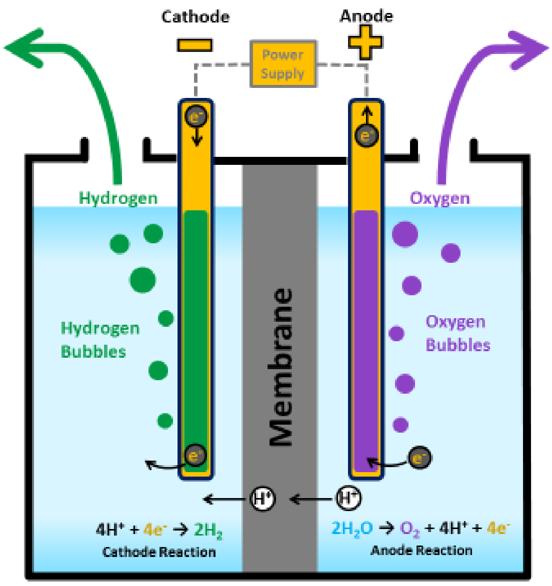

Figure 9. Reaction in a Polymer Electrolyte Membrane Water Electrolyser

PEM water electrolysis (or PEMWE) is characterized by dynamic response times, large operational ranges, high efficiencies, and very high gas purities.

3.2 Pressurized gas hydrogen storage

A hydrogen molecule has some characteristics (small size, lower molecular weight compared to all compounds and its high reactivity) that give it a high-energy density in mass. In contrast, hydrogen has a low energy density per volume that is lower than other common fuels because of its extremely low density. The main objective of the storage system is to increase its density so as the greatest amount of mass of hydrogen is stored in the lowest volume.

There are several methods for storing hydrogen, the most common are: compressed gas, in liquid form, absorbed in metal hydrides, and synthesized hydrocarbons. Common pressure of compressed hydrogen gas after PEM Electrolysis is of the order of 15-30 bar, and the usual solution adopted is further compression, to a final pressure which depends on the final application:

- Stationary storage: 200-350 bar
- Mobility: 700 bar[5]

Range of pressures for hydrogen storage and its capacity of kg per m^3 (density) are showed in the following graphic, where area tagged as 2 corresponds to compressed hydrogen:

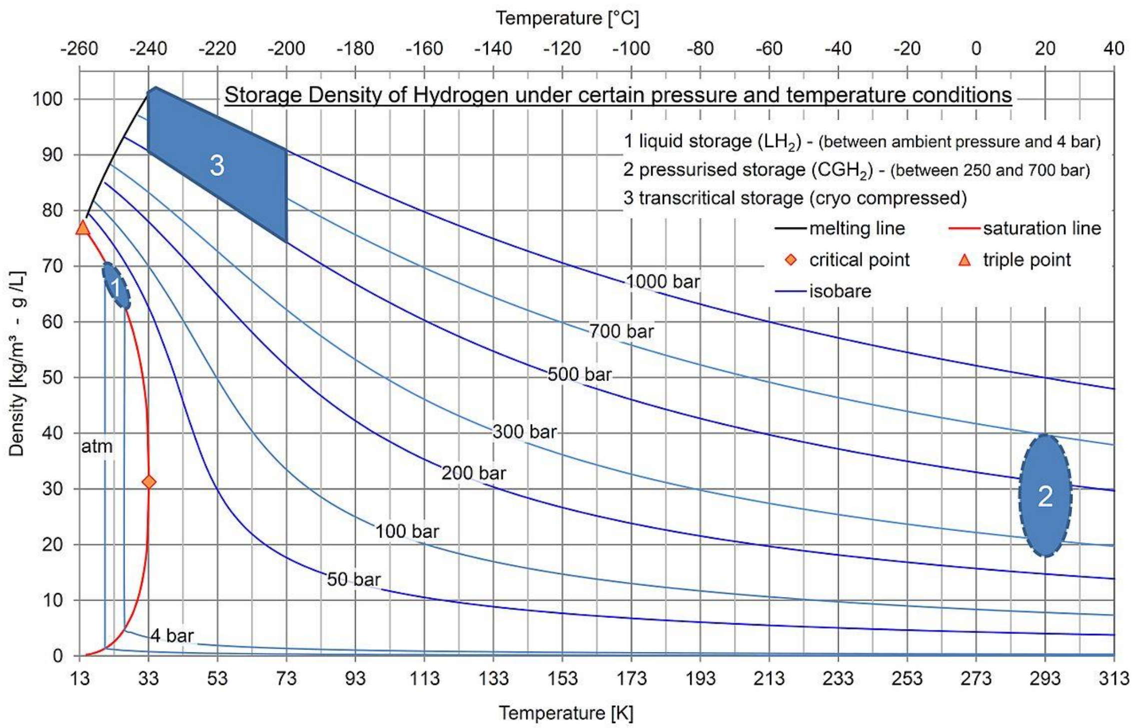

Figure 10. Storage density of Hydrogen (Source: Dresden Institute)

3.3 Fuel Cell

A fuel cell is an electrochemical reactor where hydrogen is continuously converted into electrical energy. The reactions at the anode and cathode in the fuel cell are:

$H_2 \rightarrow 2H^+ + 4e^-$	$2H_2 \rightarrow 4H^+ + 4e^-$	Anode Reaction
$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	Cathode Reaction
$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	$2H_2 + O_2 \rightarrow 2H_2O$	Total Reaction

Figure 11. Reaction of a PEMFC

The anode of the cell is fed with hydrogen (fuel), where it is oxidized on the platinum catalyst (diffuser / catalyst layer), and produces electrons and also protons when dissociates, H^+. The electrons flow through an external electrical circuit and are used to produce electric current. Moreover, the protons are transported from the anode to the cathode through the electrolyte (membrane). The cathode is fed with oxygen, which reacts with the protons, transported across the membrane and electrons via the electrical circuit. The final product of the reaction occurring at the cathode is water vapour.

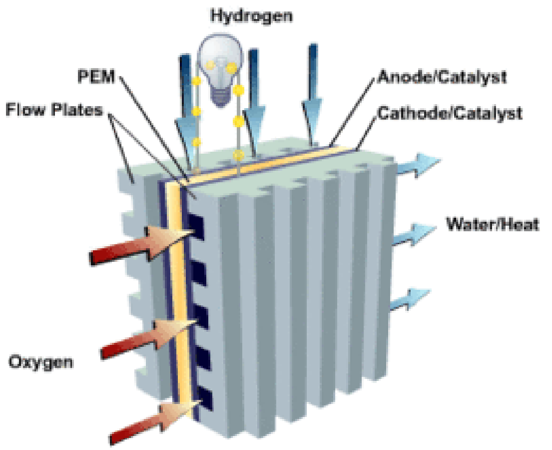

Figure 12. Operating principle of a PEM Fuel Cell

The electrical power output of the fuel cell depends on the demanded load.

Depending on the operating temperature and the type of electrolyte, fuel cells are classified according to the following figure:

	Temperature	Power	Efficiency	Electrolyte
PEMFC	50 – 120 ºC	1 W – 12 kW	55%	Proton exchange membrane
AFC	65 – 220 ºC	5 – 150 kW	55%	Alkaline electrolyte
PAFC	150 – 220 ºC	250 W – 200 kW	32 – 85%	Phosphoric acid
MCFC	600 – 650 ºC	250 kW – 10 MW	60 – 85%	Carbonates
DMFC	50 – 120 ºC	25 W – 5 kW	20%	Proton exchange membrane
SOFC	800 – 1000 ºC	5 kW – 3 MW	55 – 70%	Ceramic material

Figure 13. Fuel cell classification

4. ENERGY STORAGE SOLUTIONS FOR OFF-GRID INSTALLATIONS EVALUATED IN THIS REPORT

4.1 Assessment of relevant storage technologies

Locations where access to the main grid is not possible or where the grid is of low quality is a potential market where PV installations integrated with PEMWE and H2 storage can be a solution. Benchmarking of technologies currently used in those applications will help to identify those niche markets where hydrogen can become a better alternative for energy storage.

Specific markets will be targeted in order to take advantage of the great capacity of hydrogen to store a great amount of energy, a quick answer to discharge and a high-energy density. Present report focuses in two of these target markets already identified in the DoA:

- Target market 1: Energy system for isolated areas. It will cover isolated installations in remote locations in the EU, like mountain huts, small islands, or other remote locations, containing RES, mainly PV and small wind turbines.
- Target market 2: Replacement of diesel engines in off-grid installations to support existing/new installed RES off-grid installations. It will cover all possible replacement of diesel power in microgrids for remote rural areas, public and private buildings, industrial plants and self-consumption in residential households.

Energy storage systems introduce qualitative constraints to the system which might limit their applicability based on certain conditions. Some aspects to be taken into account as well as potential constraints to be analysed are:

- Availability of resources
- Feasibility for different locations or environments
- Industrial/political preferences

According to these characteristics, a few of the most used and technologically relevant mature technologies can be dismissed in this assessment, because they require specific conditions that might not be possible in the locations of the project

Therefore, a group of storage technologies has been chosen that could be used for the same application intended in ELY4OFF. These technologies are capable of storing enough energy during at least a few days, and provide enough power to supply the auxiliary systems during a certain time when necessary. If these considerations are carried to the graphic showed in Figure 3 (system power rating in the range of tenths of hundreds kW, and discharge time in the range of minutes/hours), it can be seen that basically batteries and super caps are the technologies most appropriate. The following sections give the basic principles and a detailed description of those technologies. Also the particular strengths and operational characteristics of each one are outlined.

4.1.1 Lead -Acid (Pb-A)

Operating Principles

Lead acid batteries consist of flat lead plates immersed in a pool of electrolyte. Regular water addition is required for most of these batteries. They are constructed of several single cells connected in series which produce a voltage.

A battery cell consists of two lead plates covered with a paste of lead dioxide and a negative made of sponge lead, with an insulating material in between. The plates are enclosed in a plastic battery and submersed in an electrolyte consisting of water and sulfuric acid.

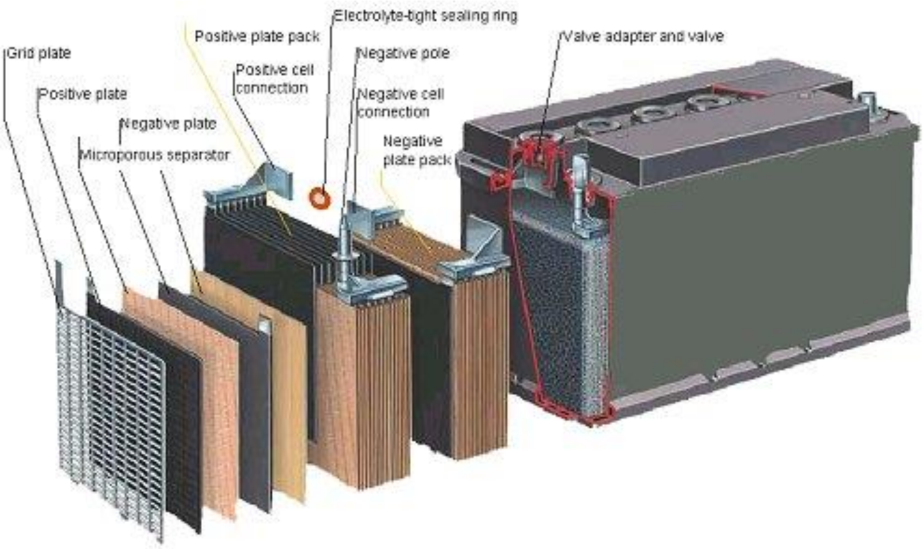

Figure 14. Schematic structure of lead acid batteries

During the Discharge Cycle, the battery is connected to a load and the chemical reaction between sulfuric acid and the lead plates produces the electricity. This chemical reaction begins to coat both positive and negative plates with a substance called lead sulphate also known as sulfation. As the battery continues to discharge, lead sulphate coats more and more of the plates and battery voltage begins to decrease.

During the Charge Cycle Lead sulphate is reconverted into lead and sulfuric acid. If they are not immediately recharged, the lead sulphate will begin to form hard crystals, which cannot be reconverted by a fixed voltage battery charge. It is important to know that lead acid batteries are not properly recharged with a fixed voltage charger, they require a variable charging based on the state of charge of the batteries to reconvert all the lead sulphate. During this process, a portion of the electrolyte and water is also converted into its original elements, hydrogen and oxygen. These gasses are very flammable and they are the reason that these batteries must be vented outside.

Periodic Equalization Charges (at higher voltage than nominal) are necessary in order to reduce stratification and sulfation, preventing battery from suffering early failures.[6]

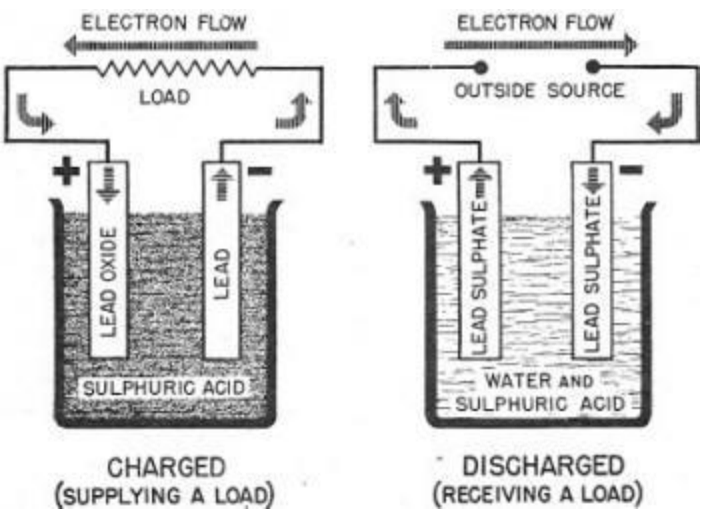

Figure 15. Charge and Discharge Cycles of a Pb-A battery

Advantages and limitations

- Advantages
  - ✓ Inexpensive and simple to manufacture
  - ✓ Mature, reliable and well- understood technology
  - ✓ Low self-discharge
  - ✓ Low maintenance requirements
  - ✓ Capable of high discharge rates

- Limitations
  - ✓ Cannot be stored in a discharge condition.
  - ✓ Low energy density
  - ✓ Allows only a limited number of full discharge cycles
  - ✓ Environmentally unfriendly
  - ✓ Transportation restrictions on flooded lead acid
  - ✓ Thermal runaway can occur with improper charging

Current Status and Applications

Lead acid was the first rechargeable battery for commercial use and despite its advanced age, the lead chemistry continues to be in wide use today.

Currently they are commercially mature re-chargeable batteries and they are used mainly in the following applications:

- Automotive and traction applications
- Back-up/emergency power for electrical installations
- Submarines
- UPS (Uninterruptible Power Supplies)
- Lighting
- High current drain applications
- DC connection to grid

Current research efforts are targeted at the inclusion of carbon into the negative plate of the battery to improve the peak power handling capacity of the cells, reduce the need for maintenance and improve the deep discharge capability and cycle life of the technology.

4.1.2 Lithium-Ion (Li-ion)

Operating Principles

Lithium-ion batteries are made of one or more power cell, composed as the rest of the batteries by a positive electrode, a negative electrode and the electrolyte between them. The positive is made from lithium-cobalt oxide in older batteries and from lithium-iron phosphate in the new ones. The negative electrode is generally made from carbon (graphite).

During the Charging Cycle, the positive electrode gives up some of its lithium ions, which move through the electrolyte to the negative and remain there. The electrons also flow from the positive to the negative electrode, but taking the longer path around the other circuit and storing energy during the process.

During the Discharging Cycle, the lithium ions move back across the electrolyte to the positive electrode, producing the energy that powers the battery. The electrons take the longer path to the positive electrode, supplying energy to the load.

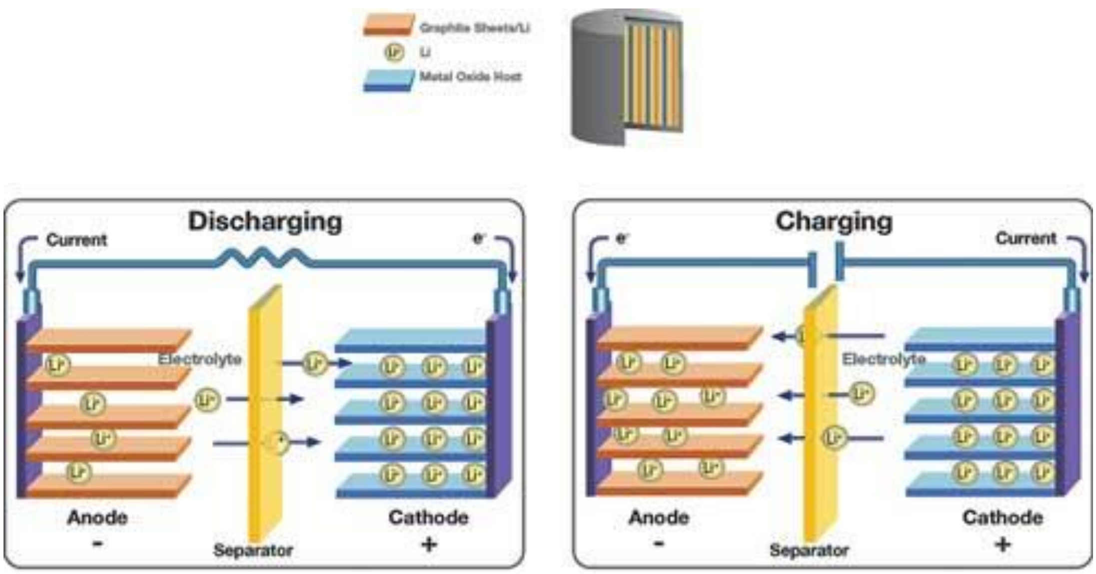

Figure 16. Charge and Discharge Cycles of a Li-Ion battery[7]

Advantages and limitations

- Advantages
  - ✓ High energy density
  - ✓ Relatively low self-discharge
  - ✓ Low maintenance
  - ✓ No memory effect

- Limitations
  - ✓ Requires protection circuit
  - ✓ Subject to aging, even if not in use
  - ✓ Moderate discharge current
  - ✓ Subject to transportation regulations
  - ✓ Expensive to manufacture

Current Status and Applications

Lithium ion batteries are now the dominant type of batteries found in small portable electronic applications. This is due to their high-energy density, light-weight and high efficiencies. A part of this application, they are also suitable for:

- Mobile phones, laptops and a wide range of consumer products
- Electric and hybrid vehicles
- Becoming available in standby power

Its cost is very high to be used competitively in high power storage systems, and has no viable recycling process, although today there is a great effort to develop these batteries and they have a huge potential, being increasingly used in grid scale energy storage applications.

With respect to integration with RE storage, they have lower weight (a third part of a Pb-A) and they need less space, which is the reason for the use in mobility. They are set to be the dominant battery for the electric vehicle market, and their development for this market is driving their costs down.[8]

4.1.4 Nickel-Cadmium (Ni-Cd)

Operating Principle

They contain a nickel hydroxide positive electrode, a cadmium hydroxide negative electrode, a separator, and an alkaline electrolyte formed by a 30% of KOH (potassium hydroxide) in distilled water.

During the Charging Cycle current is applied, and the negative plates lose oxygen and begin forming metallic cadmium. The nickel hydroxide in the positive plates becomes more highly oxidized. This process continues until the current finish or until all the oxygen is removed from the negative plates and only cadmium remains. Toward the end of the charging cycle the cells emit gas. This gas is caused by decomposition of the water in the electrolyte into hydrogen and oxygen. The voltage used during charging determines when gassing will occur. To completely charge the battery, some gassing must take place, thus some water will be used.

During the Discharging Cycle the chemical action is reversed and the chemical energy becomes electrical energy. In this process, the level of electrolyte rises and at full charge, the electrolyte will be at its highest level. Therefore, water should be added only three or four hours after the battery is full charged.[9]

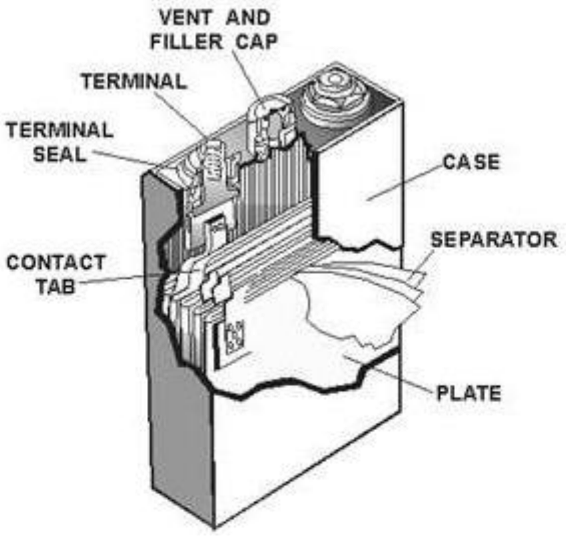

Figure 17. Schematic construction of a Ni-Cd battery

Advantages and limitations

- Advantages
  - ✓ Fast and simple charge
  - ✓ High number of discharge cycles
  - ✓ Good load performance
  - ✓ Long shelf life
  - ✓ Simple storage and transportation
  - ✓ Good low temperature performance
  - ✓ Less maintenance than Pb-A
  - ✓ Available in a wide range of sizes and performance options

- Limitations
  - ✓ Relatively low energy density
  - ✓ Memory effect
  - ✓ Environmentally unfriendly
  - ✓ Has relatively high self-discharge

Current Status and Applications

Nickel-cadmium are the most mature of the Nickel variants. They are relatively inexpensive for low power applications, but for high capacity storage they are three or four times more expensive than lead acid.

Currently in the EU and under the Battery Directive, sales of Ni-Cd batteries to consumers have been greatly reduced. This is because the toxicity of the Cadmium makes it very hard to envision a large amount of further research in this technology. They cause high impact on the environment, so in EU and many other countries now operate recycling programs to capture and reprocess old batteries.

The main applications are:

- Motorised equipment

- Power tools *
- Two way Radios
- Commercial and industrial portable products*
- Medical instrumentation
- Emergency lightning

* These applications and many others have been forbidden in the EU since 2016 due to the Battery Directive.[10]

4.1.5 Sodium-Sulphur (Na-S)

Operating Principle

The active materials in Na-S are molten sulphur as the positive electrode and molten sodium as the negative. The electrodes are separated by a solid ceramic, sodium aluminium, which also serves as thee electrolyte. The temperature of operation in the system must be regulated at around 300°C.

During discharge electrons are stripped off the sodium metal leading to formation of the sodium ions that then move through the electrolyte to the positive electrode compartment. The electron that are stripped off the sodium metal move through the circuit and then go back into the battery at the positive electrode, where they are taken up by the molten sulphur to form polysulfide.

During charge, this process is reversed. The battery must be kept hot (>300°C) to facilitate the process, supported by heaters that are part of the battery system.

These batteries present a hazard, because they spontaneously burn in contact with air and moisture, thus the system must be protected from water and oxidizing atmospheres.

Due to the temperature requirements, these types of cells become more economically viable with bigger size as the relative heat conservation increases. They have a very small self-discharge because the electrolyte is a very poor conductor of electrons, but they have a huge self-consumption of power in order to kept hot the process.

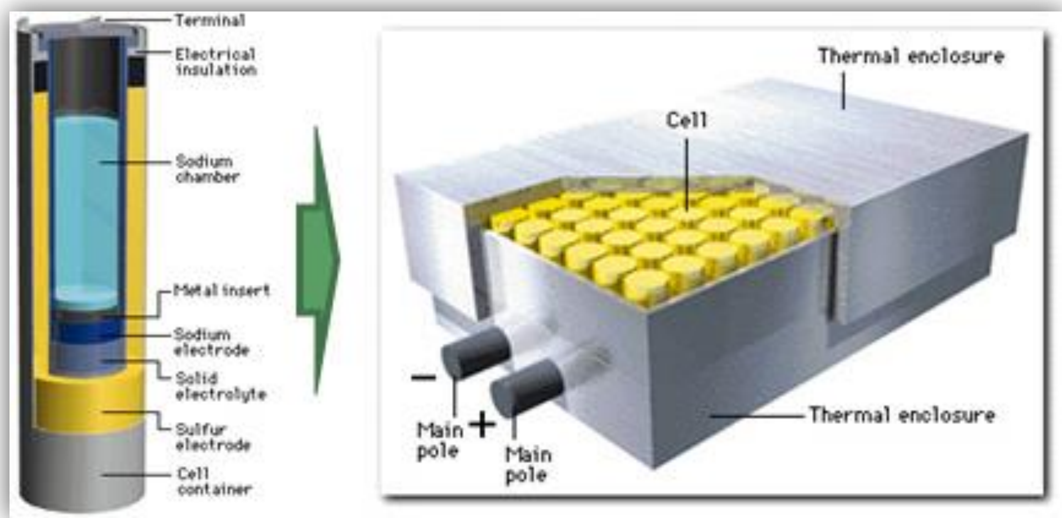

Figure 18. Schematic structure of a sodium-sulphur battery

Advantages and limitations

- Advantages
  - ✓ High energy density and efficiency
  - ✓ Small self-discharge
  - ✓ Low cost materials and high availability of them

- Limitations
  - ✓ Corrosion
  - ✓ Security: necessary to add elements in the cell to prevent reaction between the electrodes.
  - ✓ Cell failure cause complete failure of the battery
  - ✓ High maintenance cost
  - ✓ Must be kept at high temperature (300°C)

Current status and applications

They are most suited to stationary grid applications due to high operating temperatures and corrosive nature of sodium polysulphide. Their parameters and characteristics make the technology a great candidate for applications in electrical networks ranging from rapid discharges in a short time to energy management services over longer periods, very suitable for the displacement of the load and to avoid the peaks of load. Figure 18 shows a project in Japan where 34MW (245 MWh) NAS are integrated with a 51 MW wind farm to provide grid services.

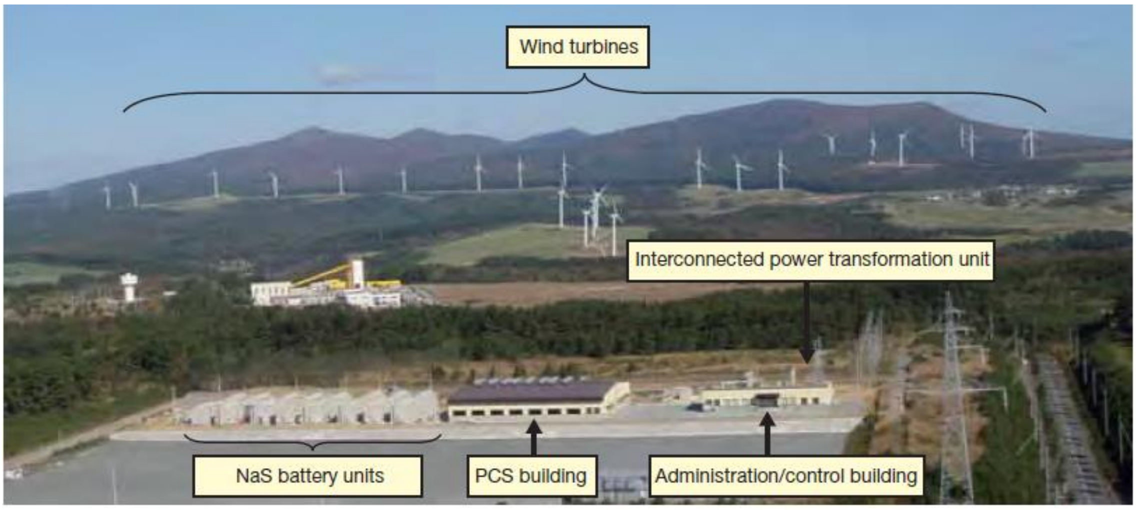

Figure 19. Wind Turbines Plant in Aomori (Japan) with 17 Sodium-Sulphur batteries of 2 MW [11]

4.1.6 ZEBRA Sodium Nickel Chloride (Na-$NiCl_2$)

A kind of Na batteries have been developed, called ZEBRA (Zero Emission Battery Research Activities) and they are characterized by a high temperature, operating around 300 °C, like Na-S batteries. These batteries are made of Sodium Nickel Chloride (Na-$NiCl_2$) and have the same operating principle than Na-S, showing a series of advantages and limitations over them:

- Advantages
  - ✓ High energy density
  - ✓ Large cells possible (up to 500 Ah)
  - ✓ Cycle life better than 1000 cycles
  - ✓ Tolerant of short circuits
  - ✓ Cell failure does not cause complete failure of the battery
  - ✓ Safer than Na-S
  - ✓ Low cost maintenance
- Limitations
  - ✓ Limited range of available sizes and capacities (>20 kWh)
  - ✓ Still in development, low commercial production of them over the world
  - ✓ High internal resistance
  - ✓ Molten sodium electrode
  - ✓ High operation temperature
  - ✓ Preheating needed to get battery up to the 270 °C operating temperature. Uses 14 % of its own capacity per day to maintain temperature when not in use.
  - ✓ Thermal management needed

4.1.7 Metal-air

Operating Principle

Metal-air batteries are unique because one of the reactants (air) doesn't have to be stored in the battery and hence this type of batteries has a very specific energy density. They consist of a metal (like lithium or zinc) for the anode, air as the cathode (which is drawn in from the environment) and usually a liquid electrolyte.

Companies and researchers like the idea of an air battery because oxygen is abundant, free, and doesn't require a heavy casing to keep it inside a battery cell. So the theoretically amazing metal air battery for an EV could be ultra-lightweight, and have a long-lasting regenerative cathode.[12]

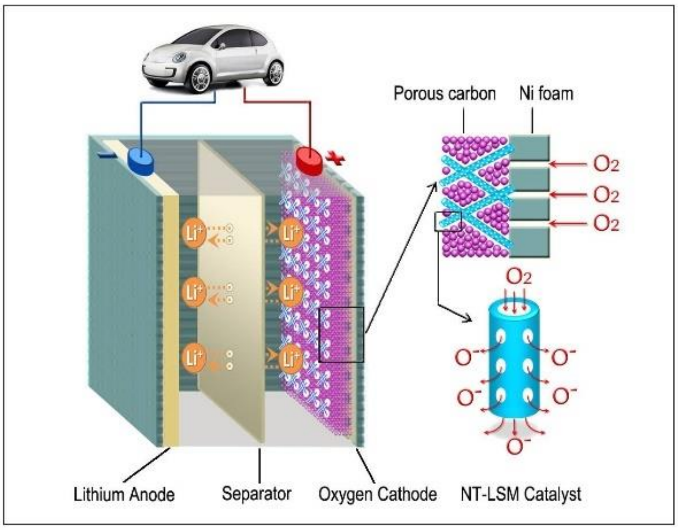

Figure 20. Schematic principle of metal air (lithium air) batteries

The main advantages and limitations are:

- Advantages
  - ✓ High energy density
  - ✓ Flat discharge voltage
  - ✓ Long life
  - ✓ Non-toxic
  - ✓ Low cost

- Limitations
  - ✓ Dependent on environmental conditions
  - ✓ Limited power density
  - ✓ Limited operating temperature range

Prototypes in mobility, like a 150 kWh battery financed by Mercedes Benz in Germany or a Zn-air battery integrated in a bus in EEUU are one of the most important milestones in the R&D process. Currently, more investment, research and development are necessary to obtain direct results using this technology, and it is presumed a few decades until this technology can be commercialized.[11]

4.1.8 Redox Flow Batteries

Operating principle

RFB are a form of battery in which the electrolyte contains one or more dissolved electro-active species which flow through a power cell/reactor where the chemical energy is converted to electricity. They are based on the reduction-oxidation reaction between two electrolytes. The reaction is reversible allowing the battery to be charged, discharged and recharged. The electrolytes are stored in external tanks and pumped through separate circuits for positive and negative species, while an ion exchange membrane separates them within the reaction chamber.

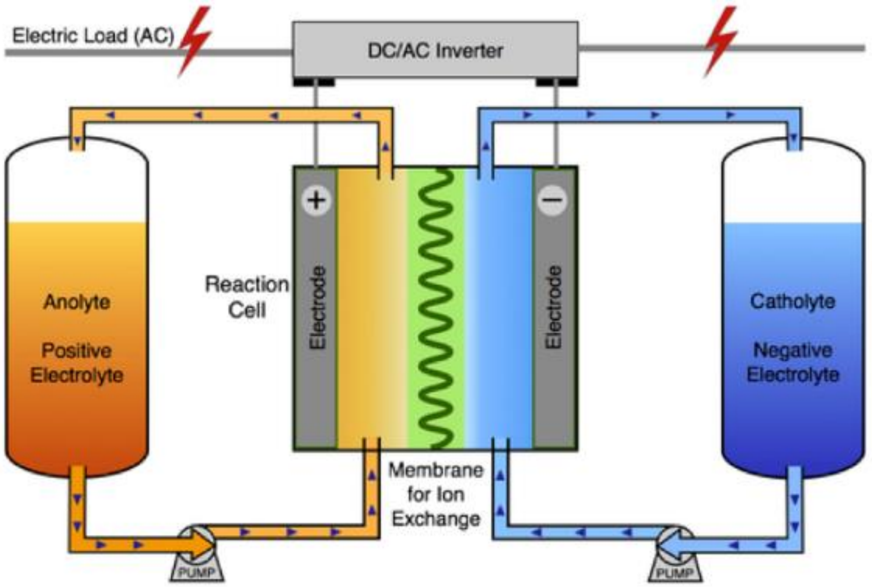

Figure 21. Schematic principle of Redox Flow Batteries

Flow batteries can release energy continuously at a high rate of discharge for up to 10h. Their storage capacity depends on the size of the tanks, which means their capacity can be increased as much as is desired. They also have no self-discharge as there is no reaction outside of the reaction chamber. Unlike with fuel cells where only the electro-active chemicals (e.g. hydrogen, methanol, and oxygen) flow through the reactor and the electrolyte remains at all times within the reactor, flow batteries drive (both) the electrolyte flows through the reactor.

Current status and applications

The main applications in which these batteries can excel are:

- UPS
- Stabilize the load and supply during power peaks
- Telecommunications
- Integration of wind and photovoltaic renewables
- Medium to high power applications (not the best technology for EV or domestic applications)

One attraction of flow batteries to EV applications is the ability to "recharge" them by simply replacing the electrolyte by filling up the fuel tank for an internal combustion engine. However, the high volume of these batteries due to the tanks makes this technology not suitable for mobility.

Today, the total capacity and power installed is still very scarce, but there are a lot of demonstrations systems, such as CellCube from American Vanadium, which is starting to be commercialized; or Subaru Wind Farm in Japan, which is used to stabilize and store wind power with a system of 4MW/6 MWh.

Figure 22. Demonstrator and Commercial CellCube Vanadium Redox Batteries System [11]

Types currently available

1) Vanadium Redox Batteries (VRB)

These are the main type of Redox Flow Batteries demonstration and commercial applications. VRB exploits the ability of Vanadium to exist in four different oxidation states and uses this property to perform a battery which has only one electroactive element instead of two.

They consists of an assembly of power cells in which the two electrolytes are separated by a proton exchange membrane. Both electrolytes are vanadium-based, the electrolyte in the positive half-cells contains VO2+ and VO2+ ions, the electrolyte in the negative half-cells, V3+ and V2+ ions. When the vanadium battery is being charged, the VO^{2+} ions in the positive half-cell are converted to VO_2^{+} ions when electrons are removed from the positive terminal of the battery. Similarly, in the negative half-cell, electrons are introduced converting the V^{3+} ions into V^{2+}.

The main advantages and limitations are:

- Advantages
  - ✓ Quick response times
  - ✓ High electricity-to-electricity equalization requirement
  - ✓ Low maintenance
  - ✓ Tolerance to overcharge and overdischarge
  - ✓ Deep discharge without affecting the cycle life
  - ✓ Very High cycle file
  - ✓ No self-discharge

- Limitations
  - ✓ High cost
  - ✓ Low energy density
  - ✓ High volume due to the tanks

In vanadium flow batteries, both half-cells are additionally connected to storage tanks and pumps so that very large volumes of the electrolytes can be circulated through the cell. This circulation of liquid electrolytes is somewhat cumbersome and does restrict the use of vanadium flow batteries in mobile applications, effectively confining them to large fixed installations. They have several potential applications in enhance power quality, UPS, peal shaving, increased security of supply and integration with renewable energy systems, and are focused on stationary applications due to the relatively low energy density.

2) Zinc Bromine Batteries (ZRB)

ZRB offer the high cell voltages of flow batteries and the highest energy density among currently available, with a 100% depth of discharge without causing any damage to the battery.

In this type of battery, two aqueous solutions, based on Zn and Br, are stored in separate tanks. These solutions flow through the electrochemical cell producing reversible reactions. During the discharge process, the bromine, Br_2, is converted to Br^- at the positive electrode. At the negative electrode, the metallic Zn is converted to Zn^{2+} ion.

Small projects comprising 5-kW/10 kWh systems are being deployed in rural Australia as an alternative to installing new power lines. In the United States, electric utilities plan to conduct early trials of 0.5-MW/2.8-MWh transportable systems for grid support and reliability.

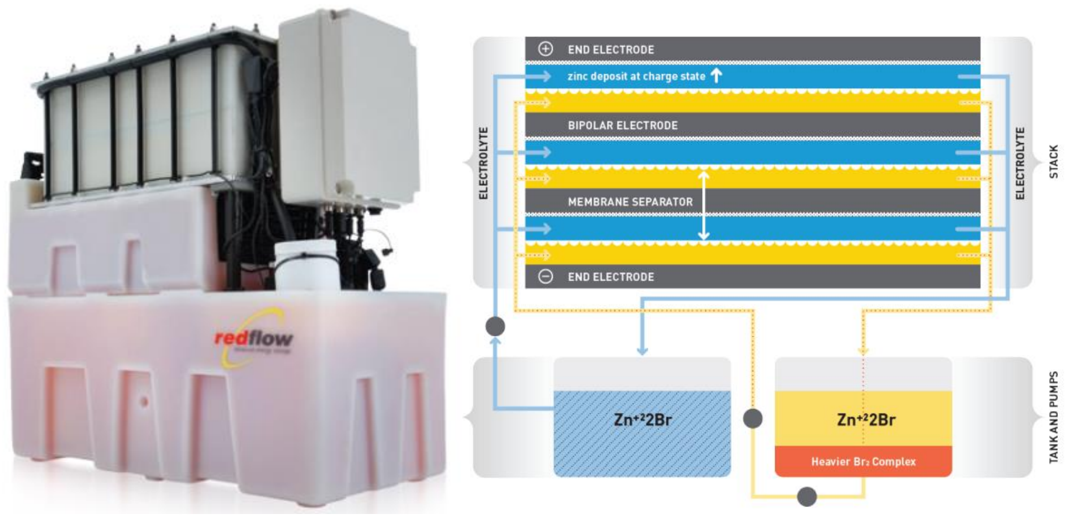

Figure 23. Zinc Bromine 5 kW battery developed in Australia[11]

3) Polysulphide Bromide Batteries (PSB)

PSB is a regenerative fuel cell technology that provides a reversible electrochemical reaction between two salt solutions electrolytes and has been verified in the laboratory and demonstrated at multi-kW in the UK. Two prototypes were built in UK and EEUU but because of engineering problems, the installations were never commissioned.

RWE Company (the main PSB drivers) stated that they believed the technology would be viable but was still a few years from being truly commercial.[8]

4.1.9 Electrostatics: supercapacitors

Operating principle

They are a type of high power high energy density capacitor and they have the same operating principle.

The supercapacitor shares its physical design with all capacitors. That is, it consists of two metal plates, which are typically aluminium, or other conductors, separated by an insulator. The insulator may be something as simple as air, or more complex such as ceramic or plastic film. However, the major difference between the supercapacitor and ordinary capacitors are that the conductors have a coating of a porous powdery substance called activated carbon, which is then soaked in an electrolyte and the insulator is incredibly thin.

So, although the structure of a supercapacitor and an ordinary capacitor is identical, there are two major differences between them — the relative size of the metal conductors and the space between them. In other words, larger conductors with the added area supplied by the porous substance are separated by a smaller space and aided by the electrolyte, which allows the supercapacitor to store more electric charge. It can be compared as two capacitors in series.

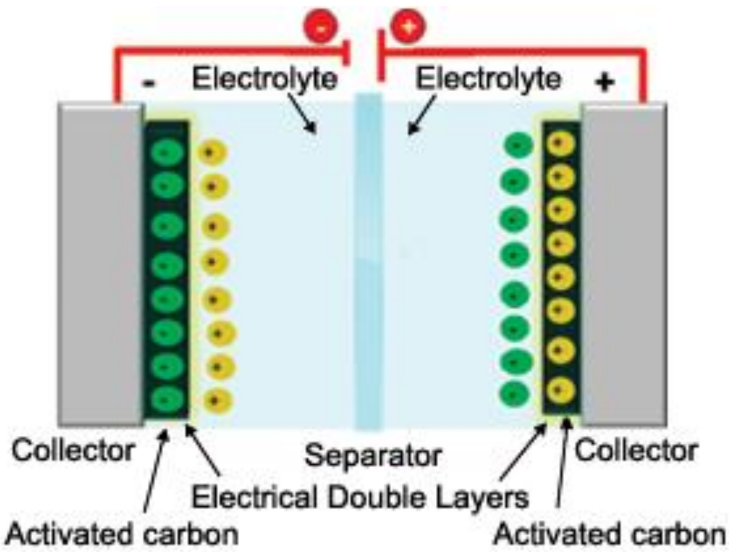

Figure 24. Schematic principle of a supercapacitor (Source: MR Innovator in Electronics)

The energy transfer that takes place within the structure of the supercapacitor is what separates it from a battery since the static charge created between the two plates moves much faster than the liquid-aided chemical charge that takes place within a battery.

The way it works is that as voltage is applied, a supercapacitor charges, meaning negative ions rapidly flow to one side of the capacitor and positive ions to the other. This quickly creates an electrical field. Furthermore, the combination of the activated carbon coating and electrolyte soak causes two layers of ions to form within the supercapacitor, creating a double layer of charge, thus leading some to label these as "double layer capacitors."

When the electrical energy of the supercapacitor is discharged, the charge on the plate decreases quickly as all the electrons on one plate flow through the external circuit.

Advantages and limitations

The energy density of supercapacitors is generally an order of magnitude less than that of conventional batteries, but the power density is generally one or two orders of magnitude greater. They can also be cycled much more effectively, generally showing very little degradation over thousands of charge/discharge cycles, despite the fact that they require more complex electronic control to avoid discharge.

- Advantages
  - ✓ Unlimited cycle life, because they work electrostatically, rather than reversible chemical reactions
  - ✓ Power density is generally one or two orders of magnitude greater than batteries, low resistance enables high load currents
  - ✓ Charges in seconds
  - ✓ Simple charging
  - ✓ Safe
  - ✓ Excellent low-temperature charge and discharged performance
- Limitations
  - ✓ Low energy density, an order of magnitude less than batteries
  - ✓ Linear discharge voltage prevents using the full energy spectrum
  - ✓ High self-discharge, higher than most batteries
  - ✓ Low cell voltage; requires series connections with voltage balancing
  - ✓ High cost per watt

Current status and applications

The main applications for supercapacitors are:

- Coupled with wind turbines, where very large supercapacitors help to smooth out the intermittent power supplied.
- Increasingly being used as temporary energy stores for regenerative breaking in electrical and hybrid vehicles.
- UPS systems: the supercapacitor can be used either as a battery replacement or as a short-term redundant back-up supply.

- Consumer electronics, computer, and communications applications. Supercapacitors are frequently designed into these products for memory protection.
- Can be used in solar arrays and are also are a good fit for micro-energy harvesting applications, which by definition do not require much energy storage. Vibrational energy created by rotating machinery, for example, is stored in the supercapacitor after first being converted to electrical energy by a harvesting device. Using supercapacitors can eliminate the need for replacing batteries or the expense of running a power line to a rechargeable battery.
- In Japan, supercapacitors are employed in commercial building to reduce grid consumption at peak demands and during power outages.

Currently, the main target of the supercapacitors is to be used for increasing the efficiency of hybrid electric vehicles in several ways. Today's hybrid vehicles typically turn off the engine completely when the car comes to a stop, however briefly, and then very efficiently start it again using energy stored in supercapacitors. Trains, planes, and automotive sector account for about 40 percent of today's $400 million worldwide supercapacitor market. Transportation applications include maglev trains, power and braking recuperation systems, truck lifts, and track switching.

Commercially supercapacitors are available with energy densities of 5 Wh/kg, although experimental variants exist based on Graphene materials with 28.5 Wh/kg.

Figure 25. Demo installation of Supercapacitors for UPS

Until recently, the supercapacitor market has grown largely at the expense of conventional capacitors. Currently, the technology seems ready to invade the lithium-ion battery market share for smart phones and other devices that perform multiple functions more or less simultaneously, and therefore, have similar spiky power-to-available-energy profiles[13].

4.2 Characteristic synthesis of relevant energy storage solutions

Considering the basic principles of the different types of storage and knowing their state of art, a comparison of the different relevant features and parameters is performed in order to choose the best option.

Technical parameters shown in Table 3, Techno-economic comparison, are the following ones:

- *Maximum capacity*: is the maximum range of amount of energy that the accumulator can store during a period of time.
- *Maximum power*: maximum range of the discharge power for which the respective storage technology can be applied.
- *Efficiency*: the ratio between the power provided by the battery when discharging and the power provided to the battery when charging.
- *Storage duration*: time the device can deliver the energy until it is discharged.
- *€/kWh*: price per unit of capacity installed. Is not included the O&M cost, which is a percentage of the capacity installed.
- *Investment (€/kW)*: price per unit of power installed.
- *Lifespan*: expected life in years for a good way of operation of the device.
- *Cycling capacity*: number of cycles of charge that the device is able to perform without losing capacity.
- *Energy density*: is the amount of energy stored in a battery per unit of volume or mass.

Table 3 shows a comparison of the different storage technologies explained before, from the point of view of duration, capacity and costs. The benchmarking will be developed according to this table except for the following technologies:

- *Polysulfide Bromide Batteries and Metal Air* have been found to be not commercially available yet for the sizes and applications identified in this report; literature regarding their technical parameters is scarce and does not allow a proper comparison with the rest of the table.
- *Supercapacitors*: their application in the system described in the assessment is not common, their expected discharge time is more in the range of seconds/minutes.

	Element	Maximum Capacity (MWh)	Maximum Power (MW)	Efficiency (%)	Storage duration	€/kWh	€/kW	Lifespan (years)	Cycling capacity	Energy Density (Wh/kg)	Self-Discharge
Supercapacitors*		< 0,001	< 0,3	90	Seconds- mins	500-1000	200-400	20	High	5	-
Electrochemical batteries	Pb-A	< 40	< 20	75-90	Seconds-days	200-400	150-200	5-15	500-2000 cycles	30-40	2 - 5 % month
	Ni-Cd	< 20	< 50	72-90	Seconds - days	200-600	500-1500	< 20	1500-3000	45-80	5 - 20 % month
	Li-ion	-	< 50	85-90	Seconds - hours	300-800	700-3000	5-20	3000 at 80% SOC	90-240	1 - 5 % month
	Na-S	< 50	< 10	68-75	Seconds - hours	500-700	150-200 5	15-20	3000	70-100	no self-discharge, high self-consumption
	ZEBRA (Na-$NiCl_2$)	< 10	< 40	85-95	hours	550-750	150-1000	10-15	4500	100-200	no self-discharge
	Flow VRB	< 6	< 3	65 - 85	Hours - months	150 -1400	500-1500	<25	> 10000	20-30	no self-discharge
	Flow ZRB	< 3	< 0,5	65 - 70	Hours - months	150 - 1400	700 - 2500	<25	> 10000	50-75	no self-discharge
	Flow PSB/Metal Air*	-	-	-	-	-	-	-	-	-	-
Hydrogen		-	-	35 - 45	Hours-months	0,3 – 0,6	1500-2000	10-30	>10000	33330 (gas)	no self-discharge

Table 3. Techno-economic comparison [3,8,14,15]

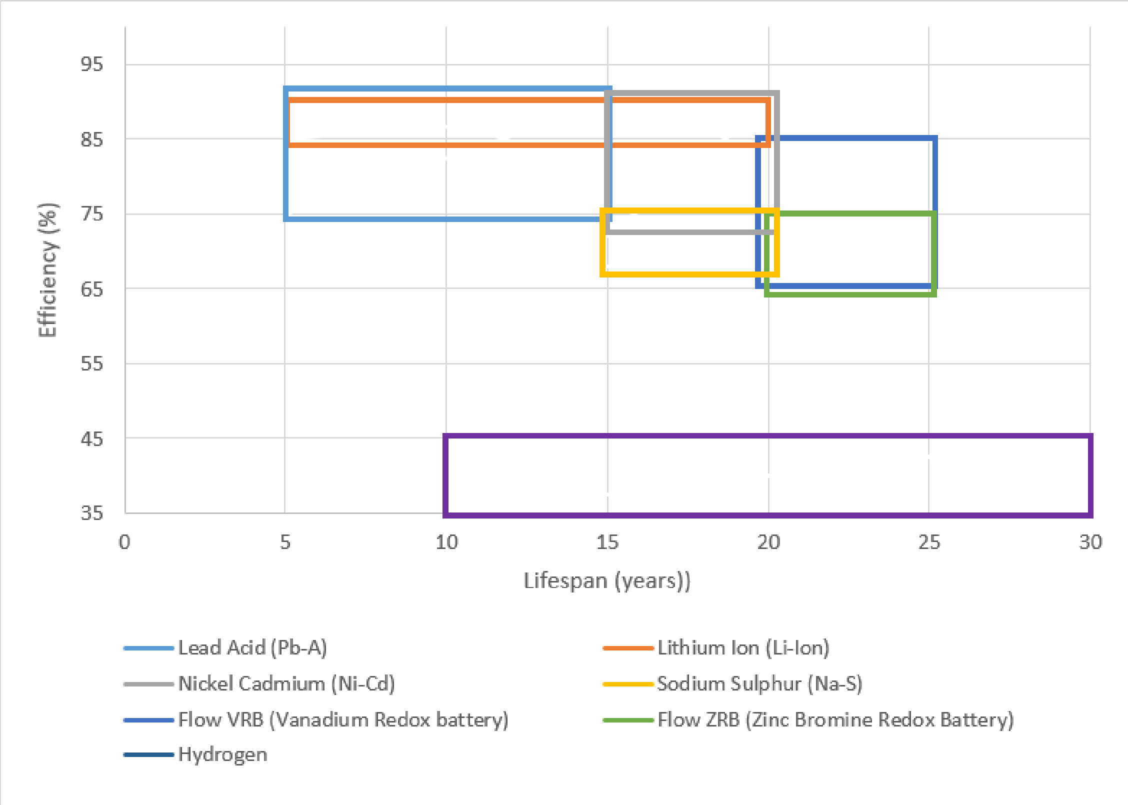

Figure 26. Overview of the main characteristics of the technologies considered

The most common technologies used to store energy in these scenarios, such Li-Ion, Pb-A and Ni-Cd, can achieve high efficiency (over 90 %). Range of lifespan for these three technologies comprises from 1000 to 3000 cycles depending on the State of Charge in the operations.

However, it was mentioned in chapter 4.1.4 that Ni-Cd is being used less and less every day, because of the toxic elements within the core and the memory effect that causes a reduction in the capacity of the battery. European Union has banned the sale of Ni-Cd in all but a select few applications, so it is called to disappear[10].

As a result of that policy, it has been considered to mention and present Ni-Cd technology in previous chapters but not to include it in the benchmarking analysis, because it does not represent a feasible technology to introduce in the short-medium term, which is the objective of this study.

Flow batteries, still being investigated but starting to be commercialized, have the lowest efficiency but their lifespan does not affect the depth of discharge and it is very large (more than 20 years, hence in the study they weren't replaced).

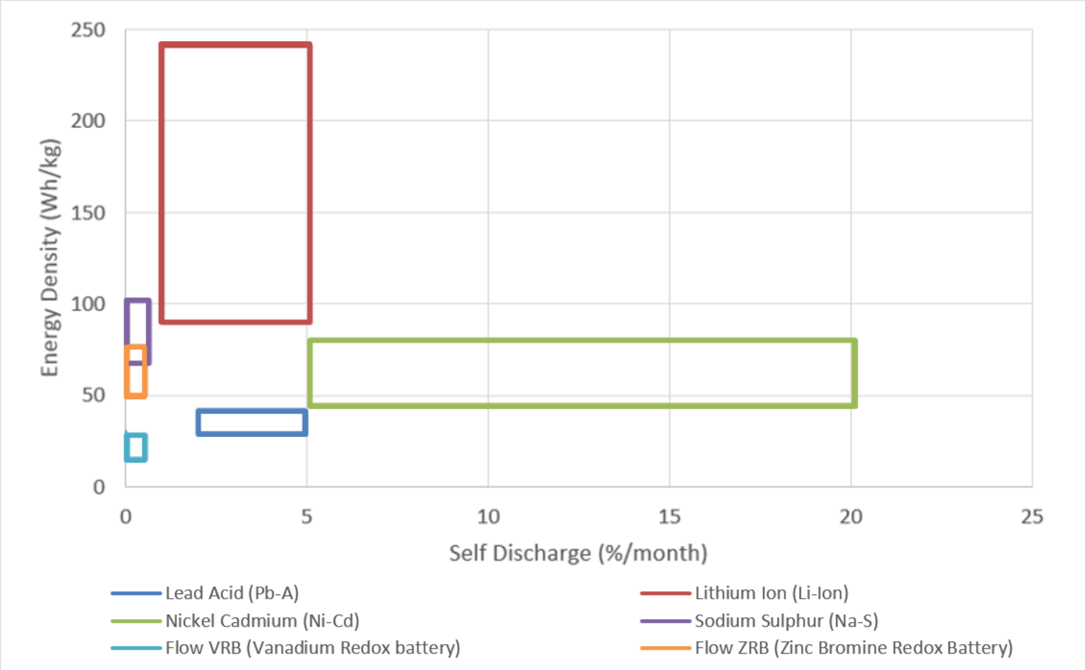

Figure 27. Overview of energy density and self-discharge of the electrochemical batteries

Flow batteries present no self-discharge because they employ external tanks to store the electrolytes and there is no reaction outside the reaction chamber. Sodium Sulphur has a very low self-discharge too, but they require a huge self-consumption to keep warm the operation (over a 10% of power per day).

Lithium Ion can achieve huge energy densities, which means they can store more energy in a smaller space than the rest of technologies, showing a low self-discharge per month too.[4.1.2]

Hydrogen storage system does not depend on chemical reactions inside the device as the electrochemical batteries. This is a great advantage because the number of cycles or the energy provided is unlimited. In case of gaseous hydrogen, it only depends on the capacity of the pressurized tanks. These tanks can store from a few kg to dozens, improving the energy supplied due to the high energy density that hydrogen carries. Moreover there is no self-discharge (when dealing with hydrogen, this concept is equivalent to hydrogen losses within the pressurized tanks), which compensates the relatively low efficiencies of the whole system.

According to the Table 3, the investment per power installed will be selected under the following requirement and used in the benchmarking:

Technology	€/kW	Selection for the benchmarking (€/kW)	Observations
Lead Acid	150-200	175	State of art average
Lithium Ion	700-3000	1800	State of art average
Sodium Sulphur	150-500	325	State of art average

Flow VRB	500-1500	1250	Higher than average because price is higher when power installed is lower, and because it is still a new technology
Flow ZRB	700-2500	1850	State of art average
Hydrogen	1500-2000	2000	State of art

Table 4. Selection of the investment for each storage technology

5. BENCHMARKING OF THE SELECTED STORAGE TECHNOLOGIES

First step for benchmarking is to define the set of boundaries, requirements and parameters in which their behaviour is going to be analysed and compared. The process is explained in the following sections.

The calculations presented in this chapter were done using the software called Odyssey. It was developed by CEA TECH (partner of the project) and allows modelling systems by gathering together different technologies (electrolyser, fuel cell, auxiliaries, hydrogen storage, batteries, PV panels…) and performing a series of simulations in which it can be analysed the behaviour and parameters of the elements

5.1 Case studies

A number of conditions and boundaries were established in order to obtain technical and economical results for the different batteries technologies analysed

The source of energy is limited to solar PV, because it is the technology used in ELY4OFF.

The study is carried out in two different arbitrary environments: Huesca (Spain) and Edinburgh (Scotland). The aim is to investigate the impact of two different locations, one with good potential for solar resource and the other with scarce resource. Furthermore, three different applications for each location are identified to assess the impact of energy consumption: single home family, mountain hut, and a hotel.

The configuration of the different elements is as follows (typical configuration of renewable energy system)

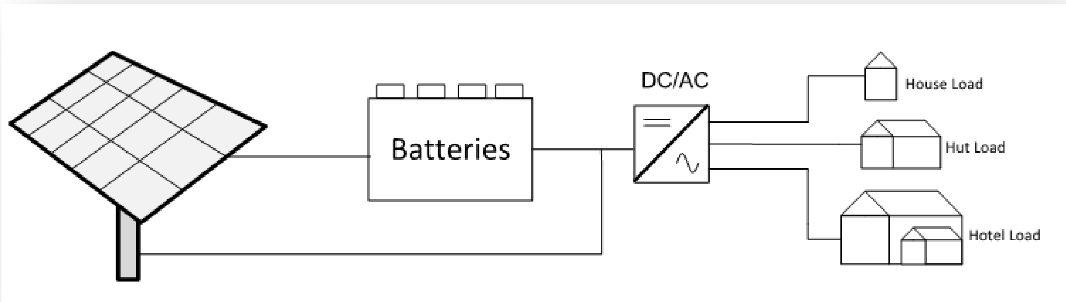

Figure 28. Characterization of the system to be analysed

In order to be able to properly compare the two locations selected, a different PV size has to be selected for a certain application. The criterion used has been to determine PV size providing the same amount of energy to the application independently of location. As consequence 5,7 kWp of PV installed in Huesca provides the same amount of energy than 10 kWp of PV installed in Edinburgh due to the lower solar resource, on a yearly basis. It has to be said that the assessment focuses exclusively on electricity generation, heat requirements have not been taken into account. On the other hand, it is clear that a back-up system is required in all the applications; it has been considered that a diesel generator supplies the electricity when batteries are depleted. However, it is not included in the economic assessment.

The energy consumption profile in the three applications has been obtained from real measurements in a Spanish hut during several months, and then adjusted as a function of the capacity. This profile is identical for both locations, so no effect of culture or climate (apart from the amount of insolation) was taken into account.

The source of solar resource data in each location was obtained by means of PVWatts software.

Parameter	Home	Hut	Hotel
Capacity	4 people	80 people	150 people
PV Edimburgh	10 kWp	105 kWp	196 kWp
PV Huesca	6 kWp	60 kWp	112 kWp
Daily energy average	5,7 kWh/d	40 kWh/d	75 kWh/d

As an example of the consumption profile, in the following figures it is shown the daily profile in the hut in a typical summer day, and the yearly profile PV generation.

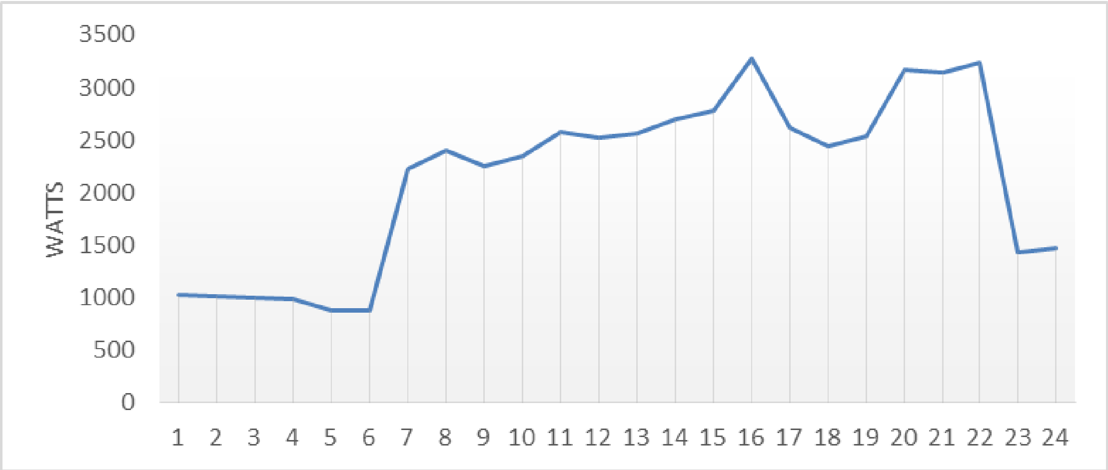

Figure 29. Daily profile of electrical load in a hut in summer

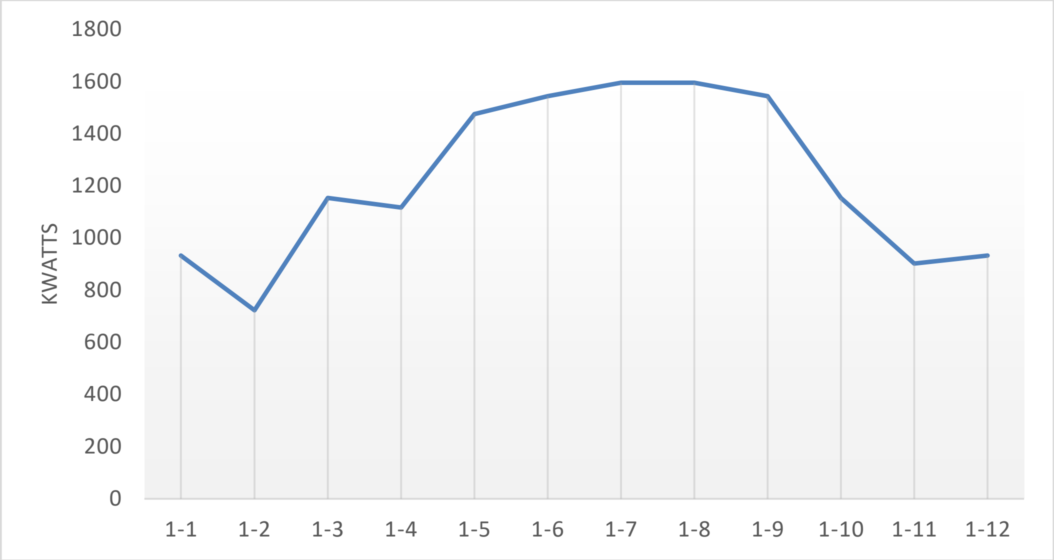

Figure 30. Yearly profile of electrical load in a hut

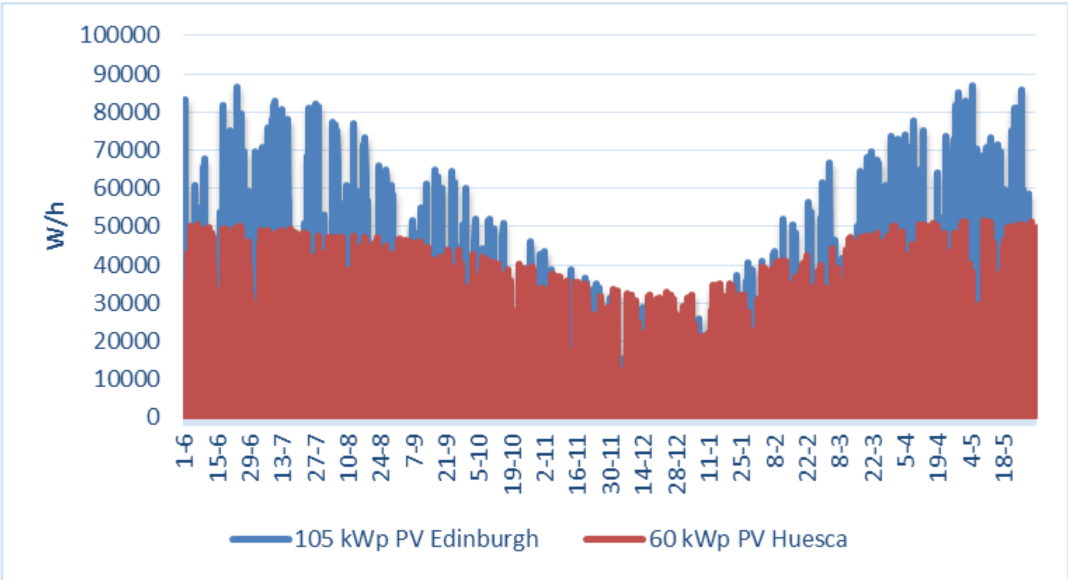

Figure 31. Yearly profile of PV generation

Input data of the batteries, such as the life span, self-discharge or cycling capacity[1], have been already presented in the Characteristic synthesis of relevant energy storage solutions. Regarding autonomy of the systems, the batteries are sized according to the information taken directly from the software PVWAtts, where there are no days without solar radiation (data are average of real values of several years), therefore the maximum autonomy is lower than one day.

[1] Cycling capacity is strongly related to the minimum State of Charge. Selection of number of charge cycles is based on the minimum SOC used in Odyssey for each technology, being 0.2 for Pb-A, 0.1 for Li-Ion and VRB, and 0 for Na-S and ZRB.

Regarding the power to power hydrogen cycle, according to the electrical load in each scenario, the following capacities have been established for the PEM electrolyser and the Fuel Cell:

H2 Cycle	Home	Hut	Hotel
PEM Electrolyser	5,2 kW	52 kW	100 kW
Fuel Cell	3 kW	3.5 kW	8 kW

Under these conditions, the necessary capacity of each technology of battery is estimated in order to meet the requirements. As results, the following parameters are calculated:

- Batteries capacity (kWh): the capacity needed to ensure the electrical load.
- Total Net Cost (TNC): includes cost of investment, replacement, maintenance and discount rate throughout the years of every element that is shown in Figure 27.

$$TNC\ (€) = \Sigma_t\ [(Investment_t + Replacement_t + O\&M_t + Fuel_t) * (1 + r)^{-t}]$$

r = discount rate

- Levelized Cost of Energy (LCoE): compares the unit cost of different technologies over their technical lifetime.

$$LCoE\left(\frac{€}{kWh}\right) = \frac{\Sigma_t\ [(Investment_t + Replacement_t + O\&M_t + Fuel_t) * (1 + r)^{-t}]}{\Sigma_t\ (Electricity_t * (1 + r)^{-t})}$$

$Investment_t$ (€), $Replacement_t$ (€) and $O\&M_t$ (€) costs are estimated from economic values (€/kW) in Table 3. Techno-economic comparison [3,8,14,15] *and capacity of the batteries given by Odyssey results (kWh).*

- Investment per power (€/kW): cost of investment per every kilowatt installed.

Other financial parameters used are:

- Discount rate: 6 %
- Time of operation: 20 years

5.2 Results of the benchmarking

Following table shows a comparison of stationary batteries in the different scenarios presented (2 locations, 3 applications). As already mentioned, the information presented is not original, it comes from a compilation of references.

Location	Application		Lead Acid (Pb-A)	Lithium Ion (Li-Ion)	Sodium Sulphur (Na-S)	Flow VRB (Vanadium Redox Battery)	Flow ZRB (Zinc Bromine Redox Battery)	Hydrogen
Huesca	*Single family home*	**Total Net Cost (TNC, €)**	17,933	19,787	24,338	19,543	32,046	46,140
		Levelized Cost of Energy (€/kWh)	0.704	0.890	0.955	0.767	1.257	1.811
		Investment per power (€/kW)	1,843	3,468	2,018	2,918	3,268	2,104
		Batteries Capacity (kWh)	11.3	10.2	11.5	9.7	9.4	*Not apply*
	Hut	**Total Net Cost (TNC, €)**	153,162	164,054	180,750	160,117	213,520	409,776
		Levelized Cost of Energy (€/kWh)	0.858	0.920	1.013	0.898	1.197	2.298
		Investment per power (€/kW)	1,843	3,468	2,018	2,918	3,268	2,280
		Batteries Capacity (kWh)	47.3	43.9	49	41	40	*Not apply*
	Hotel	**Total Net Cost (TNC, €)**	286,413	307,148	338,773	299,619	400,939	796,507
		Levelized Cost of Energy (€/kWh)	0.845	0.906	1.000	0.884	1.183	2.351
		Investment per power (€/kW)	1,843	3,468	2,018	2,918	3,268	2,297
		Batteries Capacity (kWh)	89.8	83.4	93	77.8	75.9	*Not apply*
Edinburgh	*Single family home*	**Total Net Cost (TNC, €)**	36,126	39,097	78,369	52,770	89,785	56,431
		Levelized Cost of Energy (€/kWh)	1.417	1.534	3.076	2.071	3.524	2.214
		Investment per power (€/kW)	1,843	3,468	2,018	2,918	3,268	2,628
		Batteries Capacity (kWh)	60	39	66	46	39	*Not apply*
	Hut	**Total Net Cost (TNC, €)**	191,158	205,777	281,428	207,593	344,230	460,670
		Levelized Cost of Energy (€/kWh)	1.071	1.153	1.578	1.164	1.930	2.583
		Investment per power (€/kW)	1,843	3,468	2,018	2,918	3,268	2,628
		Batteries Capacity (kWh)	149	108	158	120	107	*Not apply*
	Hotel	**Total Net Cost (TNC, €)**	441,658	394,759	511,826	397,084	558,830	892,738
		Levelized Cost of Energy (€/kWh)	1.213	1.165	1.602	1.171	1.649	2.635
		Investment per power (€/kW)	1,843	3,468	2,018	2,918	3,268	2,606
		Batteries Capacity (kWh)	298	218	314	240	217	*Not apply*

Table 5. Benchmarking

5.3 Discussion

The comparison between the scenarios in Huesca and Edinburgh shows the greater capacity of batteries that is necessary to be installed in the Scottish location, around 3-5 times higher than in Huesca, and being higher for home applications. Regarding technology, the lowest capacity required is always for ZRB followed very close by Li-Ion while the greatest is always NaS; in both cases the results are the expected due to the features of each technology regarding energy density and depth of discharge (better for Li-Ion and ZRB) and operating temperature (higher for NaS so BOP consumption is higher).

Regarding investment per power, table 4 shows the values used in the assessment (based on literature), which do not depend on location or application. The lowest is Pb-A, and the highest is for Li-Ion and ZRB. Some aspects should be mentioned on those data. For one hand, the reliability of the values is high for Pb-A, Li-Ion, and Na-S, and low for the rest, based on the capacity installed in the market, amount of references and the readiness of the technology. On the other hand, the tendency of the values in the future shows stability in Pb-A and Na-S, a probable reduction in Li-Ion, and unpredictable for the rest.[16,17]

Probably the most relevant parameter to compare the technologies is the LCOE, as it takes into account the whole life of the installation, investment cost, replacement and O&M costs during the operating life. The technology with the lowest LCOE in the majority of cases is Pb-A (followed close by the Li-Ion and Flow-VBR in Edinburgh, and by Flow-VBR and Li-Ion in Huesca), which is coherent as it is a proven technology, currently the most used and mature in the market. There is only one case where this does not happen, for hotel in Edinburgh where Li-Ion is the most competitive, followed by Flow-ZBR and then Pb-A.

It is interesting to discuss briefly the values of LCOE depending on location, to show the increment of installing the energy storage technologies in locations where solar resource is low. It is in the range of 2-3 times greater for home applications, and lowers down to 30%-60% greater in case of hotel and hut. This is the impact in cost of the greater battery capacity required as mentioned before. These data are depicted graphically in the following figure, which shows the values of LCOE for the two locations and hotel and home applications only for clarity. The differences between maximum and minimum values are always greater in Edinburgh, being more acute for home than for hotel. It can be observed also that the impact of location for home application is much greater than for hotel.

As a final recapitulation, the assessment done shows that there are three technologies that appear to be the preferred alternatives in the most part of the cases: Pb-A, Li-Ion and Flow VRB. However, the basic cost data found are much more trustworthy for the two first than the other one, so currently the technologies to consider for any application are basically Pb-A (the most used currently) and Li-Ion (their share of the market in stationary application is gradually increasing and their cost is reducing rapidly).

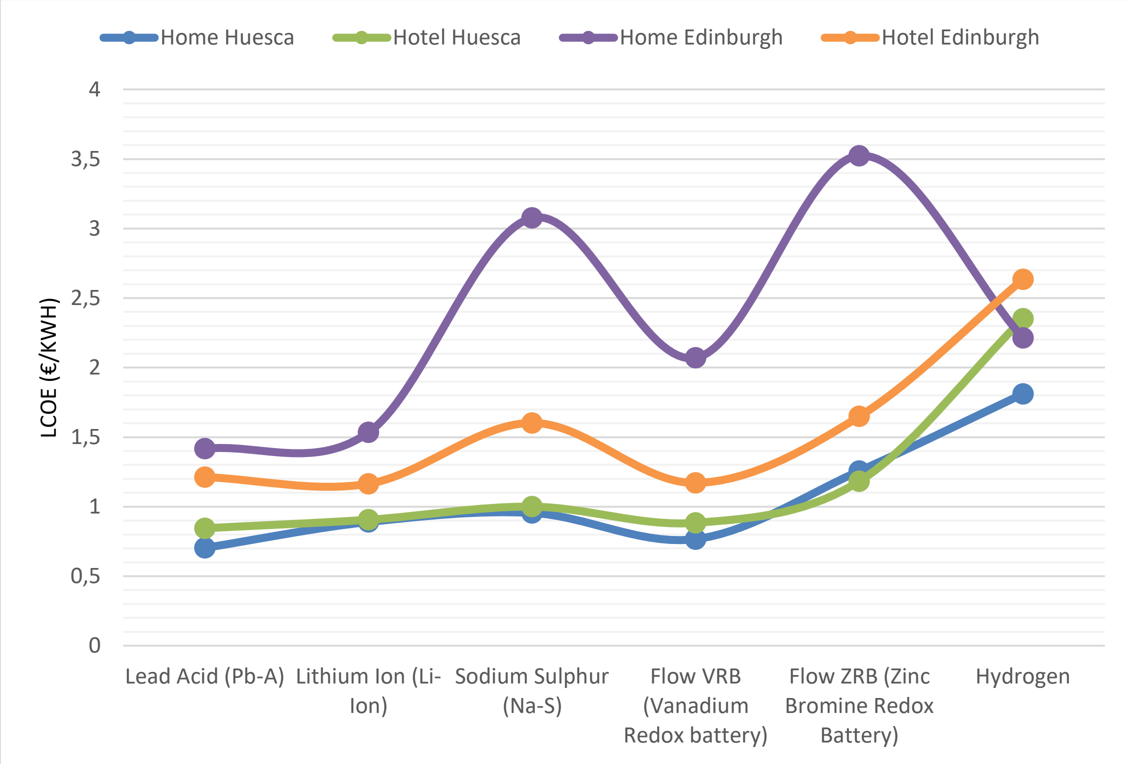

Figure 32. LCOE of each technology depending on the load and the location

It must be highlighted that in the three scenarios of Edinburgh, there is a minimum of electric load (1-1.5%) that cannot be supplied only with the batteries, no matter how much the capacity of the batteries is increased. The electrochemical batteries are unable to store and supply the necessary energy to achieve an autonomous installation. In this scenario, hydrogen can supply easily the 100% of the electrical load, thanks to its high energy density and the storage in pressurized tanks which do not have self-discharge neither problematic behaviour with low temperatures. These potential advantages result in a re-electrification hydrogen system as a viable storage method that can compete with batteries.

Results of the off-grid scenarios with higher electrical loads, such as the hotel one, prove that the Power-to-Power (PtP) hydrogen system composed by the PEM Electrolyser + pressurized storage + PEM Fuel Cell becomes more competitive as the load increases,

Therefore, hydrogen shows to be competitive in the following PtP niche markets:

- Off-grid areas, where hydrogen could compete with diesel generators and batteries. Diesel generators are still necessary in order to have an auxiliary source of energy and to avoid oversizing the capacity of the batteries. They have a low CAPEX but too much OPEX because of the cost of fuel and its transportation.
- Weak grid areas, to supply energy when the grid crashes.

The results obtained will be useful in future tasks in the project to compare H2 technologies against currently technologies and also promising technologies.

6. BIBLIOGRAPHY

1. Rashmi V. Holla. Energy Storage Methods - Superconducting Magnetic Energy Storage.
2. Deloitte. Energy Storage: Tracking the technologies that will transform the power sector.
3. Navigant Research. Energy Storage for Renewables Integration: A burgeoning Market. (2015).
4. Pike Research. Energy Storage Study Projects Boom Through 2022.
5. *Hydrogen storage: state-of-the-art and future perspective*. (Office for Official Publications of the European Communities, JRC).
6. PD Inc. Lead Acid Batteries.
7. Paul Voelker. *Trace Degradation Analysis of Lithium-Ion Battery Components*. (2014).
8. Edward Barbour, U. of B. Energy Storage Sense.
9. Joe Escobar. *Nickel-cadmium Batteries: Basic theory and maintenance procedures*.
10. European Commission, E. Batteries & Accumulators. (2016).
11. Morante, J. R. *El almacenamiento de la electricidad*. (Fundación Gas Natural Fenosa, 2014).
12. TESLA. What's a metal air battery and why is Tesla interested in it?
13. Jack Shandle, M. E. Energy Harvesting.
14. Fuel Cells and Hydrogen Joint Undertaking (FCH JU). *Multi-Annual Work plan 2014 -2020*.
15. FCH JU, M. & C. *Commercialisation of energy storage in Europe*. 96 (European Commission, 2015).
16. Future Market Insights. *Lead Acid Battery Market: Global Industry Analysis and Opportunity Assessment 2014 - 2020*. 75
17. Future Market Insights. *Sodium Sulfur Batteries Market: Global Industry Analysis and Opportunity Assessment 2015-2025*. (2017).