UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master's Thesis

UTILITY-SCALE APPLICATIONS OF ENERGY STORAGE

Author: **José Javier Rueda Montes**
Supervisor: **Dra. Alezeia González García**

Madrid, July 2019

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Summary

The solutions for a great deployment of Renewable Energy Sources are currently under discussion. Energy storage is presented as a great opportunity, but it is crucial to analyze the characteristics and applications of storage technologies to avoid system inefficiencies when drafting a suitable regulation framework.

In this document, the main factors which affect the development of an efficient role for storage have been analyzed and some promising business models are proposed.

First of all, the definition of energy storage is studied. The existing technologies are presented and a brief analysis of the economic aspects of storage is developed in order to focus the business models on the most developed and least costly ones. Lithium-ion batteries are currently the most cost efficient technology thanks to the economies of scale achieved by the automotive industry, which is the main driver for their development. Also, these batteries present good characteristics when analyzing power and energy rates and response time.

Then, the applications for energy storage technologies are described and analyzed. Several classifications are studied and finally a suitable one is proposed according to the opportunities to create value and generate business. Lithium-ion batteries can serve all the applications analyzed for electric systems except the long-term ones. Therefore, these batteries are chosen to develop the business models that are the focus of the thesis.

The value chain of battery production is studied in detail in order to identify possible risks that might affect the agents participating in this market as well as the maturity of it. While the mining of the raw materials and battery production is focused in Asia, the final consumption of batteries is more spread (America, Europe and Asia).

Later, an analysis of the regulation around key issues is developed. The present market design presents many barriers to the entrance of storage in it since it is not technology neutral. Storage is presented as a solution for electric systems in the long term (capacity mechanisms), daily scope (day ahead market) and short term (balancing and reserves). Also, the ownership of storage assets is discussed, which might favor the appearance of dedicated business models. Finally, some insights are given related to tariff design in order to reduce the existing barriers.

Finally, with all the information gathered about technologies, applications and regulatory issues, some promising business models that create value are studied. Three of them - Hybrid Power Plant, Active Customer and Local Markets - are developed in detail due to their current feasibility and interest for the utility sector. For these business models a case study is analyzed from a qualitative perspective. The Hybrid Power Plant business model focuses on supporting power plants to provide services to the system as frequency regulation. Active Customer enables clients to manage their consumption and as a result reduce their electricity bill cost. Local Markets is presented as an alternative for DSOs to own storage assets by acquiring services from private owned batteries.

The conclusion obtained is that, although there is still a great margin for development for storage technologies, currently there are solutions in the market that might allow to introduce efficiencies in the system with the appropriate regulatory framework.

Acknowledgment

To my family, for all the support and faith that they have always put in me.

To my beloved friends, for all the moments we have shared together this last year in which we have been able to disconnect from the daily routine.

To my supervisor, Alezeia, for all the patience and dedication you have shown me.

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1 Introduction

The European Union has committed to decrease the emissions of CO_2 a 40% by 2030 [1], not only in the electricity sector but in the energy sector, which includes transportation and industry sectors. Moreover, the Directive reflects a commitment on achieving a 32% share of renewable energy in the technology mix. The decarbonization process requires a transition from thermal to renewable sources of energy. This is the reason behind the increase in Renewable Energy Sources (RES) capacity installed in the electricity sector and the development of the electromobility in the transportation sector. However, renewable generation introduces some complexity in the operation of the system and does not bring stability to it. The objectives proposed for 2030 in Europe are aligned with the energy policy trends in other systems worldwide, such as California and Japan, in which a great deployment of renewable sources is needed.

Some problems regarding high renewable energy penetration may arise: a remarkable example is the difficulty to manage the intermittency of the generation. An interesting solution for this problem is to manage and control the new flexibility resources to match the generation available at any temporal horizon given, from real time operation to long term planning [2]. Energy storage is a key technology to control power systems, as it allows to save the surplus of energy generated and consume it when necessary. Currently, the most promising and flexible storage technology are batteries. However, more storage technologies should be considered in the future according to different energy storage applications to search for the most cost efficient one.

The business models chosen in order to solve the problems that a great deployment of Renewable Energy Sources may cause are currently under discussion. Energy storage is presented as a great opportunity, but it is crucial to analyze the characteristics and applications of this technology to avoid system inefficiencies when drafting the regulation frameworks.

Hence, the motivation of this thesis is to study the storage applications that present feasible and efficient opportunities to propose the business models that may be developed related to this technology and afterwards, to analyze the regulatory barriers and best practices currently present in electric systems.

The main objective of this thesis is to define some business models related to batteries and study the main regulatory aspects that might affect them.

In addition, some specific objectives can be inferred to fulfill the thesis goals:

- Assess the value of energy storage in the current electric systems taking into account all applications.
- Provide business ideas to facilitate the introduction of energy storage in electric systems.
- Analyze a set of regulatory measures to promote energy storage and reduce the barriers found, in some regions of interest.

First of all, section 2 presents the main technologies that currently allow to store energy, technical and economic aspects are analyzed. Secondly, section 3 presents the applications of energy storage will be discussed, with a focus in batteries, in order to learn how to create value with them. Then, in section 4 some insights of the market dynamics currently taking place will be given. Following, section 5 presents some regulation policies will be studied in order to determine which are the main regulatory barriers of energy storage. After that, in section 6 , the business models are presented from the Utility perspective. The value proposition, the key partners, main sources of revenue and regulatory aspects are analyzed for the most important ones. Finally, section 7 presents the conclusions achieved as well as the main contributions from the author and the future work to be carried out.

2 What is energy storage?

In this section, the definition of energy storage is studied. Later, the existing technologies are presented and a brief analysis of the economic aspects of storage is developed. The main objective of this section is to set the current discussions about storage and clarify them in order to be able to develop a sound analysis in the next sections.

2.1 Definition

Although the definition of energy storage is currently under discussion, the European Commission has proposed the following one, which can be used as a standard [3]:

> "Energy storage is deferring an amount of the electricity that was generated to the moment of use, either as final energy or converted into another energy carrier."

To some extent, energy storage consists of energy transfers from electricity to other energy states. As a result, it is very important to define the limits of which technologies are considered storage and which not. For example, pumped hydro storage is based on the transfer from electric energy to potential energy and batteries transform the chemical energy of their components into electricity. These technologies and more will be explained later.

The discussion for a common definition for energy storage is mainly caused by these limits since there are conflicts of interest between the different stakeholders (companies, governments, …) affected.

It is important to highlight that the definition of energy storage is the first and most important step to design an appropriate regulation that may or may not enable agents to benefit from this already existing technology, energy storage.

This thesis proposes that, among other issues, the appropriate definition of energy storage should take into account these principles:

- Time and location deferring. The basic principle of energy storage is the deferring of electricity supply to the moment of use, as the EC says. In addition, there are some applications, especially electromobility that introduces location deferring as a key principle.
- Technology neutrality. In order not to favor some technologies and avoid a loss of competence and opportunities.
- Efficiency. Energy storage should promote the most economic efficient technology for each solution.

2.2 Technologies

Hereunder, storage technologies are classified according to their operating principle although there are plenty of different classifications available. In addition, the strengths, weaknesses and some cost insights of each technology will be briefly explained.

The most common classification [4] includes five categories: mechanical, thermal, electrical, electrochemical and chemical storage, as seen in Figure 1. However, the technologies included in each category may vary and they are not fixed since the classification changes according to the evolution and research in progress.

The main variables to be analyzed are the size of storage, through power and energy rates, the time of response and the cost of these technologies.

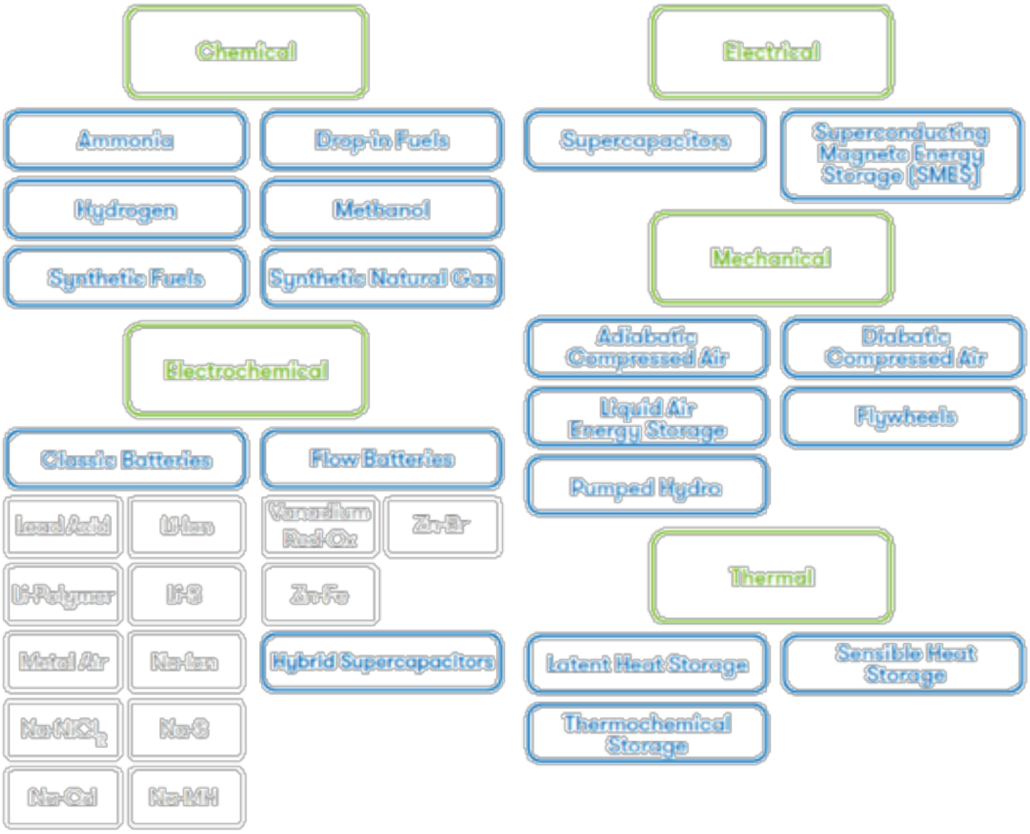

Figure 1: Overview of energy storage technologies [4]

2.2.1 Electrochemical

These technology is included in systems, which are commonly called batteries. In batteries, chemical energy is stored and converted to electricity and vice-versa in electrochemical reactions. They generally have very fast response times and are suitable for short term applications. However, they present some limitations since the fast reaction rates might erode the active materials transforming them in secondary components non reversible.

Hereunder, the most developed technologies are presented. These technologies are Lithium-ion, Lead acid, NaS and flow based. The global challenge is to develop chemistries based on abundant materials as Al and Si, with the appropriate characteristics.

2.2.1.1 Lithium-ion batteries (Li-ion)

A Lithium-ion battery is a storage system based on electrochemical reactions that happen between a positive electrode and a negative one. The positive electrode is called cathode and contains a metal oxide while the negative electrode is called anode and is made of carbon materials. The electrodes are separated by polymeric materials which allow the electrons to flow.

The charging and discharging processes are depicted in Figure 2.

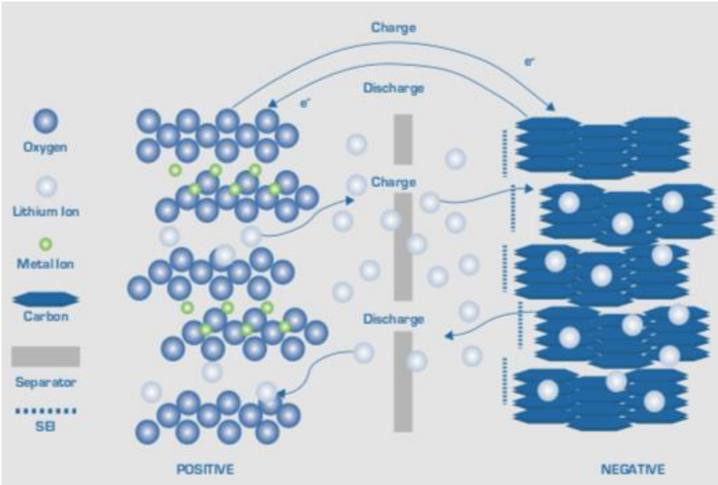

Figure 2: Charge/discharge process in Li-ion batteries [5]

Since it is one of the most developed technologies of electrochemical storage for electric systems, it is present for high and low power and energy ranges. The discharge time varies from minutes to hours while the reaction time is very short, some milliseconds. The efficiency of Li-ion batteries can achieve a maximum of 98% at room temperature [5].

Thanks to the mass production of batteries for the automotive and energy markets the costs will be reduced in the future. It is very important to differentiate clearly from the cost of the battery cells and the cost of the battery solutions, which also include the cost of the control systems, communications and even administrative costs. Technology improvements will be focused in improving energy density and lifetime.

2.2.1.2 Lead-acid batteries

Lead-acid batteries are also storage systems based on electrochemical reactions between a cathode and anode. In this case, the cathode is made of lead dioxide and the anode of lead and they are built in an sulphuric acid electrolyte.

Figure 3 shows the charging and discharging scheme for this technology.

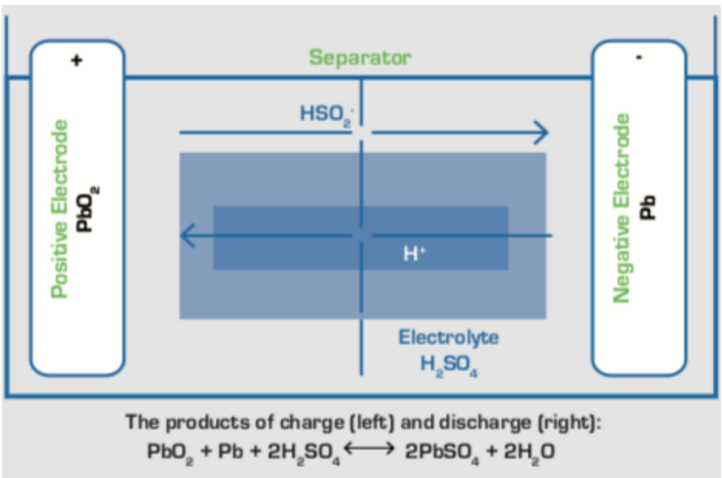

Figure 3: Charge/discharge process in Lead-acid batteries [5]

Lead-acid batteries are one of the most mature and cheapest storage technologies. These batteries are widely used as car starters for combustion vehicles. The discharge time range is wide, from minutes to 20 hours, and as other battery technologies, their reaction time is very short, milliseconds [5].

Although it is the oldest technology, there is room for technical improvement. The use of new materials can increase the specific power rates and will help increase the cycle life too. The challenge is presented when using this technology for cycling purposes, since currently Lead acid batteries are only used for supplying current peaks during the engine start of vehicles.

2.2.1.3 Sodium Sulphur batteries (NaS)

In Sodium-Sulphur batteries, the cathode is made of molten Sulphur and the anode of molten Sodium. The electrodes are separated by ceramic sodium which only allows charged sodium ions to pass through. In order to maintain the electrodes in a molten state, temperature is kept around 300° C with independent heaters.

Sodium Sulphur batteries have similar nominal power values and discharge times as Lithium-ion batteries, the most common ones.

This technology is very dangerous due to the high fire risk it presents. Safety is enhanced by implementing a great number of measures such as fuses, insulation boards and firefighting measures [5].

2.2.1.4 Flow batteries

Flow batteries do not use the same principle as the rest of batteries explained before. Flow batteries use two liquid electrolytes, one positively and the other one negatively charged, which are separated by a membrane. The ions pass through the membrane and complete the chemical reactions.

The key characteristic of this technology is the complete decoupling between power and energy ratings. On the one hand, the power rate is determined by the size of the membrane that allow the reactions. On the other hand, the energy rate is determined by the size of the electrolytes tanks. Thanks to this, the capacity of flow batteries can be easily increased by increasing the size of the tanks who store the electrolytes that are pumped into the battery.

Several combinations of chemicals are possible for these batteries. The most common ones are Va and Zn-Br. In lower Technology Readiness Levels, Zn-air and Al-air chemistries can be found but, as said, they are not well developed yet.

Figure 4 illustrates the working principle of a flow battery.

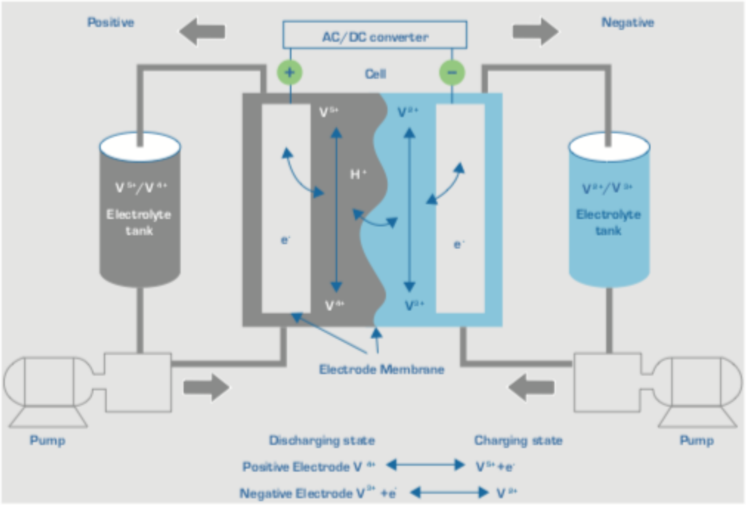

Figure 4: Charge/discharge process in a flow battery [5]

2.2.2 Mechanical

These technologies store energy in various forms of kinetic or potential energy. The main ones are Pumped Hydro Storage, which is currently the most deployed form of storage worldwide and Compressed Air Storage which, on the contrary, is on research.

2.2.2.1 Pumped Hydro Storage (PHS)

Pumped Hydro Storage (PHS) stores electrical energy by utilizing the potential energy of water. Water can be pumped and stored in an upper reservoir when prices are low or when there is high availability of electricity. On demand, water can be released through a conventional hydro turbine and transformed into electricity.

Generally speaking, PHS is the most mature storage concept in respect of installed capacity and storage volume. There are over 170 GW of pumped storage capacity in operation worldwide. Opportunities are mostly focused on mountainous regions in Switzerland, Austria, Germany, Spain and Portugal.

Pumped Hydro Storage characteristics depend on the reservoir and the hydro power plant associated. This technology can provide peak power up to GWs and store GWhs of energy, which provides a very interesting solution for long term storing. The main disadvantages are the low efficiency and the high environmental costs associated to the construction of the upper reservoir [5]. However, if the upper reservoir already exists from natural sources, the costs and environmental impact are reduced considerably.

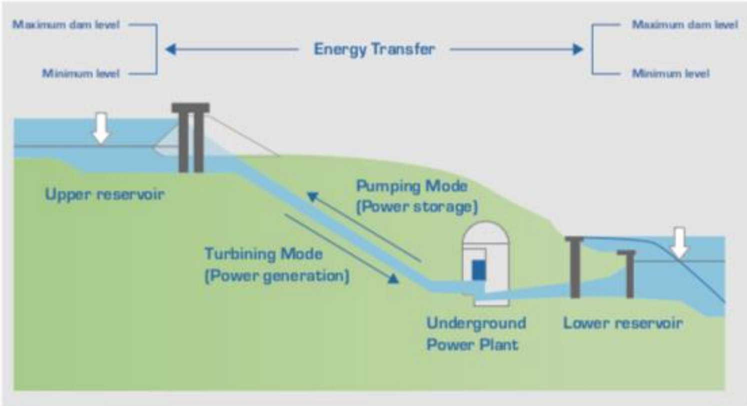

Figure 5: Working principle of Pumped Hydro Storage [5]

2.2.2.2 *Compressed Air Energy Storage (CAES)*

Compressed Air Energy Storage systems are very similar to Pumped Hydro Storage, but these systems store compressed air in underground caverns instead of water in reservoirs. The caverns usually are located at hundreds of meters below the ground. When electricity is needed, the air is used in a turbine to produce energy.

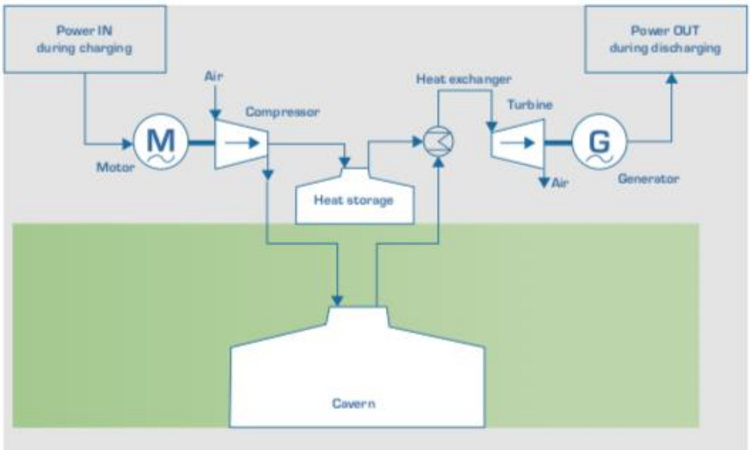

Figure 6: Working principle of Compressed Air Energy Storage [5]

CAES systems are in the process of demonstration and are not yet commercially available. Projected units will have a storage capacity of 10 GWh and generate electrical power of about 200 MW [5].

2.2.2.3 *Flywheels*

Flywheels work by accelerating a rotor to a very high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy.

Flywheels commonly use electricity to accelerate and decelerate the rotor of the system. However, flywheel devices that use mechanical energy instead of electricity to move the rotor are being currently developed.

2.2.3 Chemical

These technologies store energy in chemicals that appear in gaseous, liquid or solid form and energy is released in chemical reactions. Chemical storage is based on Hydrogen production, which can be further processed into ammonia, methane or methanol.

2.2.3.1 Hydrogen & Power-to-Gas

This technology works thanks to the electrolysis process, in which electricity is used to produce hydrogen and oxygen from water. The oxygen is released and the hydrogen stored. Then, electricity is generated on demand by combining hydrogen with oxygen in the so-called fuel cells or in gas turbines.

The three main final uses of the hydrogen obtained are the chemistry industry, the automotive industry and the injection into the gas grid, as hydrogen or methane. This technology is very useful when associated with renewable power plants since it allows to avoid curtailments and store the surplus of production by injecting it into the gas grid.

The decarbonization of the energy sector usually is associated with an electrification of the systems. However, it is very challenging to be able to electrify the big consumers and degasify industries. Power-to-Gas allows to produce a clean gas through the curtailments of renewable plants therefore decarbonizing these industries that rely heavily on gas.

The main unique characteristic of Power-to-Gas is that its discharge time varies from hours to several weeks, which makes it a great solution for long term storage applications. In addition, it provides wide ranges for power and energy values, up to several GW/GWh. However, the reaction time is slow, a few minutes, so this technology may not be appropriated for fast response applications [5].

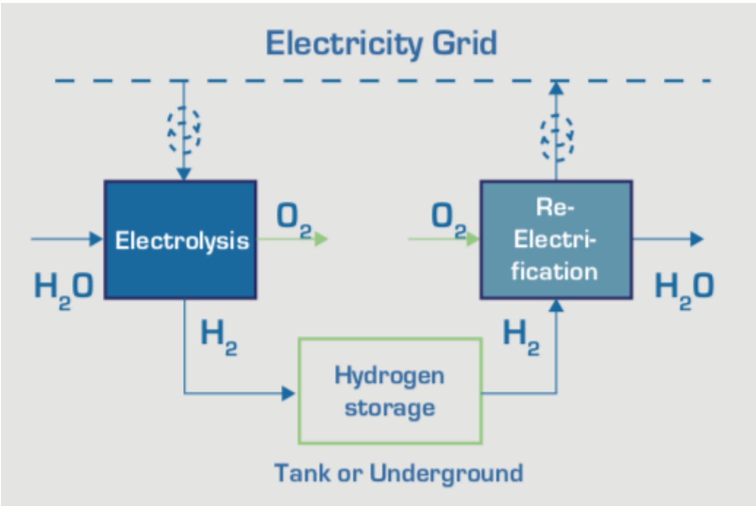

Figure 7: Scheme of Power-to-Hydrogen Storage [5]

There are more technologies existing under the Chemical classification that take advantage of the Hydrogen produced in Power-to-Hydrogen storage, when the Hydrogen is not reused to produce electricity.

2.2.3.2 Ammonia

In Power-to-Ammonia storage, Hydrogen is produced by water electrolysis while Nitrogen is got through an air separation unit. Both gases are converted to Ammonia by using a chemical reaction.

The scheme is shown in Figure 8.

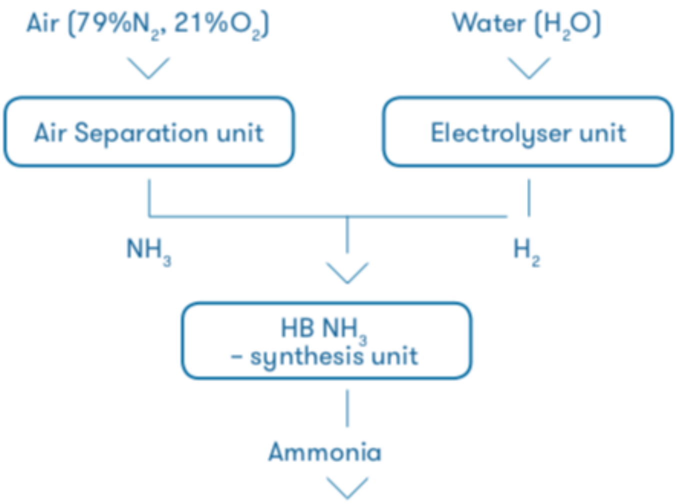

Figure 8: Ammonia production scheme [5]

It is very important to mention that, according to the definition of energy storage, some authors do not include Power-to-Ammonia or other technologies as Power-to-Methane as energy storage since the products obtained are not used to produce electricity in the future. Energy storage is defined as deferring the electricity produced from the moment of use. These technologies take advantage of the excess of renewable production, to avoid curtailments and produce Ammonia and Methane with them.

2.2.4 Thermal

These technologies store heat, which is generated from electricity by heat pumps or boilers and stored in different materials. Then heat can be converted into electricity again through turbines.

As before, when talking about Power-to-Heat it is very important to realize that when the heat produced is not used to produce electricity again, it is not clear that it can be called energy storage. It depends on the limits proposed on the definition of energy storage.

For example, in a household system without storage, usually electricity is used for comfort applications. In this situation, a Power-to-Heat solution may only be accepted as storage if the heat obtained is later used for comfort applications.

However, there are applications in which the heat stored is used to produce electricity again. Solar thermal power plants work on this principle by heating molten salts during the day that are then used to produce electricity when the solar resource is not available.

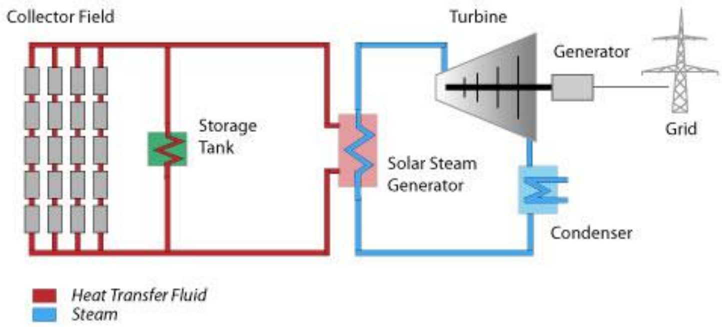

Figure 9: Solar thermal power plant working principle, [6]

The existing technologies related to Power-to-Heat are briefly explained below:

- Sensible thermal storage relies on increasing the temperature of a material that returns a large share of heat when cooled.
- Latent thermal storage relies on the energy absorbed or released during a phase change in a material with a small temperature range.
- Thermo-chemical storage uses chemical components, which store heat through changes in their chemical bonds. The chemical reactions are reversible to recover the heat when necessary.

2.2.5 Electrical – supercapacitors

Electrical storage is considered the only pure electricity storage since it stores energy in the form of electrons. In contrast to batteries, only electrostatic effects are used for the storage of the electrical energy.

The most developed technology in this category is the Electrochemical Double Layer Capacitor (EDLC), which is based on the electrostatic effects between two separated carbon electrodes.

Figure 10 illustrates the working principle of the Double Layer Capacitor.

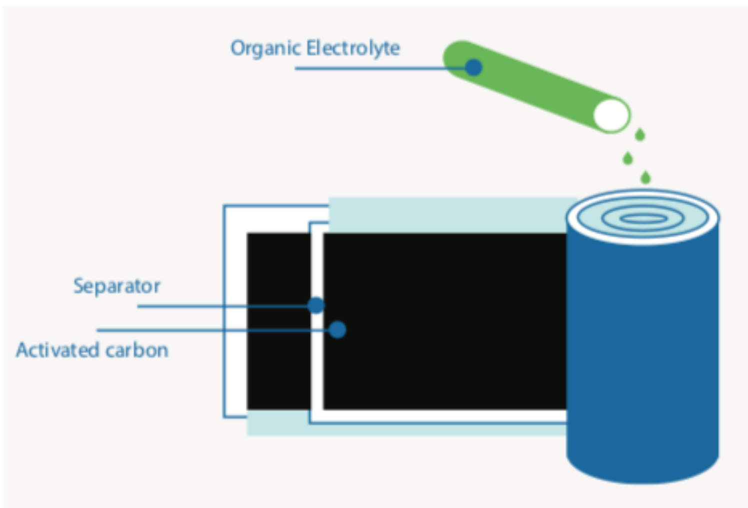

Figure 10: Basic EDLC design [5]

The electrical storage is able of providing a high power output during a very short response time. The discharge time is very low so it is a great technology for very short-term storage applications. In addition, the efficiency is very high, up to a 90% [5].

2.2.6 Summary technological indicators

Figure 11 shows the classification of the different technologies according to their storing size (kWh) and their discharge time (s).

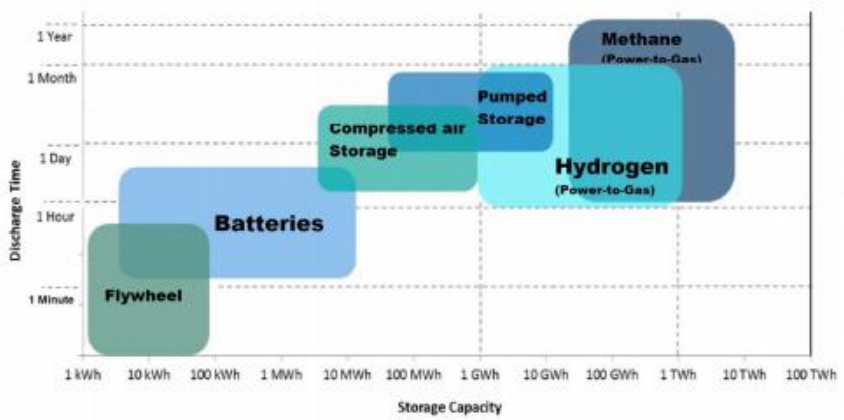

Figure 11: Classification of energy storage technologies by capacity and discharge time [3]

Table 1 shows the main technical characteristics of the technologies analyzed before.

Technology	Max * power	Max * energy	Efficiency	Time response	Energy density
Lithium-ion batteries	50 MW	100 MWh	90-98%	Milliseconds	180 Wh/kg
Lead acid batteries	Some MW	10 MWh	75-85%	Milliseconds	35 Wh/kg
NaS batteries	50 MW	400 MWh	70-80%	Milliseconds	206 Wh/kg
Flow batteries	Some MW	Some MWh	70-75%	Milliseconds	25 Wh/liter
Pumped Hydro	3 GW	100 GWh	70-85%	Seconds-minutes	3 Wh/kg
Power-to-Gas	1 GW	Some GWhs	20-40%	Minutes	2550 kWh/m^3
Supercapacitors	Some MW	Some kWhs	90%	Milliseconds	7 Wh/kg

Table 1: Summary technical characteristics of storage technologies

* Based on real projects

2.3 Economic aspects

Although some storage technologies are still being developed and research is being carried out, it can be said that the technology is mature from a technical point of view.

However, from an economical point of view, the technology may not be ready to be implemented. The most important indicator to analyze the cost of an storage technology is the LCOS, Levelized Cost of Storage. LCOS may seem similar to the Levelized Cost of Electricity (LCOE) but it does not represent the same concept since both activities, storage and generation, are radically different. The LCOE represents the average cost per unit of energy produced and the LCOS focuses on the use of the energy stored, since not always participates in the energy markets.

The definition of LCOS is under discussion, mainly because it is a new concept and it cannot be defined until storage or the possible applications it may serve are well defined too. The cost of the storage depends on the technology and on the application it serves, that is why some authors talk about an indicator based on capacity (€/kW) and another based on energy terms (€/kWh).

Although the formula for calculating the LCOS is under discussion and depends on the author consulted, it is simplified as the following:

$$LCOS = \frac{Capital\ cost + Energy_{IN}\ (\$)}{Energy_{OUT}\ (\$)}$$

Which represents an income for the amount of energy discharged (Energy out) and a cost for the energy charged (Energy in) and the capital cost.

The LCOS varies according to the application the storage asset is used for, since the costs for charging and the revenues obtained vary as it will be explained in the next section. The consultancy firm Lazard [7], carries out every year since 2015 a study analyzing the evolution of the LCOS for several storage technologies. This study is based on industrial and commercial solutions with empirical data of revenues and costs. Although it is not based on a formula or calculations, it provides a very illustrative snapshot of the market situation.

As it can be seen in Figure 12 and Figure 13, the scenarios analyzed in 2018 have been different battery technologies in what they call “In front of the meter” and “Behind the meter” applications. The most economically efficient solution are Lithium-ion batteries for utility-scale applications followed closely by the new technology of flow batteries based on Zn-Br.

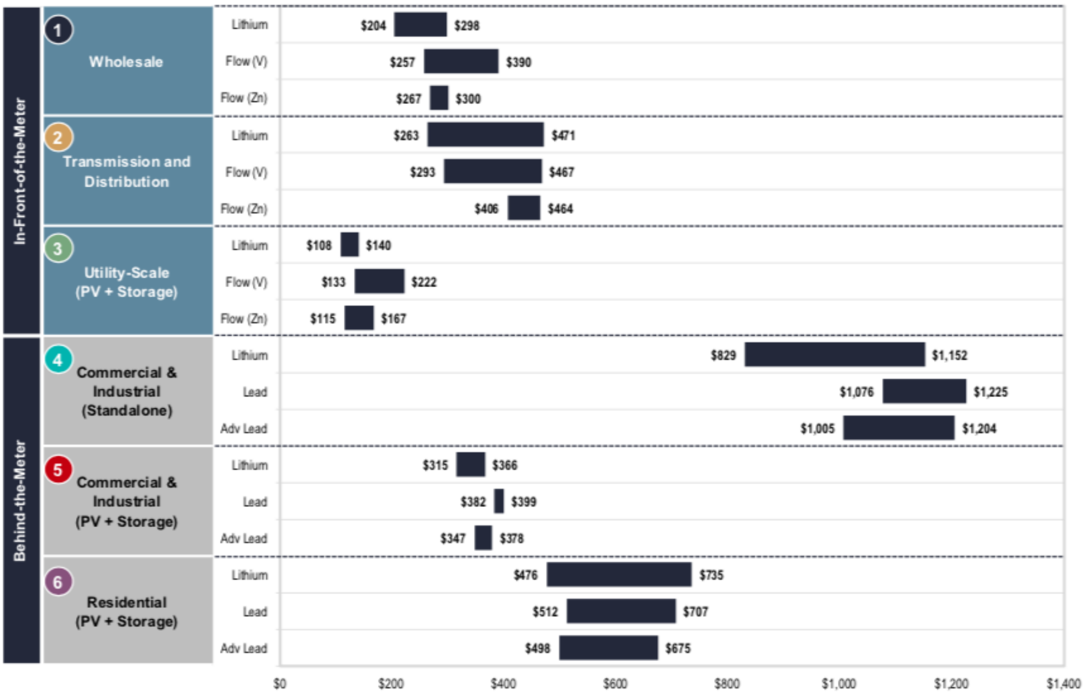

Figure 12: Levelized Cost of Storage ($/MWh), [7]

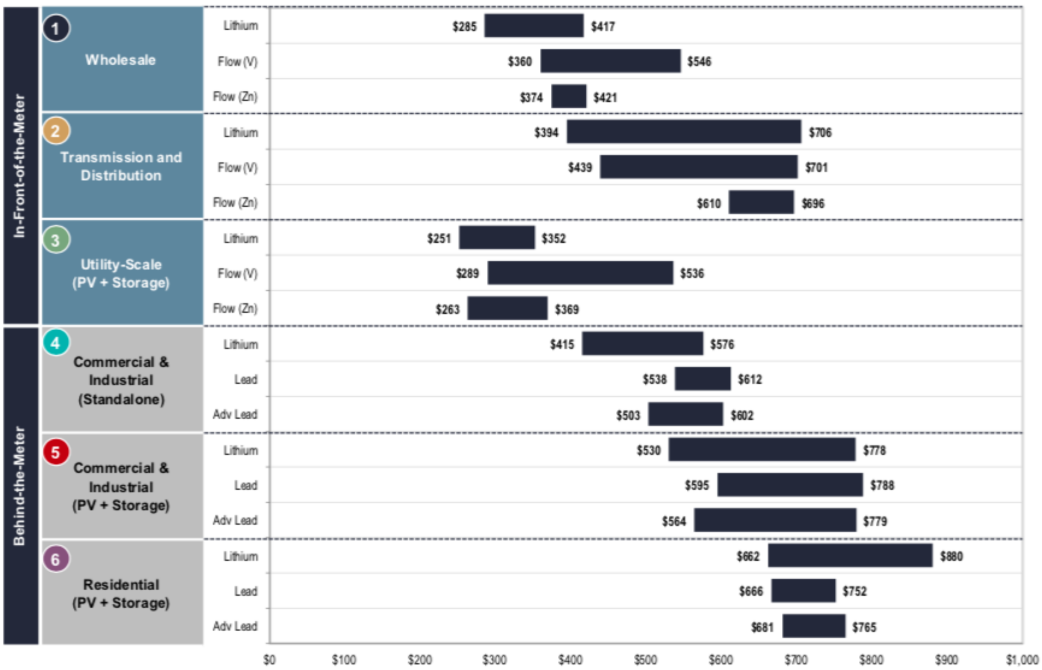

Figure 13: Levelized Cost of Storage ($/kW-year), [7]

Figure 14 shows the evolution of the capital cost of these technologies. As it can be seen, the capital cost of batteries is experiencing a reduction trend, which is more acute for Lithium-ion and Flow Zinc batteries. The main reason for this cost reduction is the presence of economies of scale in the production of Li-ion batteries due to the research and great development carried out by leading agents in stationary applications and electromobility. The formulation of enabler regulation for the development of battery markets is also a remarkable driver for the technology development.

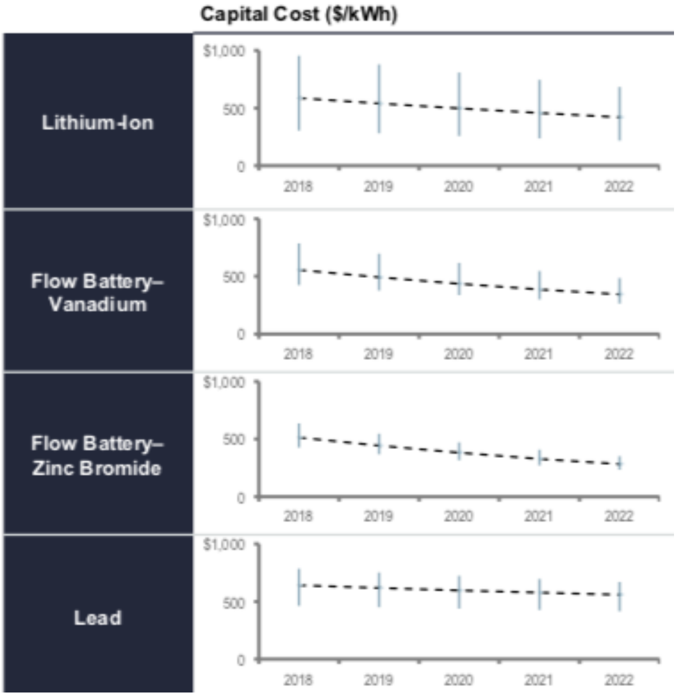

Figure 14: Capital cost outlook by technology, [7]

In the next section, the applications of energy storage will be analyzed focusing on electrochemical storage, most known as batteries, and the reasons why they are being developed so fast.

3 Applications

3.1 Introduction

Currently, the applications of these technologies and their classification are also under discussion. The stakeholders mentioned in the previous section, utilities, governments, regulators…, present different classifications according to their interests and their geographical influence. In some regions some applications are more interesting than others mainly due to the design of the power systems.

In order to design an appropriate regulation that allow energy storage to compete against conventional technologies, it is a key factor to analyze which are the applications of storage to be efficient and technology neutral.

The objective of this section is to define a common classification that makes sense for every stakeholder of the sector, and it will be done according to several criteria.

The existing classifications divide them according to three main factors:

- Time scope: short-term, daily or long-term.
- Beneficiary: agents or the system.
- Use: energy or power.

In this section, the applications for energy storage technologies are described and analyzed. The main focus of this section is to present the proposals present in the literature and reformulate the classification according to the opportunities to create value and generate business. Also, it tries to clarify the common points and resolve the possible overlaps among them.

3.2 Time scope classifications

IRENA [8], the International Renewable Energy Agency, defines the different time scopes as the following:

- The short term storage relates to applications in which the charging and discharging [8] happen between seconds and a few minutes. For these applications, high power technologies are well suited, such as electricity storage systems or mechanical flywheels. Li-ion batteries are also presented as a good solution.
- Daily storage is defined as applications in which charging and discharging processes occur between minutes to several hours. The most appropriated technologies for these applications are electrochemical batteries, as well as, pumped hydro storage and compressed air storage.
- The long term storage features applications in which energy is stored for weeks or months, that is why it is also called seasonal storage. The most common technologies for storing energy long periods of time are power-to-gas, which relies on gas storage systems, or pumped hydro storage, which relies on the high reservoir capacities. Also, flow batteries will allow for weekly storage as investment costs are being reduced. According to the WEC [9], these technologies will allow applications such as bridging periods with low renewable production to high ones.

3.3 Beneficiary related classifications

Secondly, the beneficiary variable will be analyzed, that is, who is the stakeholder that benefits from the storage technology. The institution IRENA [8], mentioned before, states three groups of applications:

3.3.1 System operator: grid services

With the decrease of thermal power plants and the lack of inertia associated, services such as frequency control have to be provided by the new agents entering the market, essentially renewable energy sources and energy storage. The main characteristics needed to participate in grid services are fast response times and great scalability, then making battery storage systems a great candidate for these applications.

3.3.2 Final consumers: behind-the-meter applications

These applications relate to self-consumption through distributed generation from storage systems. The main objective of these applications is to reduce the electricity bill by reducing the amount of energy consumed from the network. Energy storage systems allow for peak shaving and valley filling in order to level the load curve and shifting the electricity grid consumption from the expensive hours to the cheap ones.

3.3.3 Isolated consumers: off-grid applications

Energy storage, alongside with renewable energy sources, is being used to replace diesel generators in off-grid areas, usually rural places or islands where there is no access to the grid. Storage systems allow a clean energy supply for remote locations by reducing the emissions and noise from diesel generators.

3.4 Use related classifications

However, this classification fails to define the sector in which energy storage technologies can be applied, which can lead to wrong conclusions when dealing with liberalized and regulated businesses. For this reason, the last analysis will take into account the use variable, which basically divide applications into power or energy applications. In power applications, the most important characteristic of the technology is the ability to provide a great peak of power during a short time. However, in energy applications, the key ability is to provide energy during a long time, no matter which is the peak provided.

In this context the EASE and EERA published a Roadmap in 2017 [4] explaining the existing applications at that time. As said before, since this market is being shaped and it is not mature enough, this classification is considered to be outdated. However, for the purpose of explanatory reasons, the classification from 2017 will be analyzed.

Generation	System Operation	Transmission	Distribution	Retail
Ancillary services	Ancillary services	Congestion (avoid redispatch)	Voltage control	Peak shaving (kW)
Arbitrage			Congestion management	Time-of-use management (arbitrage)
Capacity firming			O&M	Self-production (PV)
			Microgrids	Microgrids
			Quality service	

Table 2: Energy storage classification according to EASE & EERA, [4]

As seen in Table 2, the analysis by EASE-EERA defines applications for each of the sectors of the value chain for electricity production.

3.4.1 Generation

For the generation sector, both conventional and renewable energy sources but especially RES technologies, the main applications that provide a value to the agent are the arbitrage, the participation in remunerated ancillary services and the capacity firming.

Arbitrage consists on taking advantage of a price difference in a market to buy when the price is low and sell when it is high. In the specific field of electricity, this practice is now possible because storage allows to buy, store and sell this electricity in the power wholesale market. It will be seen later, but this application is also viable for the final consumer since it also participates in the wholesale market through its retailer. For the same reason, TSOs and DSOs cannot benefit from arbitrage since they do not participate in the wholesale market as agents.

Capacity firming is especially focused in renewable energy sources, but even conventional generators can benefit from it. It consists on using energy storage to produce a constant output from a variable output, that is why it especially focused on wind and solar generation. Capacity firming allow these resources to reduce costs due to imbalances, which cannot be avoided due to the nature of the technology. These resources are open to variations in the wind or sun availability. It is important to notice that this application does not solve the problem of unavailability in the long term, but in the short-term.

The participation in ancillary services is strongly tied with the system operation sector, which sometimes makes it difficult to allocate this application. Renewable energy sources historically have not been able to provide ancillary services to the system operator. Nowadays, renewable technologies are able to participate in these services by providing downward reserve. However, with the support of storage, they are able to store some reserve energy that later can be provided as upward reserve.

3.4.2 System operation

The system operator can also benefit from energy storage, mainly because they can provide ancillary services. As said before, the benefits storage provide are very similar than to the generation sector. In this situation, the storage technology does not support a generator that participates in the ancillary services, but it is the storage technology who provides the service, and as a consequence, it is remunerated. Due to the nature of some storage technologies, a new service to provide frequency regulation is created [10] called Enhanced Frequency Response, which consists on an even faster response than the so-called Primary Regulation. To be fair with the definition of storage, which aims to give technology neutrality, every generation technology can participate in this new fast frequency regulation. In reality, due to the fast response times of energy storage, conventional generation is out of this market.

3.4.3 Transmission (TSO)

Transmission System Operators (TSOs) may benefit from storage in order to reduce congestions and manage them more efficiently to avoid market distortions. The installation of energy storage technologies at the transmission network level may help avoiding redispatches when transmission lines are congested. However, this application presents clearer benefits at the distribution level, since the technology to store great amounts of energy at the transmission voltage level is not well developed yet.

3.4.4 Distribution (DSO)

For the Distribution System Operators (DSOs), energy storage is presented as an asset that can provide voltage control, congestion management and quality service improvement. In addition, the application of storage to microgrids is quite interesting and it is quite related to the retail sector as well, so it will be analyzed in that sector.

The application of energy storage to congestion management allows to redirect the flows of energy in the network to avoid congestions and increase efficiency, as explained for the transmission network level. In addition, storage can help with the network control by controlling the voltage of the nodes, as it helps controlling the frequency at the transmission level.

When talking about quality service improvement, it is very important to remind that distribution networks are designed meshed to provide reliability to the system. The installation of energy storage devices along with distributed generation may allow to redesign the network in a radial configuration thus reducing the cost of breakers and control components and increasing the quality of service when a fault occurs. Also, batteries might be presented as a great alternative for diesel generators that are usually used during the clearing of a fault in the grid. Storage, altogether with distributed generation, might help to improve quality of supply by facilitating the operation of grids in island mode.

3.4.5 Retail

Currently, due to market dynamics, the retail sector is where storage is more present. The applications it has for the final consumer are very clear since they provide simple and transparent savings for the clients.

Storage provides peak shaving to the clients, which allow them to reduce their contracted capacity thus reducing their electricity bill costs. Peak shaving means to avoid the appearance of peaks in the load curves of consumers. Storage technologies use the excess of electricity stored to provide energy when peak demand appears, so from the point of view of the grid, the consumption looks flat.

However, the application that provides greater value to final consumers is arbitrage. As explained before, it empowers the consumers to manage their consumption and allocate it according to different hours of the day.

Household consumers or industries with PV installations for self-consumption can also benefit from the storing capacity of these technologies, which allow them to avoid supply intermittency and even becoming prosumers who sell their energy excess to the grid.

In microgrids, storage provides a great support for the generation units present, while providing congestion management. Since microgrids, by definition, are isolated from the network, storage technologies allow the management of the energy that flows in the microgrid.

3.4.6 Heating sector

In the European Energy Storage Roadmap published in 2017 by EASE and EERA [4], energy storage applications are divided into the electricity and heat sectors mainly. The great majority of applications apply to the electricity sector, as shown before. However, in the heat sector, which is not the focus of this thesis but it is important to mention, the applications include district heating system, in which storage is used to decouple electricity and heat generation or to overcome unexpected shutdowns, and industrial processes. Thermal energy storage in the industry allows guaranteeing the continuity of supply of heat produced from renewable electricity and flexibility in the operation of cogeneration plants. Last but not least, thermal energy storage can be used to increase the efficiency of industrial processes by storing the heat waste for electricity production.

3.5 Proposal

The classification proposed for this thesis will follow the criteria presented in the definition of storage and is presented in Figure 15.

First of all, energy storage applications should clearly differentiate between two sectors that are currently the ones driving investment and research in these technologies. These two applications are storage for electromobility and stationary applications, in which it can be seen a clear difference in the location deferral of energy generation and consumption. Although at first sight the limits between these two sector may look clear, great research is being carried out in the field of Vehicle-to-grid applications, which might be the boundary between electromobility and stationary applications.

Secondly, with a focus on the time scope, stationary applications should be divided between short-term, daily and long-term applications. As explained before, short-term ranges from seconds to minutes with a focus in power applications, daily includes power and energy applications from minutes to hours and long-term contains applications in which energy has to be stored from days to weeks or even months.

Short-term applications may include the support to generation assets by capacity firming or ancillary services, or even the participation of standalone storage in these services. Also, for the distribution system operators it can provide network control.

The daily applications are mainly focused in obtaining a benefit from the variable demand and market prices from arbitrage or peak shaving applications. For DSOs, storage is a very interesting solution to avoid congestions that may occur on a daily basis.

Finally, the long-term applications are focused on avoiding curtailments of renewable electricity by storing the excesses on technologies that allow for storing long times, such as Power-to-gas or Pumped Hydro Storage.

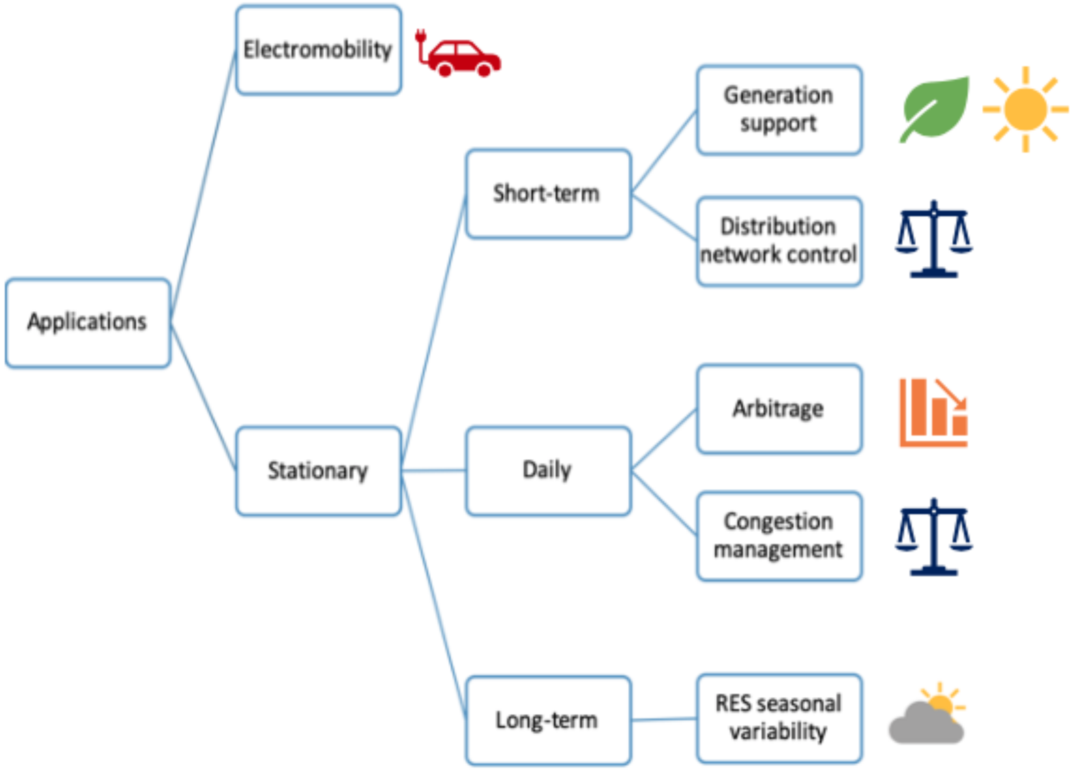

Figure 15: Energy Storage applications classification

In the next section, the market dynamics of batteries are analyzed. The focus is on batteries since it has already been stated in this work that they are the most developed technology and present a wide range of applications, with the only exception of long-term storage.

4 Market Dynamics

4.1 Introduction

In the previous section the applications of energy storage have been defined and explained in order to provide a better understanding of the possible sources of income from these technologies.

It is important to notice that currently the great majority of these applications are being driven by electrochemical storage technologies, more specifically, by Lithium-ion batteries. The reason behind this is that Li-ion batteries have been developed and optimized by the automotive industry which uses them for the Electromobility application, and also they present great characteristics (power, energy and reaction time) for short-term and daily applications. As said before, long-term applications need of Power-to-gas or mechanical storage technologies.

The production of batteries involves a great amount of agents who participate in it, from the extraction of the raw materials to the delivery to the final consumer, what is most known as the value chain. The value chain of batteries can be seen in Figure 16.

Figure 16: Value chain of the production of batteries

However, the value chain is not well defined yet, since the market is not developed yet. As an example, the number of companies that focus only in the pack manufacturing is very reduced. Due to the synergies between cells, packs and batteries, companies focus more on producing the whole product or just the cells rather than the packs alone.

In this section, the market dynamics of Li-ion batteries will be analyzed in order to understand how the economic and market aspects can affect the agents that will in the end benefit from energy storage.

4.2 Raw materials

Lithium-ion batteries are made of metals which are used for the cathode and anode parts and also chemicals or plastics used as electrolytes and separators. According to the different battery generations, the materials used for the cathode and anode change and evolve to more efficient configurations.

Currently, the most common materials for the battery cathode are $LiNiCoMnO_2$, known as NCM, and $LiNiCoAlO_2$, known as NCA. The anode is composed of carbon and silicon. As generations evolve, the ratio of Nickel increases, to provide a higher energy density to the battery cells, up to NCM 6:2:2 or NCM 8:1:1. Also, the anode evolves by including silicon to maximize performance and longevity [11].

The supply of these materials is ensured by three ways: the supply from external countries, the supply from domestic sources and the supply from recycled batteries [12].

As it can be seen in Figure 17, the production of battery raw materials is very concentrated in a few countries. In particular, 64% of Cobalt comes from the Democratic Republic of Congo and 69% of graphite comes from China, which might give these countries a dominant position in the batteries market. Although the production of Lithium is more scattered, the majority of the world's Lithium refining facilities are located in China, which ensures the dominant position it already has. This situation is far from the optimal since the provision of raw material is in hands of countries with a high geopolitical and humanitarian risk.

From the European perspective, the production of raw materials and its future potential is shown in Figure 18. As it can be seen, the domestic supply of raw material, with the exception of Cobalt, is very limited and might provide a supply risk for the battery industry. The key aspect is that producing the materials in Europe is not competitive due to the low prices from China and Latin America although the deposits exist and are potentially viable.

Finland presents itself as the major supplier of Cobalt, accounting for almost 66% of the whole production in the European Union.

In the future, the production of Cobalt, Nickel and Lithium will increase considerably due to the increase in the demand of these materials for batteries, as it is shown in Figure 19.

As a result, by 2025, 60% of the production of Cobalt and 70% of the Lithium one will be intended for batteries. As the production increases in order to meet the increasingly demand of batteries for electromobility and stationary applications, the unitary cost will observe a decreasing trend.

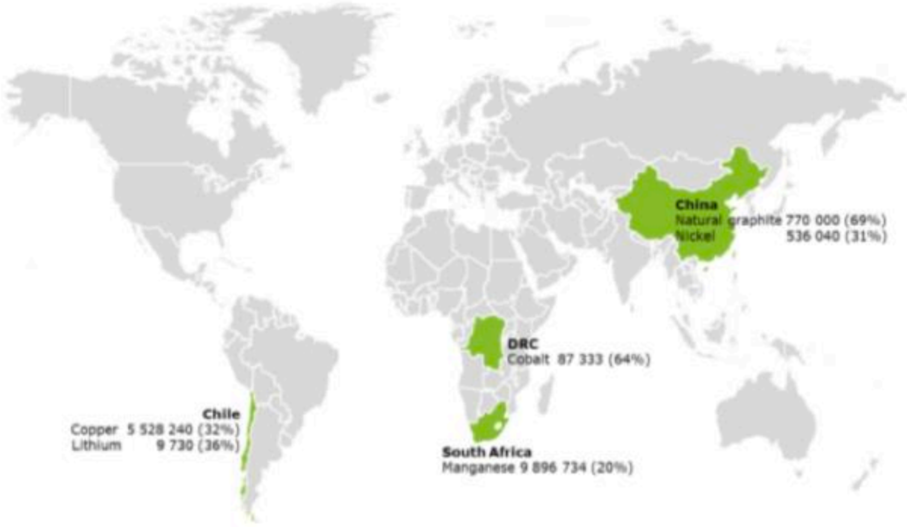

Figure 17 Countries accounting for largest share of global production of battery materials, [12]

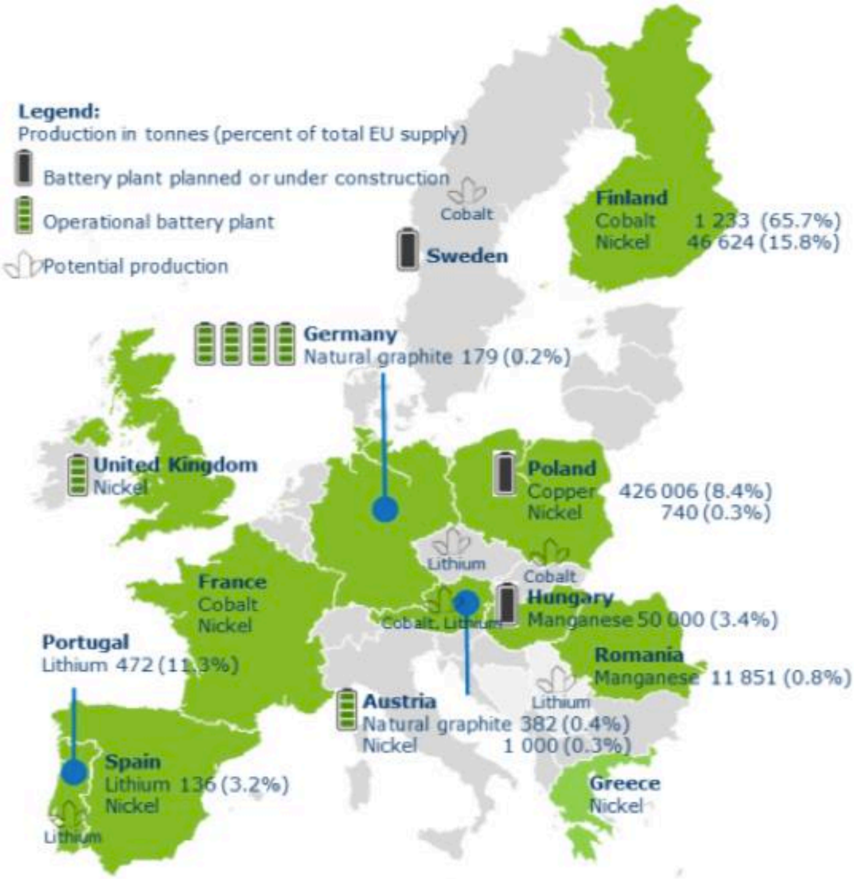

Figure 18: Mine production and potential of battery raw materials, [12]

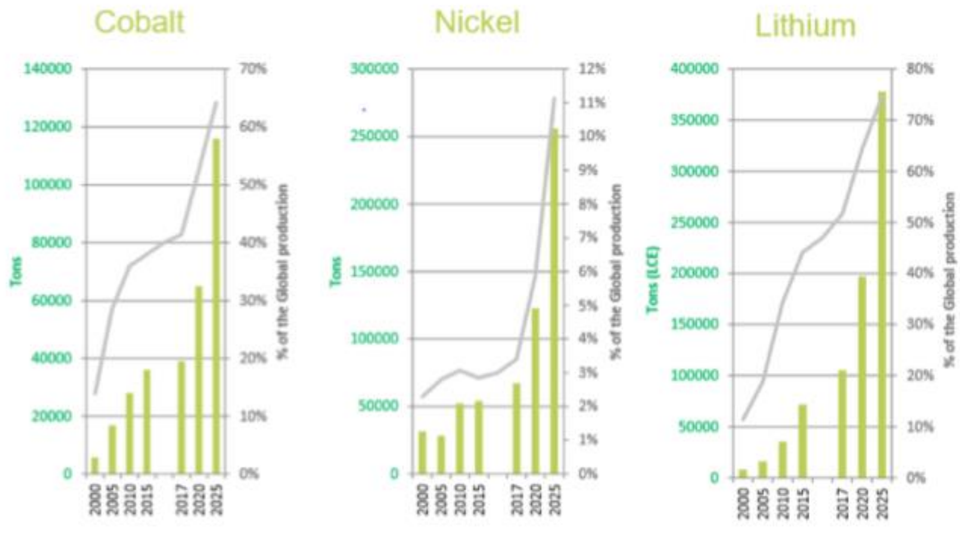

Figure 19: Metal production for batteries, [12]

4.3 Battery cells

The raw materials mentioned before are used to manufacture cell batteries, which will later be assembled together to form packs or battery modules.

The cost trend for battery cells in the recent years can be seen in Figure 20. In addition, the future cost of a complete battery pack can be seen in Figure 21. The cost of the battery cells will follow the same trend as in Figure 20.

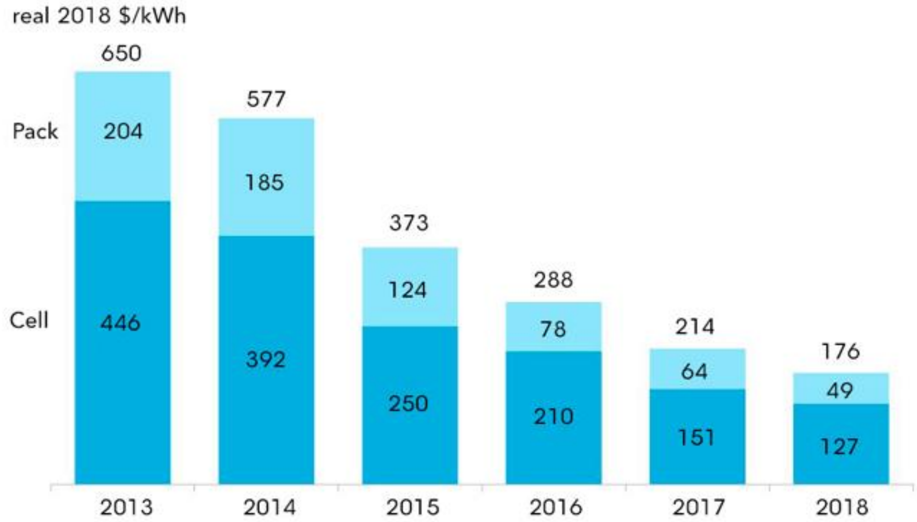

Figure 20: Lithium-ion battery prices: pack and cell split, [13]

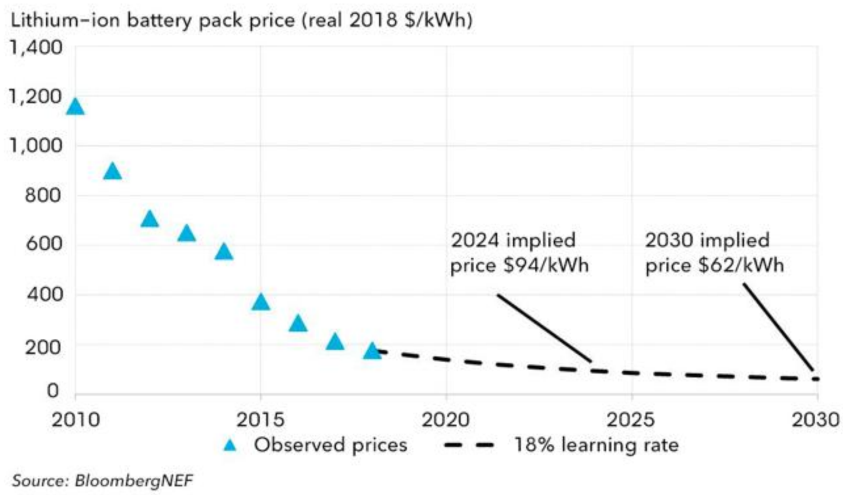

Figure 21: Lithium-ion battery price outlook, [13]

Table 3 shows the main producers of battery cells worldwide. However, as it has been said before, it is very difficult to stablish the limits between producing cells, packs or the whole battery module. Companies are starting to integrate in their processes the production of batteries, from the raw materials to the final product.

Company	Country
Panasonic	Japan
BYD	China
LG Chem	South Korea
CATL	China
Samsung SDI	South Korea
GS Yuasa	Japan
A123 Systems	United States

Table 3: Battery cell producers worldwide

Regarding the market structure, almost all the production of cells worldwide occurs in Asia, being Japan, South Korea and China the leaders of this industry. This leadership is driven by the automotive industry which has positioned in favor of the electromobility as the future of it. In addition, Asia has been investing in technology development and research which has favored the appearance of the technological companies that now lead the battery cell market.

4.4 Battery modules

Nowadays, Lithium-ion batteries are being produced mainly to meet the demand from the automotive sector and to supply stationary applications. Due to the different characteristics of each industry, the manufacturers do not usually supply both sectors.

In the electromobility industry, the main leaders are Asian companies. However, it is important to mention the company Tesla, from the United States. Tesla is by far the leader of the American market, and it is already introducing itself into the Asian one. A new Gigafactory, which will allow Tesla to produce its Model 3 in Shanghai, is currently being built and will be finished by the end of 2019 [14].

From the utility-scale point of view, battery producers usually act as distributors as well. However, the figure of a distribution company which buys the batteries and installs them in the clients site is not dismissed. The great leader in this sector is the before mentioned company Tesla, which does not only produce electric cars but batteries solutions. When you purchase a Tesla battery pack, the company provides you with the installation service as well as customer support services. In addition, it might be interesting to study how the market will evolve, as customers will increasingly demand these products to their utilities. Utilities should be aware of this market trends to not lose the opportunity to become battery distributors and position themselves as leaders in this new market.

It is important to mention that although Europe is not currently a leader in the production of batteries, it is trying to position itself as a leader region in which they believe it will be the next revolution. France and Germany have created an alliance in which they will invest 700 millions and 1000 millions euros respectively until 2022 to produce batteries. Their ambition is that these factories will produce batteries to cover between 20% and 30% of the worldwide demand in 2030 [15].

4.5 Final consumer applications

Although the great majority of battery suppliers are located in Asia, the final consumers of this solutions are located in Europe and the US.

The trend of storage deployment worldwide can be observed in Figure 22. The estimation presents a great increase of storage projects at utility scale. Moreover, according to Lazard [7], the key issues for the increasing in this trend might be explicit policies, performance-based incentives and favorable market fundamentals.

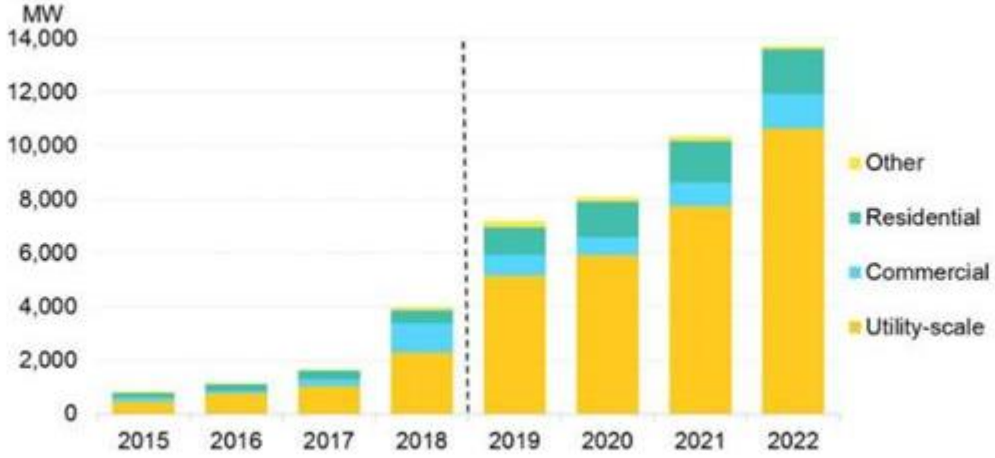

Figure 22: Annual global storage deployments, Bloomberg

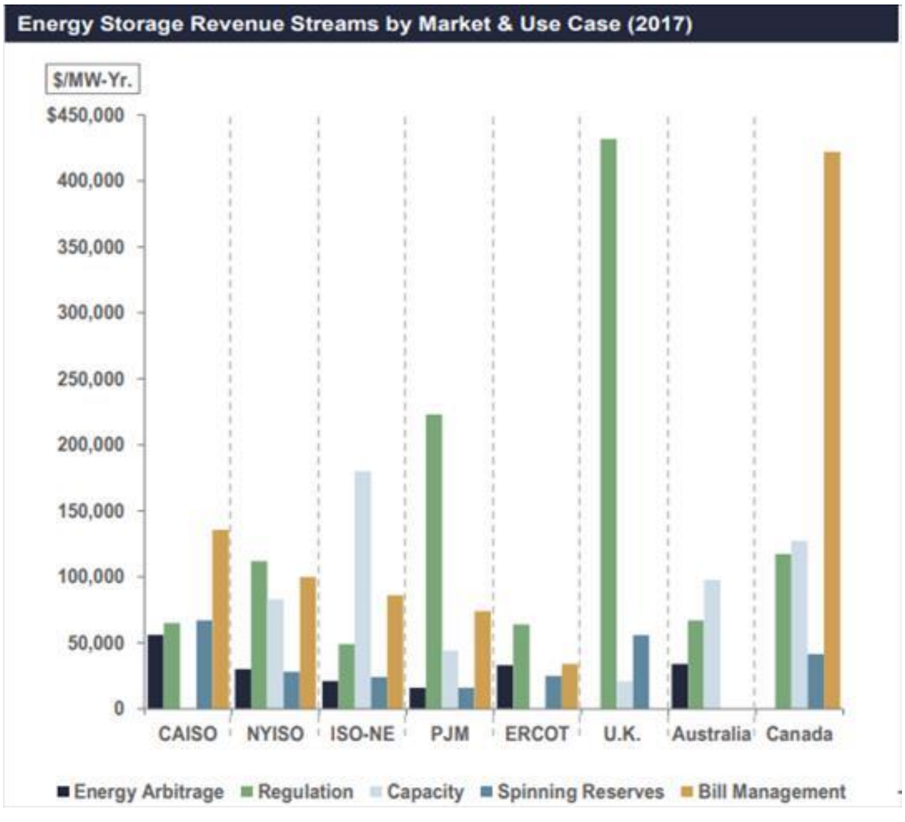

Figure 23: Energy storage revenues at utility-scale, [7]

As it can be seen in Figure 23, the development of utility-scale applications is greatly affected by the regulation present in every system. California has developed a target policy fixing objectives of 1325 MW installed for 2020. Also, it has provided subsidies of $45M for battery deployments.

In Europe, France and Germany are the great leaders of battery storage. France has developed the "EDF Plan de Stockage Electrique" which aims to implement 10 GW more of storage by 2035 around the world [16].

Regarding the automotive sector, the sale of electric vehicles is surprisingly high in the Nordic countries of Europe, especially in Norway. However, in absolute terms, the leading countries are China and the United States, as it can be seen in Figure 24.

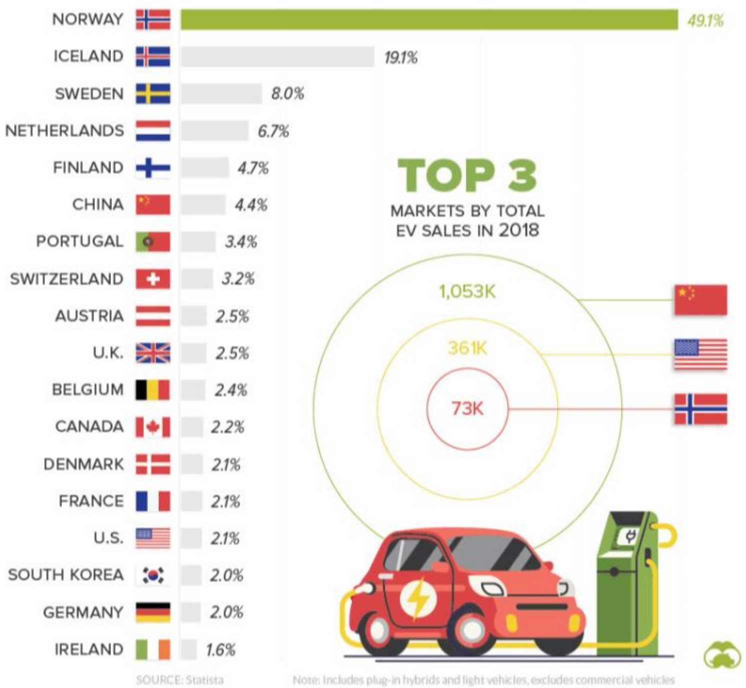

Figure 24: EV sales by country in 2018

5 Regulation policies

The objective of this section is to analyze the regulatory framework around battery storage according to some key issues. Within each regulatory aspect, the main barriers and good practices found will be explained as well as the influence they might have on the business models that will be developed later in the next section.

5.1 Market design

In the European Union, the electricity sector is currently regulated by the Electricity Directive (Directive 2009/72/EC) and the Renewable Energy Directive (Directive 2009/28/EC) among others. These directives include definitions for generation, transmission, distribution and supply but not for the term energy storage. The European regulation includes energy storage as a generation asset and not as a separate component of the electricity production value chain. The absence of a definition for energy storage is considered a great barrier for the introduction of these technologies. The characteristics of storage are quite different to the generation assets so comparing them from a regulatory perspective represents a lack of competitiveness. The definition of storage is the first step for presenting the rules that would regulate the participation of these assets in the energy markets or the services they can provide for system operation.

Recently, the European Commission has included a definition of energy storage in the new "Clean Energy for All Europeans" proposals, as it is stated in 2.1 . However, energy storage still is considered as a generation asset, which can be considered a barrier since the characteristics are not the same. While generation power plants only produce electricity, storage assets need to consume it, charge, and produce it later, discharge.

In the short term, this charging and discharging process presents a problem in the day-ahead market. Energy storage operators submit complex bids for the purchase of energy when the prices are low and the sale of it when prices are higher. These bids consist on linked block orders to make sure that the asset will not be committed for an infeasible operation point. In addition, these orders include a minimum income condition so that the selling order compensates the purchase one and generates a profit. Although it may seem a great solution for the operation of energy storage assets, this bidding format does not optimize the operation of them since the operators must forecast beforehand in which periods place the orders. This situation presents a risk on the volatility of prices that makes revenue streams difficult to predict, therefore moving away investors.

In the long term, storage assets should be allowed to participate in the Capacity Remuneration Mechanisms, as it happens in the US. According to the FERC Order 841 [17], batteries are allowed to de-rate their capacity to meet duration requirements. In California or New York, the required time for participating in the capacity markets is 4 hours, so a 1 MW/ 1 MWh battery should bid 0,25 MW to fulfill this requirement. Small resources are also allowed to participate in these markets through aggregation, to avoid penalties for underperformance.

5.2 Ownership

The ownership of energy storage assets is considered to be a hot topic in the regulation of several power systems. While in the European Union the ownership of storage is forbidden to regulated entities for unbundling reasons, in the US it is allowed.

Energy storage facilities may provide network services as frequency regulation or congestion management in a more efficient way than generation assets currently due. Some storage technologies present faster response times than generation plants which make them ideal solutions for frequency regulation. However, system operators owning these assets should not be allowed to operate them since they may obtain benefits from the free markets.

TSOs and DSOs are considered as natural monopolies and therefore, their allowed revenues are regulated by the regulatory authority. Allowing these entities to participate in the markets is considered as an abuse of dominant position since they are monopolies. According to the new directive on market design of the Clean Energy Package [18], released on June 2019:

"Distribution system operators shall not own, develop, manage or operate energy storage facilities."

Only in exceptional situations, in which no other market party is interested in providing a storage service or cannot deliver it at a reasonable cost, and these facilities are necessary for the DSOs to fulfill their obligations and the regulatory authority has approved it, the system operators are allowed to invest in storage facilities. In these cases, the regulatory authorities should periodically reassess the interest of market parties involved in that activity.

The ownership issue is presented as a barrier for the development of storage facilities because the full potential of these technologies is lost. The regulatory challenge is to guarantee that storage assets can create value by participating in the energy markets and by providing services to the system operator. A solution for this problem might be the business model known as local markets [19].

Since system operators are not allowed to own and operate storage facilities, this business model defends the possibility of hiring network services from private owned storage assets. The owner of the facility could provide network services to the TSO or DSO and also, participate in the energy markets every time it is not committed by the system operators.

This solution is well defined especially for distribution grids, in which the location of the assets is critical for improving quality of supply and congestion management. In addition, this business model would introduce a great number of small players into the market improving competition and transparency in a local area.

5.3 Network Codes

As explained before, currently storage assets are treated as generation assets although their technical characteristics differ considerably. The main difference between these two technologies is the decoupling between power and energy production. Currently, the cost of battery storage for power applications is low, but for energy applications is very expensive. In this context, batteries are considered a great solution for fast response situations, as frequency regulation, but not so great for continuous energy ones.

The Network Codes dictate the technical standards that facilities participating in the market have to comply with in order to operate in the market. Although storage is allowed to participate in the markets, these rules are defined for generation plants and loads.

The main barrier found in the Network Codes for the deployment of storage at utility scale is the required time for providing reserves, which deeply affects the costs of facilities providing these services.

ENTSO-E has proposed in the Network Code on Load-Frequency Control and Reserves (LFCR) that units providing Frequency Containment Reserve have to be able to activate its capacity for 30 minutes or more. Currently, in the majority of Member States this required time is 15 minutes [20].

Although it may seem that the increase of the time period is not a great concern for generation assets, for storage facilities this increase from 15 to 30 minutes has a huge financial impact. This increase means that batteries have to be able to provide twice the amount of energy as previously. Existing facilities may not be able to provide this service anymore, and for future facilities this supposes a huge increase in the cost of the battery. The application of this Network Code will delay the development of a competitive technology, which is very promising for these specific applications since it brings flexibility into the systems. Not only it will damage the future of batteries but it will increase the cost of FCR services and therefore, the cost of electricity.

New regulations should be technology neutral in order to avoid damaging competition and the entry of new participants in the markets. Also, ENTSO-E should be able to demonstrate that the extension to 30 minutes of the activation time for reserves is fundamental for the system reliability. Otherwise, it should be kept at 15 minutes in order to not discriminate energy storage technologies damaging its development.

5.4 Tariff design

Another regulatory discussion around energy storage is the possibility of imposing double fees and taxes to these facilities with the existing tariff frameworks. Storage assets consume electricity when charging and inject it back into the grid when discharging. Since in some Member States of the EU, both processes are being taxed, consumption and production, energy storage owners have to pay double fees [21].

First of all, this situation is not the same in every Member State and it is important to set common rules to avoid differences. The tariff framework does not have to be the same since it has to reflect specific issues of each network but every framework should focus on common guidelines. Otherwise, a storage facility could be installed in one country with favorable regulation to provide cross-border services to other state with a more restrictive regulation, and this way obtain a benefit.

The second main point is that regulation should set a tariff based on the concept of cost causality, in which the costs caused by storage assets are recovered. Since nowadays storage is a marginal technology, if they do not pay for the grid they use, other users might pay for it and the effect is almost negligible. However, when the implementation of this technology will be global, the tariff should represent with accuracy which costs are due to storage facilities and charge for the net injection or withdrawal of electricity.

It is important to mention that storage assets might provide services to the grid regarding quality of supply and investment deferral. This way, providing these services might lower the cost impact they have on the grid and eventually they could even earn a profit, which could be recognized by means of a tariff reduction.

Finally, another important issues are that tariffs designed with long netting intervals kill the incentive for storage since they use the grid as virtual storage. Also, another barrier for storage are the tariffs without time discrimination because the incentive for arbitraging is eliminated.

5.5 Battery market creation

With the appearance of energy storage and the growing role that batteries will play in power systems and in the electro mobility sector, the possibility of developing a technology market in Europe arises.

According to some forecasts, Europe could capture the value of this market which accounts for 250 billion € each year from 2025 onwards. In order to do so, it will need to build between 10 to 20 Gigafactories, which are battery cell mass production facilities.

To take advantage of this situation, the European Commission has drafted an Strategic Action Plan for batteries which aims to put Europe in the leader position in a key industry for the future. The Commission plans to cover the whole value chain of the battery production focusing on sustainability while supporting jobs and growth in the economy [22].

Regarding raw materials, the strategy aims at securing the access to these materials for the European Union. The three key issues are the sourcing of raw materials from outside of the EU, the domestic production of these materials and the supply of secondary raw materials from recycling batteries.

At the production scale, the Commission plans to support European battery cell producers by bringing industry players together and creating partnerships among the different Member States. This support has to be strengthen through research and innovation in conventional and new technologies. Research is crucial in the batteries sector since it is a mature technology that has not been consolidated yet. Also, the Strategic Action Plan aims to develop a highly skilled workforce to make Europe an attractive location for experts in batteries production.

The European Commission plans to implement these solutions to position itself as a leader in the battery production market while supporting the sustainability of the processes by reducing the carbon footprint to the lowest and ensuring consistency with a regulatory framework that supports batteries and storage.

Finally, the Commission asks the European stakeholders to take a step forward and develop industry projects to establish a competitive battery value chain in Europe. Also, it calls on the participating Member States to support these projects with national instruments and funding mechanisms and accelerate the permitting procedures for these initiatives based on the battery value chain.

6 Business models

6.1 Introduction

The applications discussed in the previous section can be summarized into six categories, that will help to define the business models that create value for batteries. These categories are RES generation support, system services, energy management, aggregator, electromobility and long-term storage.

Batteries are not currently focused in providing value for long-term storage applications since more research and technology development is needed in order to be competitive against other technologies such as Power-to-gas or Pumped Hydro storage. However, is it important to mention it as in the future this situation might change.

Also, although batteries are the most developed storage technology in the automotive industry, the purpose of this document is to analyze the business models at utility scale. The business models related to this sector will be mentioned and briefly explained but not studied deeply, since they take advantage of the EVs batteries, during the charging or during their second life, from a stationary perspective.

Within RES generation support are included applications in which batteries provide either power and energy services. Batteries facilitate renewable power plants to participate in the markets.

Moreover, batteries can provide system services by themselves, what is better known as a standalone installation. The main problem that this model presents is that from a regulatory perspective the property of storage assets is being discussed. In Europe, TSOs and DSOs cannot own storage assets since they might provide them with an income stream from the market which is not allowed to a regulated company.

Energy management refers to the applications in which generators or consumers obtain a benefit from managing the energy they produce or demand. Storage empowers the agents to optimize their energy supply. In this scenario, it is important to study the economic feasibility of arbitrage as a revenue from the business models to be analyzed. Arbitrage might be seen as an opportunity market, in which the first entrants benefit from a great differential of prices, generating a great profit that attracts more competition. The problem is that, as new flexibility resources come into the market, the differential of prices is reduced.

An aggregator is a company that operates a set of Distributed Energy Resources, flexible demand and distributed generation facilities, in order to trade the energy and flexibility available from single clients to the electricity markets. It aggregates the generation and demand of consumers that do not have the means to operate their assets and trade in the energy markets. These service providers create an aggregated controllable load and sell it as one single resource. Aggregators help the consumers to optimize their facilities since they usually have a greater knowledge of the electric sector and better IT infrastructure to communicate with the system and market operators. The key benefit from aggregation is the diversity of the portfolio, which ensures the delivery of the service even when some individual consumers may not be operative.

This section aims to propose some business models in which batteries create value for their owners based on the applications explained before. Three business models will be developed in detail due to their current feasibility and interest for the utility sector.

6.2 Hybrid Power Plant

6.2.1 Value proposition

In this business model, the battery acts as a support for a power plant. The battery may be designed for power or energy applications, since the support and service it provides may vary. The economics of the business model are affected by the technology of the power plant, since the services needed for thermal power plant differ from those given to a renewable power plant.

From the point of view of a thermal generator, the battery allows it to manage its production and adjust its output production to the requirements of the system operator. Value is created when the battery is used for frequency regulation instead of the thermal turbine, providing a faster and more efficient service. Also, the use life of the turbine is increased.

For a renewable generator, the battery is even more important than for a thermal generator, since it also allows it to avoid curtailments which energy can be sold later in the market. This way, these power plants reduce their dependency on natural resources as the sun or the wind which are not controllable. Also, nowadays renewable power plants run at its maximum operation point to maximize their benefits. However, with the ability to store energy, they may prefer to reduce its production in order to participate in other markets such as the reserves or the balancing ones.

6.2.2 Customers and partners

The position of the Utility in this business model and therefore, the key partners and clients, may vary according to the Utility operational strategy.

In the first scenario, shown in Table 4, the Utility is the owner and operator of the battery. This case is suitable for agents without barriers for financing or for utilities with a great know-how in battery operation. Since the Utility is the owner of the asset, the technology risk is covered completely by it.

Partners	**Utility**	**Clients**
- Battery supplier - O&M - Bank	- Battery owner - Operator	- System (TSO)

Table 4: Hybrid Power Plant. Scenario 1

The key partner is the supplier of the battery, which it might conduct as well the maintenance of the facility. Also, the bank who lends the money for the battery is considered to be an important partner. The funding of the battery is a key issue since it might compromise the ownership of the asset in favor of other property schemes, as the renting.

In the second scenario, shown in Table 5, the Utility decides to rent the battery to avoid bearing the whole technology risk. This situation might be appropriate for small utilities in which the cost of the battery exceeds the budget of the project or in which the strategy of the company is to reduce the CAPEX costs.

Renting the battery for the whole life of it is more expensive than buying it, but reduces the risk considerably since this one is shared with the owner and supplier of the asset.

Partners	Utility	Clients
- Owner - O&M	- Rent - Operator	- System (TSO)

Table 5: Hybrid Power Plant. Scenario 2

The key partner is the owner of the battery, which might be the supplier as well. Since it knows better than the Utility the product, it shares part of the risk and therefore, it is more appropriate for project funding.

6.2.3 Key activities and resources

The key activity of the Hybrid Power Plant business model is the operation of the battery to participate in the markets. Wholesale markets are designed for generation and consumption assets and battery systems might find problems when participating in them. As explained in section 5.1 , the bidding format does not allow batteries to optimize its revenues since they have to predict the maximum and minimum prices the day ahead and ensure that the volume cleared for charging is the same as the cleared for discharging.

In addition, it is very important to define measures to confirm that the energy obtained from the grid during the charging process comes from renewable sources. Otherwise, the renewable power plant supported by the battery cannot be considered as a clean energy producer.

If the Utility owns the battery solution, it is responsible for performing the maintenance of the asset.

The main resources that allow this business model to work correctly are the battery itself and the control center. The control center, from which the participation in markets or ancillary services takes place can be the same as the one needed for the power plant or not. The optimal situation is to integrate the control of the battery system in the existing control center to reduce costs.

6.2.4 Regulatory aspects

One of the main barriers for this business model is the current regulation around the remuneration of the ancillary services. The remuneration of the ancillary services may be a significant revenue stream for batteries according to the system operator in every country.

In Spain, the primary frequency regulation, which is done automatically by the generators and its aim is to contain the frequency within a range when there is an outage or imbalance, is not remunerated. The reason behind this lack of remuneration is that it is done by every agent in the system and it is internalized as an operating cost. However, this way of thinking is obsolete, since nowadays there are technologies as PV panels or batteries which can produce electricity without a rotor spinning. If this service was remunerated, PV panels will need to install batteries to give this type of services and get the remuneration.

Also, in the UK the system operator has created a fast frequency regulation service, called Enhanced Frequency Response, which remunerates the ability to restore the frequency in the system ultra-fast. This service is considered technology neutral, although the time response requirements are so strict that only battery technologies have managed to fulfill them.

Another important regulatory issue that may affect this business model is the technical requirements presented in the Network Codes.

In the EU, the Network Codes include requirements for access and connection to the grid, participation in the markets and capacity allocation among others. Currently they are being revised to make them compatible with the new technologies, such as energy storage, aggregators, distributed generation and so on. The definition of the Network Codes need to consider the technical characteristics of energy storage, and batteries especially, since they are not the same as conventional generation in order to remove the barriers that are present for these technologies.

Also, it is important to consider the issue of certifying the origin of the energy that is stored in the batteries, in renewable assets. When the battery is charged with energy from the grid, this energy might come from coal or gas power plants. Later, the energy stored is feed back into the grid as renewable energy since it comes from a renewable power plant, but it is not true. To solve this issue it is interest to analyze the possibility of obtaining green certificates with the purchase of energy, which might be done with the new technology called Blockchain. Also, another ideas are that charging can only be allowed when the generation mix exceeds a certain percentage of renewables. The most restrictive solution is to forbid battery charging from the grid, which would certainly signify a barrier for this technology. This solution needs to install an independent meter for the battery, to guarantee the supply of auxiliary services to the power plant.

Last but not least, a controllable output and firm capacity reduce significantly the risk of this projects by making it easier to recover the investments costs. Thanks to the value created by batteries, investors may see an opportunity to invest in low risk projects through long-term contracts.

6.2.5 Revenue stream

According to the services provided, that depends on the client and on the regulatory aspects in each country, the revenues received by the battery may differ.

Whenever the battery is supporting a thermal power plant, the main revenues will come from the participation in the ancillary services and the capacity mechanisms. The price of ancillary services is supposed to increase in the next years since the installation of renewable energy sources is increasing. Renewable power plants, without battery support, create imbalances in the grid which will increase the price of system services or frequency regulation. Also, the battery may allow the thermal power plant to participate in capacity auctions, earning revenues for it. During scarcity periods, the battery provides a firm capacity output increasing the availability rates of the plant.

If the battery is installed to support a renewable asset, the main income streams will come from the participation in ancillary services. Batteries perform better and will take advantage of those services designed for fast frequency regulation. Also, the reduction of imbalances is considered as a great revenue for these technologies. While thermal power plants may not incur in great imbalances but when an outage happens, for renewable power plants these costs are much more important. Due to its dependency on natural phenomenon, it is very important to accurate forecast the meteorology and therefore the energy production to avoid cost imbalances. However, this is not always possible and then, being able to store energy to supply it when forecasts fail, is crucial for renewable assets. In addition, another source of income for this business model is the avoidance of curtailments. The energy curtailed may be stored and sold later into the market no matter if prices are high or low, since the energy stored would have been lost any other way.

Another revenue stream is the arbitrage in the energy markets, which is considered to be an opportunistic market. Although it might seem that in a mature market, the benefit for new facilities could be null, as the load curve is flat, it is not true. The key variable that has not been taken into account is the cost of storage. As the cost of storage is reduced, the allowed differential of prices in the market to make it profitable is lower too. In a great designed market, the equilibrium is found, and storage facilities arbitraging would obtain the revenues that compensate the investment cost. The situation is very similar to the non-served energy, in which the equilibrium is found between the energy non served and the cost of the power plant producing at the peak. In addition, it would be interesting to study the participation of batteries in capacity mechanisms auctions when investment is not recovered by arbitraging.

6.2.6 Case example

As an example, the revenues of this business model are analyzed in the Spanish system. Since the remuneration of ancillary services as primary regulation is not remunerated yet, arbitrage is the only source of income studied in this example.

The costs of the Li-ion battery are taken from the LCOS analysis carried out previously, in section 2.3 , which are around 108 and 140 $/MWh.

The revenues come from the Spanish system database [23] for the year 2018. The average daily price differential is obtained in order to assess the incomes derived from the arbitrage activity. The maximum daily price differential is found the 12nd of March 2018, 66,34 €/MWh and the yearly average value is 20,52 €/MWh.

It can be seen clearly that this business model is not sustainable from an economic perspective for the Spanish system. Not only the maximum possible benefit obtained from arbitrage is lower than the LCOS, but as mentioned in section 5.1 , the actual wholesale market bidding format does not allow to optimize the revenues from this activity. However, it has already been mentioned that arbitrage is not the only source of income. In other systems in which frequency regulation is being remunerated, these prices have reached 5000 $/MW [24], boosting the revenues of this business model and making it completely viable.

6.3 Active Customer

6.3.1 Value proposition

The focus of this business model is the battery, which helps the final consumer to manage, and therefore reduce, its electricity consumption. This business model present many variants since the possibilities in the operation of the battery are huge.

First of all, the battery may create value for a client just to manage its consumption. The battery allows the consumer to shift the load from the peak to the valley hours, which are cheaper. In addition, the battery empowers the consumer to trade the energy stored in the electricity markets and earning profits by arbitraging. However, it is important to mention that as well as in the previous business model, this solution by itself is not considered economically efficient. Arbitraging, in well developed markets, is not viable to recover the investment costs of a battery since the price differential is not wide enough. Also, it is considered as an opportunity market, which means that is not sustainable in time since as more batteries benefit from arbitraging, the price differential is reduced and therefore the revenues are reduced as well.

Secondly, the battery may support a client with distributed generation available. The synergies between distributed generation and energy storage are huge, since the batteries allow the customer to store the excess of electricity produced for the hours of the day in which this production is not available, that is, at night. Moreover, the excess of electricity produced can be sold in the energy markets. In this situation, the battery helps optimizing the production and revenues of this installation as if it was a conventional power plant. According to regulation, the client installation could participate in the energy markets and also in the ancillary services or reserves.

Lastly, from the demand perspective, the battery may allow the client to participate in the markets by selling its flexibility. Reducing the consumption during peak hours may provide benefits for the distribution system operators which may be passed to the final consumers. Currently, final consumers do not participate in flexibility auctions since they might not be interested in being disconnected from the grid during peak hours. However, if the battery supports your local consumption, you may sell your flexibility to disconnect in specific markets at good prices.

6.3.2 Customers and partners

The early adopters of the batteries for this business model are clients with a great electricity consumption that may benefit from a bill cost reduction. These clients might come from the industrial sector, which are more concerned in cost reduction and to which the electricity cost represents a great dependency in their productive processes.

Another type of clients that might benefit from the batteries are household communities in urban areas where the installation of distributed generation is not possible or the space needed for the battery is not available in their own households.

However, the vast majority of electricity consumers do not have the knowledge required to manage a battery or they do not perceive the economic benefit. For this type of customers, the electric utility may offer the possibility to operate the battery and optimize the clients energy consumption through the figure of an aggregator. The aggregator may operate the battery to shift the load, reduce the contracted capacity that depends on the peak consumption, participate in the energy markets or ancillary services by optimizing the RES production. Also, it provides flexibility services to the grid by representing the client. Aggregators benefit from what it is called portfolio effect so that small issues, as imbalances or maintenance, in individual clients do not affect their overall activity and performance.

In this business model, the position of the Utility might vary from two possible scenarios.

In the first scenario, shown in Table 6, the Utility acts as the solution supplier. It performs the installation of the battery in the clients location and ensures a maintenance plan that will optimize the operation of the battery for the use life.

Partners	Utility	Clients
- Battery supplier - Component suppliers	- Solution supplier - Maintenance	- Households - Communities

Table 6: Active Customer. Scenario 1

The key partner for this business model is the battery supplier, which supplies the battery asset to the Utility which in the end is the solution supplier. Also, the rest of components suppliers are considered partners of this business model.

In the second case, shown in Table 7, which at first look might be the more common one, the Utility not only supplies the solution but it also operates it. In this scenario, the Utility might act as an aggregator optimizing the client consumption, operating the battery and providing flexibility.

Partners	**Utility**	**Clients**
- Battery supplier - Components supplier - SCADA supplier	- Solution supplier - Maintenance - Aggregator	- Households - Communities - System (TSO/DSO)

Table 7: Active Customer. Scenario 2

The main partners are the same as in the previous scenario. The Utility depends on the battery supplier and the components suppliers to be able to install the solution in the clients location. In addition, it needs to acquire the services from an IT company to install a SCADA for the client in order to measure and operate the activity of the asset.

6.3.3 Key activities and resources

For this business model, the key resources associated are related to the digitalization and automatization of the consumption. The battery system needs a customer Energy Management System (EMS) to measure and control the consumption, which can be connected to the aggregator systems in case of existing this partner.

The complexity of resources associated with this business model increases when the figure of the aggregator is introduced. It is important to monitor every client load point in order to be able to predict its behavior and optimize its load. This monitorization is done through IoT systems that can be connected to the EMS or other control systems.

Lastly, maintenance of the battery system has to be taken into account as one of the key activities. The supplier of the solution can be hired to perform a periodically maintenance in order to enlarge the lifetime of the asset. Maintenance should also be performed to the distributed generation assets, in case of having them, by the supplier of them. The client should be communicated that maintenance of the assets is very important to avoid problems in the long run.

6.3.4 Regulatory aspects

In some countries, the biggest barrier for this business model has been the absence of a tariff design. The main problem appears when regulation treats a single client as a consumer and a producer, that is, two different statements. The battery allows the client to act as a consumer when it is drawing energy from the grid and a as producer when it is injecting. As a result, the client is taxed twice, for the energy produced and consumed. As seen in section 5.4 , the client should be taxed for the net injection or withdrawal from the grid.

Another problem for the client is the poorly valuation of the energy injected into the grid. The injected energy should be priced according to the local marginal price in order to attract investment in the long term and provide the appropriate short term signals to optimize the operation of the batteries.

Another interesting topic to analyze for this business model is the ownership of the storage asset when installed for communities of people. There is a need for regulation that defines the ownership of the batteries since the costs and revenues for the individual consumers will depend on it. Installing the battery without any control on it may provoke some consumers to abuse from it and earn more benefits. Instead of sharing the battery capacity, which could lead to complex technical issues, a great idea could be operate the battery as a single client, through an aggregator or other figure, and share the profits earned from it. Recently in Spain regulation has allowed to share storage assets in neighbor communities, which means a good practice for the implementation of this business model.

As explained before, the remuneration or creation of new ancillary services would represent a good practice from which final consumers can benefit. The batteries installed by these consumers can give ancillary services through aggregators or by themselves if regulation allows it.

6.3.5 Revenue stream

The core of this business model is the electricity bill cost reduction. Moreover, this reduction can be complemented with some earning coming from the participation in the markets, in ancillary services, or from the flexibility. However, these revenues may be insignificant next to the bill reduction.

The electricity bill is composed of two terms: the energy one, based on the consumption; and the contracted capacity one, based on the peak consumption during a period. Although a reduction in the electricity bill can be achieved by reducing the energy consumption, this may not be possible since it affects the client comfort and freedom. However, with the help of the battery, reducing the term associated with the contracted capacity is very simple since consumption peaks can be deferred to valley hours. The battery allows the client to store electricity from the grid during periods of low consumption and supply this electricity during peak load periods. This way, from the grid perspective, the load curve looks flat and therefore the contracted capacity can be reduced and optimized without changing the client consumption routine.

6.3.6 Case example

The example carried out for this business model focuses on the reduction of the electricity bill cost through the reduction of the contracted capacity. The contracted capacity has been assumed that accounts for the 10% of the peak load.

Figure 25 shows the daily load profile for a regular consumer. Installing a battery allows this consumer to reduce the peak consumption through load shifting and avoid paying a high amount of money for an unnecessary contracted capacity, as it is shown in Figure 26.

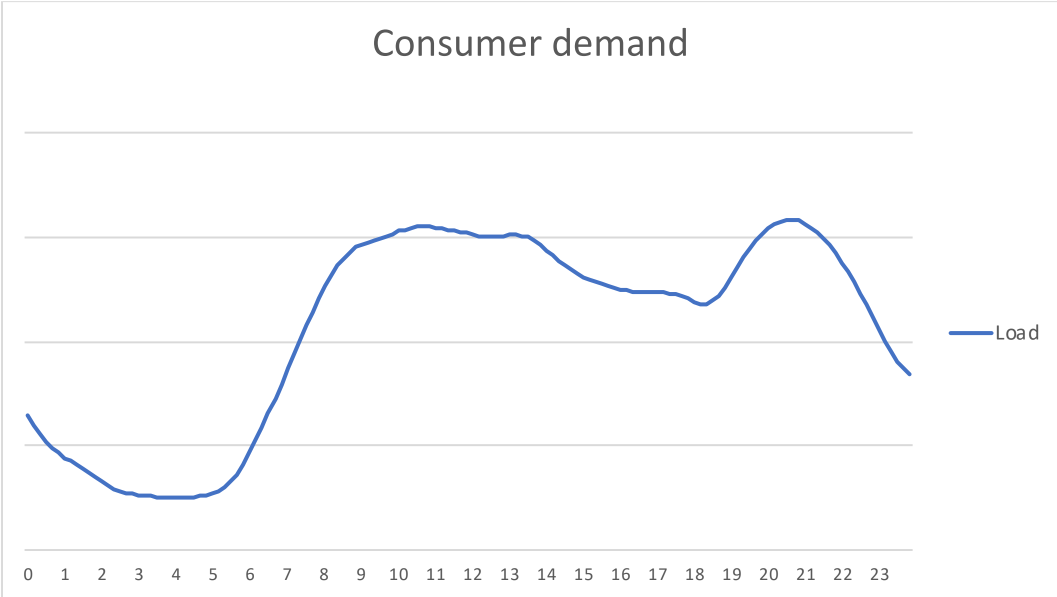

Figure 25: Load profile for a regular consumer

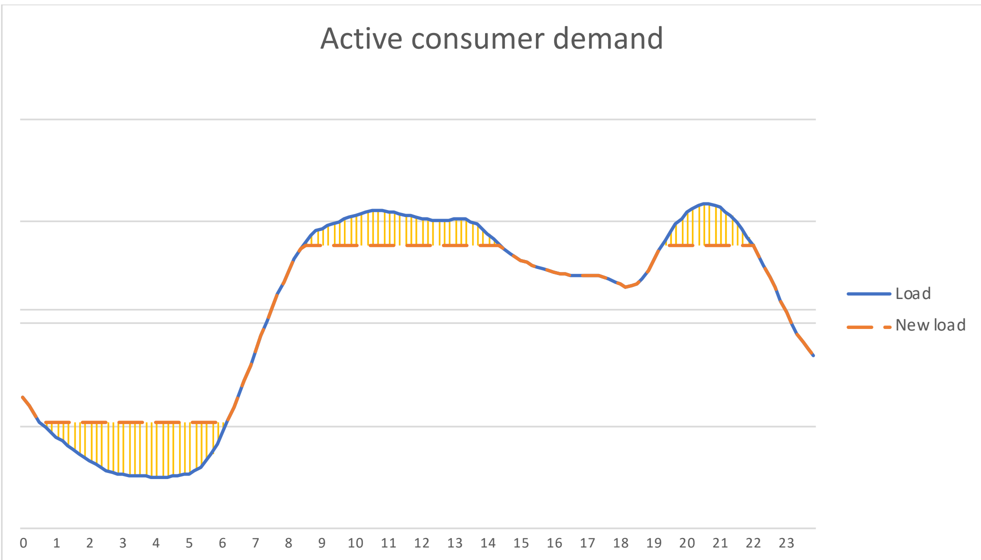

Figure 26: Load profile for an active consumer

6.4 Local Markets

6.4.1 Value proposition

This business model consists on private batteries giving services to the Distribution System Operator in order to improve the quality of the supply in its area. Quality of supply in the distribution network is affected by congestions, maintenance, outages, and in any of these situations batteries can provide efficient solutions for DSOs. At first sight it may look simple but the regulatory aspects concerning this business model make it quite complex to understand and optimize.

6.4.2 Customers and partners

This business model is thought for DSOs in countries where the ownership of storage assets by regulated entities is not allowed. Therefore, the DSOs who want to benefit from the applications that batteries have should hire these services from private owned batteries in their area.

The position of the Utility in this business model might vary, since it can act as the owner of the battery and as the DSO, who receives the services. The most critical situation is the one in which the Utility is the owner of the battery providing services to the DSO. In this case, the DSO might be from the same parent company, so it is very important to provide transparency to the transactions. Thus, the key aspects would be to respect the unbundling principles and avoid the abuse of market power. In extreme situations, the regulator could forbid the operation of the Utility as the battery owner in the areas in which it performs as the DSO.

6.4.3 Key activities and resources

This business model is characterized for providing the services in very punctual situations along the year. Therefore the main activity is the participation in the services (auctions, markets, regulated prices…) launched by the DSO, which sets the remuneration for the services acquired.

The key resources are the integrated solution that includes the battery system and the SCADA and the development of the distribution grid codes. The distribution grid codes are key in order to define the rules for access, connection and operation of batteries in the distribution network.

6.4.4 Regulatory aspects

As said before, the regulatory aspects that have influence in this business model are quite significant and therefore it is very important to analyze them individually.

The first topic is the ownership of the storage assets. Recently, the EU prohibited the ownership of energy storage facilities by regulated entities due to unbundling issues. Although regulated entities, as TSOs or DSOs, might find certain characteristics of batteries, fast response times, interesting to operate and control the systems, it is true that these facilities can participate in the markets and distort them.

However, in other countries, as the US, the ownership is allowed and system operators operate these assets to improve quality of supply or to manage congestions.

Therefore, as regulated entities cannot own storage assets, they might hire the services given by batteries to private owned ones. It is important to analyze the remuneration scheme of DSOs, since it will have an impact in the development of this business model.

Currently, in most systems, DSOs have a limited allowed revenues that depend on the investments carried out to fulfill with their requirements of quality of supply, losses and other issues. Although batteries may provide a more efficient and cheaper solution than investing in infrastructure, if the remuneration scheme does not include these services from batteries, the DSOs do not have any incentive to hire them. Otherwise, the DSO will spend money improving quality of supply and reducing congestions without being noticed by the regulator, who will not compensate it for these services acquired.

Another key regulatory issue is the development of grid codes for the distribution network, as it currently happens with the Network Codes for the transmission one. The absence of technical regulation that may define the characteristics of the services given might be seen as a barrier due to the uncertainty that it bears. Among the services batteries can provide, one of them is to ensure the supply of certain areas during outages or maintenance periods, operating the grid in island mode. Also, during peak periods, batteries can supply the peak load needed avoiding the investment in new capacity lines, what is known as investment deferral.

Finally, it is important to mention that in this business model, the location of the battery assets is critical. The distribution grids are unique and very different one of each other, and the services needed and their efficiency may differ from one node to another.

6.4.5 Revenue stream

The main source of income from this business model are the payments received from the DSO for the different services provided. However, this business model can be complemented with others, since the property of the battery is private and the client can use its battery for other issues.

Leaving aside the regulatory uncertainty from the remuneration scheme for DSOs, this income stream, once approved, is quite robust since the counterparty is a regulated entity which reduces the risk of non-payment.

6.4.6 Case example

As explained before, with this new business model, the DSO is presented with an alternative to investing in assets to improve quality of supply and reduce congestions. These assets are mainly overhead or underground lines, transformers, breakers or other components. This new possibility is to obtain services from private-owned batteries.

In this case example, the cost of new line is analyzed in comparison to the cost of the services provided by the local market of batteries. The underground medium voltage line is assumed to be 20 km long and have a voltage level of 36 kV. According to CNMC [25], the cost of a line of these characteristics is 2.898.280 €. Therefore, the charges derived from the services provided by the batteries should be less expensive than the cost of the line.

It is important to mention that although currently these services are required during peak moments, in a scenario of high penetration of electric vehicles and distributed generation, these services will be needed more frequently.

6.5 Others

6.5.1 Off-grid island support

The low demand and inexistent interconnection capacity which characterize off-grid island systems forces them to rely on fuel powered units which are more expensive and more pollutant than regular thermal plants. Also, the stability of these electricity systems is crucial, since the failure of a generating unit can provoke severe consequences. Renewable energy sources are presented as a great solution to substitute fuel units since they are cheaper, scalable and provide clean energy. The disadvantage is that their output is non-controllable and in these systems, as said before, stability is crucial.

This stability problem can be solved with the help of battery storage. Batteries provide value by supporting renewable power plants when the climatological conditions are not favorable. The benefits of this business model come from the savings on fuel from the generators, which is very expensive according to the price of the batteries.

The best example to illustrate this business model comes from an island in the South Pacific Ocean which is being 100% powered by solar energy. The energy comes from 5328 PV panels and 60 Tesla Powerpacks which can provide 6 MWh of stored energy. The batteries from Tesla allow this island to run on solar energy when the sun is not available for three days. In addition, these batteries complete a full recharge in just seven hours [26].

6.5.2 Standalone battery

This business model is quite similar to the Hybrid Power Plant since the battery can provide services to the grid and also participate in the energy markets. The main difference is that, in this case, the battery acts alone, in a standalone mode, so the value created is limited. It is more suitable for power applications like frequency regulation than energy ones, since arbitrage does not deliver a consistent revenue stream as it has been explained before.

In the UK, the TSO has created a fast frequency service called Enhanced Frequency Response [10] aimed at battery standalone solutions but from a technology neutrality point of view. The tender was opened for generators with storage support, aggregators and standalone storage, but all the providers selected for this service were standalone batteries. National Grid, the TSO, sets as requirements to be able to deliver a minimum of 1 MW up to a maximum of 50 MW of response in less than one second. The service will be dispatched automatically. This characteristics mean an advantage for faster batteries than generators and aggregators which may participate in slower frequency regulation. The income that these providers receive consist of an availability fee for the hours that had been tendered [27].

6.5.3 Transmission/Distribution System Operation

These business models are being currently implemented only in some countries due to regulatory issues. The main barrier for these models is the ownership of the storage asset, since regulated companies should not be able to obtain any benefit from the market. In the European Union, the TSOs and DSOs are not allowed to own batteries or any other storage systems for this reason.

Standalone batteries can provide ancillary services as frequency regulation, voltage control, inertia simulation and congestion management among others. These services can be remunerated and therefore the system operators may obtain a benefit.

Moreover, for quality of supply reasons, batteries can be presented as a cheaper and more efficient solution to diesel generators when managing failures in the grid.

6.5.4 Vehicle-to-grid

The business model known as Vehicle-to-grid benefits from the idea of a well-developed electric vehicle fleet in the urban areas, in which the EVs are parked in charging points. The combined availability of a great number of vehicles, which batteries can provide services to the grid, creates value for the system. The availability of these cars, by being connected to the charging points, can be remunerated by reducing the cost of charging the cars. Following this method, the battery of the EVs will not be immediately charge but will be programmed to reach the desired charge level at the desired time. However, in the meantime, the system operator operate that battery for grid services as voltage regulation or congestion management.

6.5.5 Vehicle-to-home

The business model known as Vehicle-to-home creates value for the consumer and owner of the EV since it operates the battery of its vehicle as a regular battery installed at home. The services provided by this battery are arbitrage and peak shaving mainly, therefore reducing the cost of the electricity bill. The main problem is that batteries from EV are not designed for energy management purposes, and they may deteriorate under continuous cycling periods of charge.

7 Conclusions

The objectives of this thesis were to assess the value of storage in the electricity systems, considering the technologies available and the applications they offer. Moreover, it was proposed to analyze the current storage regulatory framework to identify barriers and enablers for these technologies. Finally, the main goal was to develop promising business models that would provide benefits to the Utilities.

As a result of the work, the main contributions from the author of the thesis are:

- The proposal of the key principles that the definition of energy storage has to include.
- The proposal of a classification of applications of energy storage based on simplicity and oriented on the value created by storage.
- The identification of the main regulatory aspects that affect, as barriers or enablers, to the development of energy storage in electricity systems.
- The development of three business models that create value for the Utility - Hybrid Power Plant, Active Customer and Local Markets - and the brief mention of five more business models.

According to the technical, economic and regulatory analyses developed of energy storage and specially batteries, it can be concluded that:

Mature technology is already available in the market although there is still room for more technical development and cost reduction. Lithium-ion batteries are the most developed technology thanks to the needs of the automotive industry and big cost reductions have been experienced due to the presence of economies of scale. Power-to-Gas is presented as a promising technology for storing energy in the long term and providing a solution for the decarbonization of energy systems by using renewable gas.

The market for stationary applications is not mature yet but, with the great deployment of renewable energy sources in the coming years, it should be developed quickly in order to take advantage of the efficiencies it could create.

The regulatory framework that covers storage is not defined nor positioned as the implications of these technologies in the systems are not definitely known yet. At the EU, the technological transition evolves at a faster pace than regulation does. In many other frameworks many different promotion and incentive schemes are being tested. Therefore, the absence of a mature market and a consistent regulation introduces uncertainty which affects negatively to the development of business models around storage and batteries. Market design should be based on technology neutral products so storage can participate in the long term (capacity markets), short term (day ahead markets) and very short term (reserves and balancing).

Tariff design should focus on cost recovery, short or none netting intervals, time discrimination charges and setting the right pricing for injected energy into the grid in order to send the right signals for operation (short term) and investment (long term) to the agents.

The figure of the aggregator is going to be a key for the development of distributed energy storage since it would allow clients to obtain a benefit from their assets without the need to operate them. Also, the participation of demand, being more active and acquiring knowledge, will affect positively to the deployment of storage.

Arbitrage is considered to be an opportunistic market since the first agents participating in the market obtain a greater benefit thanks to the wide daily price differential. However, in a mature market, the equilibrium is found between the cost of batteries and the price differential. Moreover, new entrants with lower investment costs can displace other agents from the market.

The economic feasibility of the business model called Hybrid Power Plant relies heavily on the remuneration of ancillary services since the main value creation comes from the participation on frequency regulation and system services.

The main revenue stream of the business model called Active Customer is the reduction of the electricity bill cost, which can be complemented with the participation in the market through an aggregator if the client owns distributed generation. Utilities should start implementing this business model on the industry sector rather than the residential sector because complexity is reduced due to the number of clients. Also, these clients are more concerned about a reduction in the electricity cost.

The business model called Local Markets is only available in systems in which the ownership of storage by regulated entities is not allowed. Thus, DSOs can enjoy the services that batteries present but paying for them to private owned ones.

For all the business models analyzed, the long recovery times and high investment costs are also a natural barrier for a technology with a wide development room in markets with scarce of maturity.

This thesis has been a wide review and a good starting point for several issues. As a consequence, the future work to be carried out would be:

- To develop a detailed cost benefit analysis of each business model to assess quantitatively the feasibility of them with real data acquired in specific systems. Moreover, a sensitivity analysis should be carried out by taking into account the impact of different regulatory scenarios.
- To analyze the business models that have not been deeply studied for this thesis, since they might be presented as a good solution in certain systems.
- To design the most efficient way for the DSOs to obtain the battery services in the Local Markets business model, for example, through auctions in punctual situations.
- To build pilot projects to clear the unknowns related to real costs, administrative barriers or real problems derived from the operation of the assets.
- To write a detailed regulatory assessment with suggestions for the development of the a framework based on technology neutrality and economic efficiency.
- To set the bases to analyze the regulatory framework around Power-to-Gas in order to be able to develop some business models related to this promising technology in the near future.

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