MSc Program
Renewable Energy in Central & Eastern Europe

On the prospects of energy storage for increase renewable energy integration in EU

The impact on policies and market

A Master's Thesis submitted for the degree of
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supervised by

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Affidavit

I, **Danielle de Oliveira Gibbon**, hereby declare

1. that I am the sole author of the present Master Thesis, "On the prospects of energy storage for increase renewable energy integration in EU - The impact on policies and market", 68 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

The European Commission has set ambitious environmental targets for 2020. The share of renewable energy in the final consumption of energy must achieve 20% and more is expected until 2050. Wind and solar, intermittent renewable energy sources, are the technologies mostly being used in Europe, but the increase of the share of these technologies brings challenges to integrate them into the grid, maintaining energy security and grid balance.

Energy storage system can provide flexible generation and balance supply and demand, facilitating the integration of renewable energy sources. Moreover, it brings other benefits as ancillary services and increase in energy security. The technology can comply with low-carbon rules, when storing only renewable energy excess, promoting decarbonization of the electricity grid.

Many storage technologies are being developed to meet future market demand in the short and long-term. On this work, a review of the main technologies used or being researched in EU are given, with a comparison between them.

The core objective of this thesis is to define the main barriers and identify what can be done by EU countries to enable the energy storage development.

Based on literate study, the main barriers today for the development of energy storage system are found in the technology itself, needing more R&D, on the EU regulation, not giving a clear definition for energy storage, and in the electricity market, that does not reward the facilities for all services they provide to the grid, making their revenues not attractive for investors.

Regulatory changes and a new design for the market are required. Energy storage should be integrated into all current and future EU energy and climate change regulation, targets, and policies must give a clear indication about the role of energy storage systems in the electricity grid. In addition, facilities should be entitle to have fair tariffs for all services they provide to the grid system, simultaneously, being able to act in all markets. Only with this transformation and modernization, the energy storage systems can really develop and deploy in Europe.

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List of abbreviations

AFCs	Alkaline fuel cells
BES	Battery energy storage
CAES	Compressed air energy storage
CCGT	Combined-cycle gas turbine
CNG	Compressed natural gas
CO_2	Carbon dioxide
DSOs	Distribution system operators
EC	European Commission
EU	European Union
FBES	Flow batteries energy storage
FES	Flywheel energy storage
GHG	Greenhouse gases
H_2	Hydrogen
MCFCs	Molten carbonate fuel cells
MW	Megawatt
PAFCs	Phosphoric acid fuel cells
PEM	Polymer electrolyte membrane
PEMFCs	Polymer electrolyte membrane fuel cells
PHES	Pumped hydro energy storage
PtG	Power to gas
RES	Renewable energy sources
SCES	Super capacitor energy storage
SMES	Superconducting magnetic energy storage
SNG	Synthetic natural gas
SOFCs	Solid oxide fuel cells
T&D	Transmission and distribution
TES	Thermal energy storage
TSOs	Transmission system operators
VRE	Variable renewable energy

1 Introduction

The shift towards the increase of the share of renewable energy sources (RES) into the grid is seen as a key point in the European Union (EU) energy policy. The aims and targets foreseen are not only a reduction of greenhouse gases (GHG) emissions, but also a decrease on the dependence of fuel imported from non-EU countries and the decoupling of energy costs and oil prices.

The European Commission has set determined targets for 2020 - when the share of energy from renewable sources in the final consumption of energy must achieve 20%, and new challenges will be settled for the future towards a low-carbon energy system. It is true that this is a one-way path for the advance of renewable energy integration and its consolidation as important generators for the electricity grid.

Renewable energy sources can be controllable, as biomass, hydropower and geothermal, or intermittent, as wind and solar. The importance of this second group to the power generation is increasing every day. In the EU-28 countries, wind power generation more than tripled over the last decade, being the second most important source for renewable electricity, with a share of 27% of renewable source generation in 2014. Solar power also had a fast ramp-up in the past years and today is the third most important contributor, reaching 11% of the share in 2014. Both together will overcome the share of hydropower plants in the near future, still the main contributor for renewable electricity generation in Europe, supplying 42% of the renewable share in 2014 (Eurostat, 2016). It is estimated that for 2020, wind power will be the most important generator, with 40%, and the share of hydropower will drop to 30% (Scarlat, 2015). *Figure 1* shows the recent data from Eurostat about the share of each RES in the electricity generation from renewables only, which represents 27% of the total electricity production in EU and 16% of the total gross final consumption of energy in European countries in the same year.

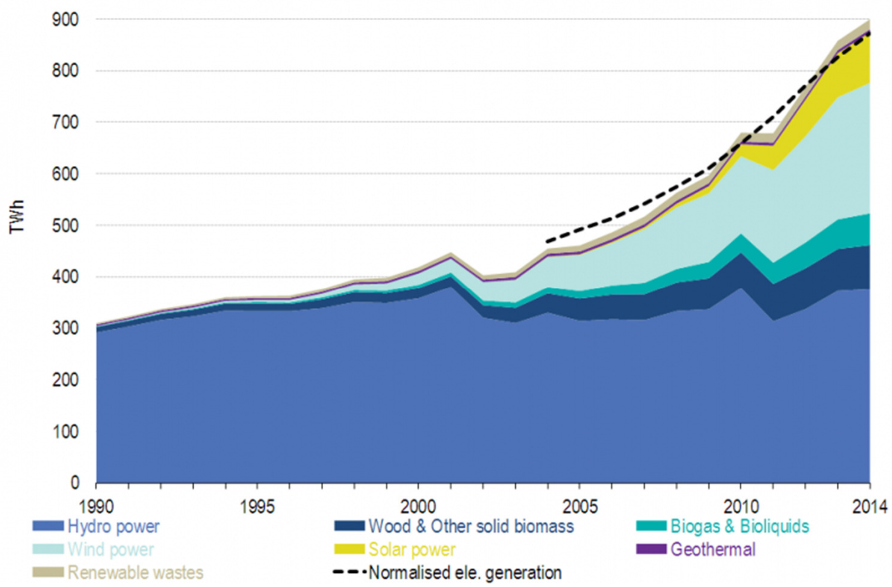

Figure 1: Gross electricity generation from RES in EU-28 (Eurostat 1990 - 2014)

However, the increase of these intermittent or, also called, variable renewable energy (VRE) can cause problems when integrating to the grid due to the variation of their power production rates among seasons, months, days and even hours as they strongly depend on weather conditions. Furthermore, these VRE also have a big impact in the electricity market, bringing volatility and even negative electricity prices. In the meantime, security and balance of the grid must be preserved, so a call for a new approach to energy storage system is launched, as it will became a key player in this new low-carbon economy and electricity system.

Storage systems can act as power regulators in this context, not only enabling grow of renewables in the electricity grid, but also helping in grid stabilization and operational support to stabilize power quality and bringing reliability and flexibility to the grid, with back-up generation to balance fluctuations and ancillary services.

Currently there is a limited storage capacity in EU energy system (around 5% of total installed capacity), which are almost exclusively from pumped hydro storage (PHES) and in mountains areas. Other forms are either minimal or at a very early stage of development.

There is a large number of developing technologies with potential to enable energy storage use in the electricity production and grid management. If the appropriate storage technology is used, variable renewable energy sources, together with hydro, biomass and bioliquids, can replace fossil fuels towards a sustainable energy grid. However, the biggest barrier is still the economical one, not having enough incentives and research support.

Changes in how energy storages are seen in the market and how they are regulated by governments, utilities, regulators and other electricity stakeholders must take place, otherwise those technologies will not be able to be implemented, with the lack of incentives.

This paper focus on the investigation of the renewable technologies available that could be used in order to increase the share of renewable sources in the European grid, facilitating the achievement of the renewable targets proposed by the European Commission.

In addition, policy action and market acceptance are needed in order to support the deployment of these energy storage options, so an investigation of what is already in place and what could be implemented to enable the success of energy storage are also explored on this work.

1.1 Motivation

There is no more doubt that renewable energy is already playing a leading role in any sustainable solution to mitigate climate change. As energy and transport usually are the sectors with more contribution to GHG emission, sustainable targets would eventually be integrated into energy policies. In fact, when the European Union set ambitious targets for renewable energy in 2008, a political agenda and framework were put in place in order to develop new technologies for RES, making them economically possible and restructuring the energy market. In the meantime, the share of RES in the energy and transport sector has been massively increasing year after year.

Now comes a second step on this path: the integration of those renewable technologies into the grid and into the management of this entire system. This is where energy storages surge as one possible solution and this is the time when new discussion on policies and frameworks is needed in order to now develop and deploy new technologies that will help to manage and control all the impacts this increase of the share of RES is triggering.

Knowing this, the motivation for this work is exactly to explore this solution and the challenges energy storage could bring to the European Union.

1.2 Core objective and questions

The intention of this work is to investigate the energy storage possibilities in Europe in order to increase the share of renewable energy sources in the European grid. With the technological review, it is important to investigate why energy storages are still not vastly implemented and what need to be changed in EU framework in order to make this happen.

Following questions constitute the framework of this paper:

Questions:

- What is energy storage and what is the maturity level of the available energy storage technologies in the European Union?
- How can the different storage technologies be compared and what are the evaluation criteria to for this?
- How electricity energy storage can bring benefits to EU members in order to achieve renewable energy targets and increase the share of renewables in the grid?
- What is the actual regulatory situation for energy storage (if there is one)?

All those questions lead to the core objective of this work:

- What can be done by EU countries to enable the energy storage development and what should be the adjustments/changes in the regulatory framework for its deployment?

1.3 Method of approach and main literature

This Master thesis was written based on literature study and on the regulatory framework analysis currently in practice in the European Europe.

Overall, the method of approach of this paper was first to collect data in literature about the subject in order to build the knowledge. Then, the data was used for a deep analysis checking technological and legal aspects, as well as best practices literature recommend for the subject. Finally, the information collected was organized and structured in order to assemble a final proposal.

The literature studied was mainly papers published in renowned scientific Journals like, *Renewable Energy*, *Renewable and Sustainable Energy Review*, *Energy*, *Energy Policy*, between others. It was taken in consideration the newest papers published in order to have the most up-to-date information.

Regulatory framework and study documents from the European Union were also used as research literature, giving bases of what is driving the European Commission discussions. Roundtable reports conducted by the European Commission and made with stakeholders for energy storage were also analyzed as this gives a great database for what is realistic in proposals for changes.

Data from the REN21, Eurostat and European Commission reports were used to underline a clear picture of what is the status of renewable energy technologies and energy storage technologies today in Europe.

Technological roadmaps on energy storage made by organizations like the International Renewable Energy Agency (IRENA), International Energy Agency (IEA), European Association for Storage of Energy (EASE) and European Energy Research Alliance (EERA) were also used as guidelines for building the proposals of this work.

1.4 Structure of work

This Master thesis is structured in five chapters, which are described further down.

Chapter one, *Introduction*, gives an overview of the topic and the importance for its discussion. The core questions that motivated this study are explained and how the work and the research was done.

On chapter two, *Energy Storage*, a description of what is considered as energy storage and what are their benefits and impacts for the electricity grid is given. It is explored how energy storages can better integrate VRE into the grid, promoting their development. Also, this chapter gives an overview of the energy storages technologies today available and/or in development, as well as their actual situation in the European electricity market. In addition, a comparison table was build based on the literature researched, identifying the key parameters for its comparison.

Chapter tree, called *EU renewable policy and targets*, brings a review of the pathway Europe is taking towards a low-carbon economy. A review of the regulatory framework is given, as well as the renewable energy targets and its success until today. How the regulation is considered in the European countries for energy storage technologies is also presented and explored.

Chapter four, *Integrating energy storage and its possible impacts on policies and markets*, brings the analysis of what could be done on the regulatory framework and market, highlighting the challenges for energy storage in Europe, the technological development and the market and regulatory barriers. A proposal, based on the literature research, to overcame these challenges is showed, identifying what the issues are, what could be changed and to whom this should be addressed in order to boost the development and deployment of energy storages.

The last chapter of this work is chapter five, *Conclusion*, which summarizes the research made.

2 Energy storage

In a simple way, energy storage is a device that store some form of energy to perform some useful operation at a needed time.

Electricity cannot be stored and must be used at the same time it is produced, so balancing supply and demand is essential for any grid. The concept of an electrical energy storage is to transform electrical energy into another form, such as chemical, kinetic, potential or thermal, which can be stored and converted into electricity again later, bringing flexibility, reliability and power quality to the grid.

Some electrical energy storages technologies are more appropriate for providing small amount of electricity for power quality applications, such as smoothing the output of variable renewable technologies within a time scale of less than an hour, minutes and even seconds. Other technologies are useful for storing and releasing large amounts of electricity over longer periods for peak savings, load leveling or energy arbitrage. The technologies can be classified in short-term and long-term storage and they are categorize by the relation between storage capacity and discharge time. In *Figure 2,* a chart with the correlation of these two parameters is shown.

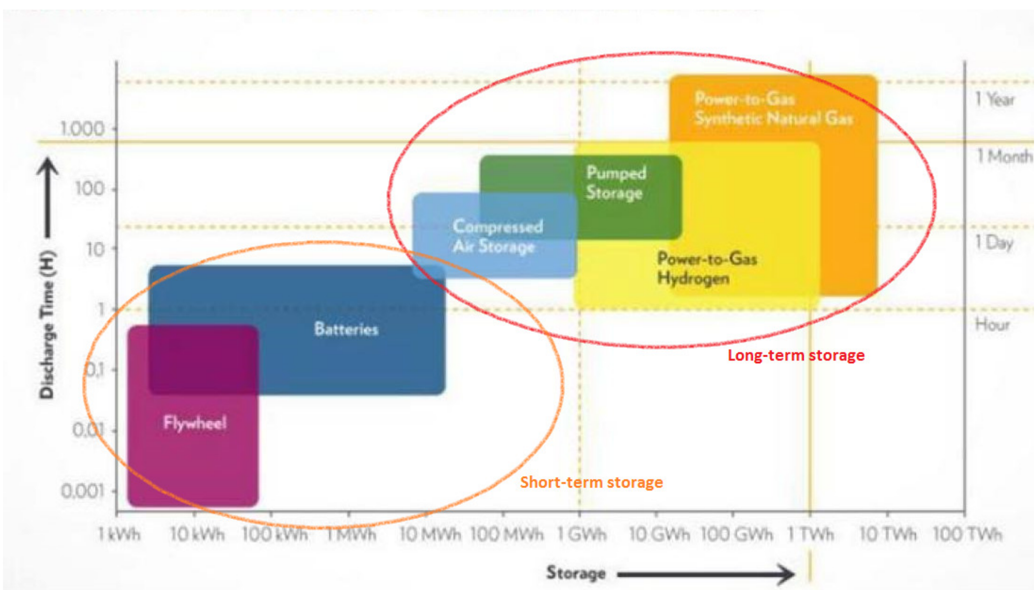

Figure 2: Energy storage technologies (adapted from ITM Power)

Short-term storage are, basically, the ones with a smaller to medium storage capacity, but providing it in a short time of period (low discharge time). On the other side, long-term storage are the ones having big capacities for a long discharge time. A clarification of the benefits that both can bring to the grid and market can be seen in *Table 1*. It is important to say that the balance between the use of storages in short and long-term is not only possible, but also very positive to the grid and to the electricity market, bringing more control, stability and security. The analyses made by the European Commission concluded that for a low-carbon energy system, energy storage would be needed at all levels of the electricity system: generation, transmission, distribution and demand (end-user) levels.

***Table 1**: Benefits of storages in today's power system*

Functionalities of storages	**Long-term**	**Short-term**
Balancing demand and supply	- adjust seasonal / weekly fluctuations (load levelling) - correct large geographical unbalances; spinning reserve - regulate variability of wind and solar - help to control energy prices volatilities	- adjust daily / hourly variation (load following) - peak shaving /valley filling - regulate variability of wind and solar (hourly/daily corrections)
Grid management	- complement to classic power plant for peak generations - emergency backup and reserves (spinning or non-spinning) - enable renewable smoothing dispatch and integration - participate in balancing markets	- voltage and frequency regulations - provide power quality management to reduce harmonics, swells and flicker problems - provide governor/inertial response - end-use applications - substitute existing ancillary services
Energy efficiency	- better efficiency of the global mix, shifting off-peak into peak energy - increase assets utilization	- demand side management - increase value of PV and local wind

Source: adapted from EC (2013) and Anuta et al. (2014)

2.1 Storage and renewable energy

Hydro and geothermal renewable sources are considered a concentrated and stable form of energy source, as the primary form of energy (water or heat) can be stored; however, intermittent renewable energy sources, such as wind, solar, tidal and wave, must be used as when they are available or they will lose energy potentials. These are called variable renewable energy (VRE).

When the share of VRE in the generation mix is lower than 15 to 20%, the grid operators are able to compensate the intermittency caused by those contributors. However, when the share exceeds 20 to 25%, the control of the intermittency must be more accurate in order to control grid perturbation (frequency, voltage and reactive power control) and congestion. It could lead to the need of cutting the supply of those contributors to the grid when demand is too low and if the excess of the variable renewable sources cannot be stored (EC, 2013).

The International Renewable Energy Agency (IRENA), launched a global roadmap called REmap 2030, challenging countries to double their share of renewable energy in the global energy mix by 2030, comparing with 2010 figures. According to this plan, the share of VRE worldwide would increase from 3% in 2014 to 20% in 2030. The increase of this share by each country if all REmap options are implemented is shown in *Figure 3* below. Many European countries will exceed 20% of variable renewable energy in their mix mainly due to the increase of wind and solar power generation, as Denmark, Germany and Spain.

Moreover, the weather prediction for the VRE is extremely important. According to the report from the European Commission made by the DG ENER (2013), a study showed that one-hour error on the wind forecast could cause a need of 5 – 7GW of electricity. This gap could be covered by energy storages, without the need to activate fossil fuel generators.

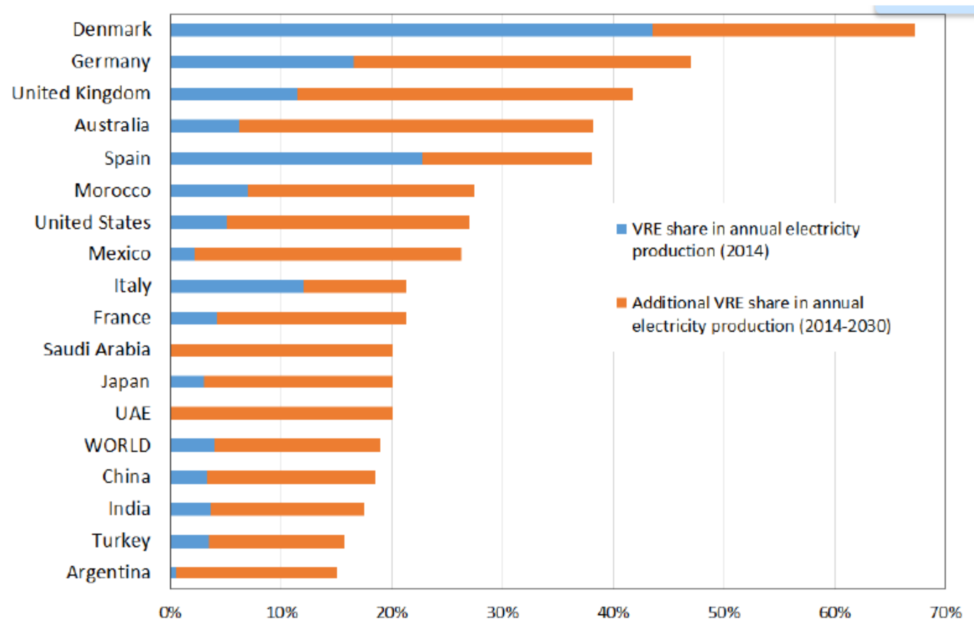

Figure 3: Share of VRE in electricity generation in 2014 and 2030 (IRENA, 2016)

Energy storage can equalize the variability in power flow from renewable generation and store renewable energy so that its generation can be scheduled to provide specific amounts of power, which can decrease the cost of integrating renewable power with the electrical grid, increasing market penetration of renewable energy.

2.2 Energy storage technologies

Many storage technologies are being developed based on different concepts and characteristics to meet future demand and the diversification of its use is important to support and better supply markets in short and long-term storage. Progress is slow today, since investments on development and research are scarce, but discussions about the subject already started among the European Commission. In *Figure 4*, the current development and maturity of energy storage technologies is given. As one can see, many technologies are still to come.

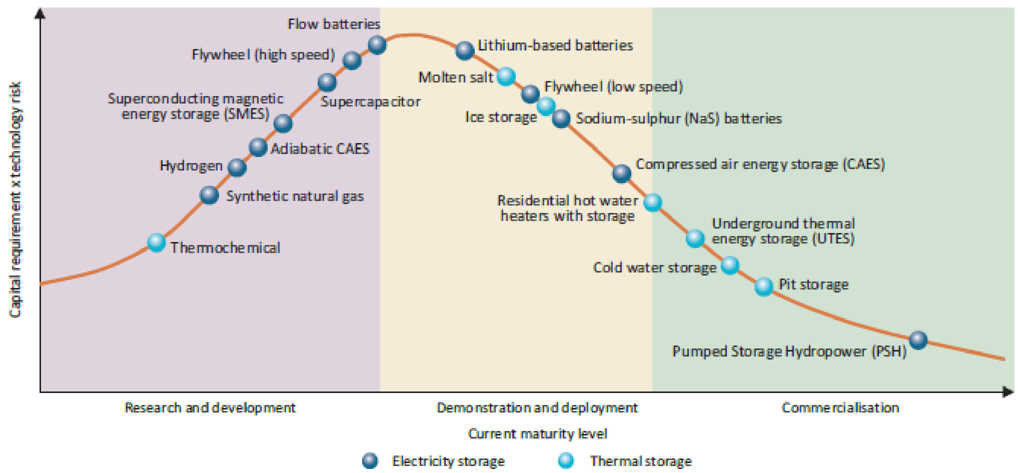

Figure 4: Maturity of energy storage technologies (IEA, 2014)

Mainly, there are four categories in which energy storage technologies can be categorized, depending of the type of energy stored. The categories are mechanical, electrical, thermal and chemical energy storages. *Figure 5* gives the classification of them with some examples of technologies for electricity storage.

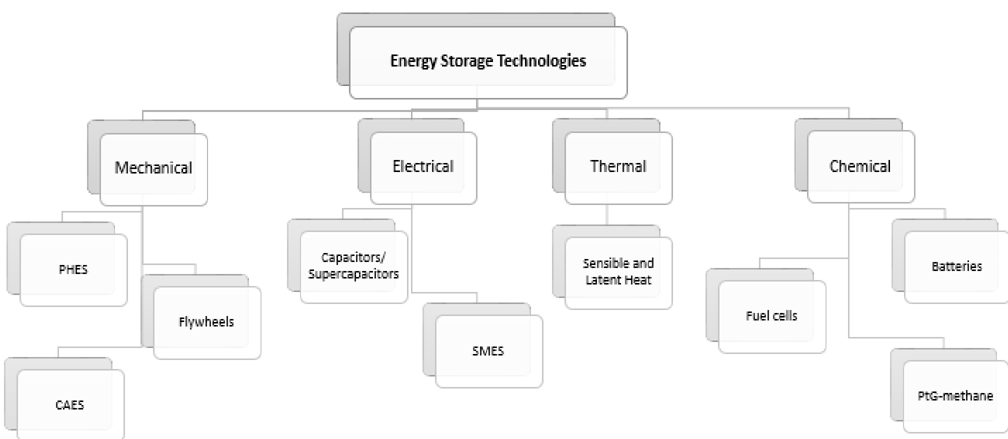

Figure 5: Classification of energy storages technologies for electricity (adapt from Evans et al, 2012)

Mechanical energy storage are the ones that make use of potential and/or kinetic energy. Electrical storage are the ones based on electrostatic and/or magnetic energy. Thermal energy storage are based on thermal energy. Lastly, chemical energy storage makes use of electrochemical and/or thermochemical energy.

As this work is focused on electricity energy storages, a review of the main technologies today most used and/or are under discussion is given.

2.2.1 Pumped hydro energy storage (PHES)

The principle of PHES is very simple, as it is shown in *Figure 6*: it consists of two basins, one in a lower level and the other in a higher level. Energy is stored by pumping water uphill, transforming electrical energy into potential energy. When electricity is needed again, the water flows downhill (due to gravitational force) passing by a turbine, which generates electricity again.

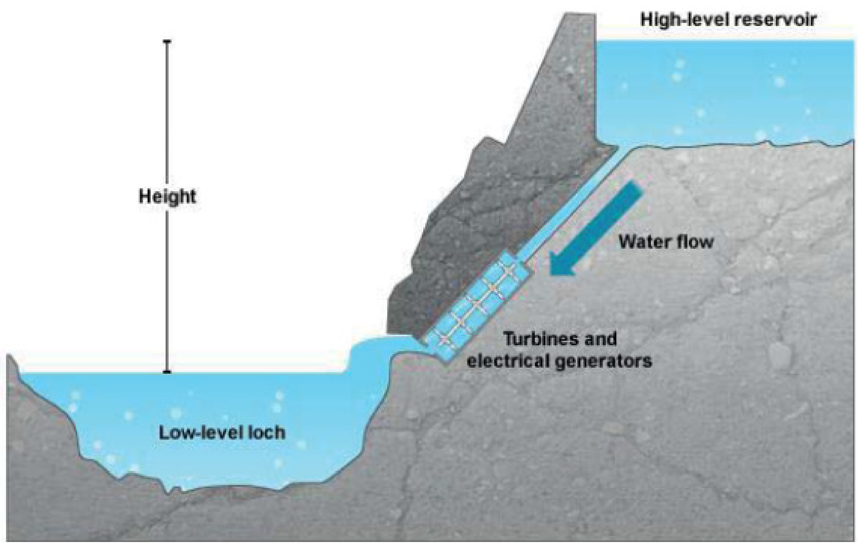

Figure 6: Basic principal of a pumped hydro storage plant (Huggins, 2010)

One big disadvantage of PHES is the strong dependence of a favorable topography. An ideal site should provide high elevation between reservoirs, large energy capacity (large reservoir) and minimal environmental impact. As PHES are today largely used, the best locations are already taken and there is not much potential left. However, new ideas are surging in order to continue to deploy this storage technology.

The underground pumped hydro energy storage (UPHES) have the same operational method as the conventional technology, differentiated only on the location of the lower reservoir, which is underground, as it is exemplified in *Figure 7*. With this new concept, proper geological location is not a barrier for the deployment of PHES anymore, since it can be constructed also in flat areas without affecting much the landscape (e.g. the upper reservoir could be an existing lake). Moreover, plants could be constructed close to some generation plant or even close to the demand, reducing transmission needs and, by consequence, reducing losses.

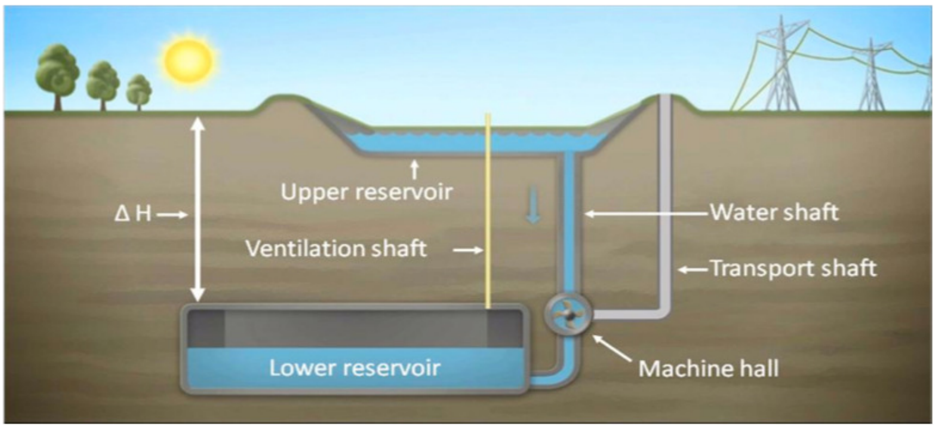

Figure 7: Underground pumped storage plant (Huynen J. et al, 2012)

The firsts PHES were built in Italy and Switzerland in 1890. After this, many investments were made all around the world, especially in US, where the capacity exceeds 20GW (EIA, 2012). In *Table 2,* a list of the main PHES in Europe is given. In 2009, the installed capacity in Europe reached 44GW.

PHES has the largest capacity and is most mature energy storage technology currently available. In the past, grids were much less interconnected and the use of PHES aimed to stabilize a small regional area, acting on energy demand. Today, Europe’s grid is much better interconnected and the construction of new large capacities is facing strong barriers. However, the focus has been in small scales as the tendency driven by the grid’s needs is to have increasingly growing number of cycles per day, as renewables bring additional volatility to the supply (EC, 2013).

Table 2: *List of existing PHES in Europe (own data)*

Operation start	PHES	Country	Capacity (MW)
1930 -1960	Niederwartha	Germany	120
1932-1975	Waldeck	Germany	695
1933	Lac-Noir	France	80
1936-1986	Bissorte	France	800
1942-1959	Hohenwarte-I	Germany	63
1943	Witzau	Germany	220
1953	Dobšiná	Slovakia	24
1954-1973	Bolarque	Spain	236
1958	Geesthacht	Germany	120
1960-1979	Malta-Reisseck	Austria	1026
1962-64/2009	Vianden	Luxembourg	1296
1963	Ffestiniog	Wales	360
1964	Erzhausen	Germany	220
1964-1965	Cruachan	Scotland	400
1965-1966	Hohenwarte-II	Germany	320
1967-1968	Sackingen	Germany	330
1967-1968	Wendefurth	Germany	80
1968	Solina	Poland	200
1969	Ronkhausen	Germany	140
1969-1970	Zydowo	Poland	150
1969-1978	Coo-Trois Ponts	Belgium	1065
1969-1981	Innerfragant	Austria	108
1972	Ruzin	Slovakia	60
1973	Roncovalgrande	Italy	1016
1974	Turlough Hill	Ireland	292
1974	Revin	France	800
1975	Wehr	Germany	900
1975	Rodund-II	Austria	276
1975	Liptovská Mara	Slovakia	198
1976	Langenprozelten	Germany	164
1978	Dalesice	Czech Republic	452
1979-1981	Markersbach	Germany	1050
1981	La Plate Taille	Belgium	144
1982	Entracque	Italy	1317

Operation start	PHES	Country	Capacity (MW)
1982	Cierny Vah	Slovakia	672
1982-1983	Aguayo	Spain	340
1983	Zarnowiec	Poland	680
1984	Dinorwig	Wales	1728
1984-1985	Edolo	Italy	1000
1985	Grand'Maison Dam	France	1800
1985-1986	Sallente	Spain	452
1987-1988	Hausling	Austria	360
1988-1989	Cortes - La Muela	Spain	700
1988-1989	Torrao	Portugal	146
1989	Koepchenwerk-II	Germany	150
1991	Koralpe	Austria	50
1991	Presenzano	Italy	1000
1996	Dluohe Strane	Czech Republic	700
1997	Niedzica	Poland	93
1998	Kruonis	Lithuania	900
2003-2004	Goldisthal	Germany	1060
2003-2012	Alqueva	Portugal	520
2006-2007	Tashlyk	Ukraine	302
2009	Kiev	Ukraine	235
2009-2011	Feldsee	Austria	140
2009	Kops-II	Austria	450
2011	Limberg-II	Austria	480

PHES should not be mixed-up with hydropower. Hydropower produces renewable electricity. PHES does not produce any it only stores energy.

There is currently no investment framework for PHES, not only because potential areas are already taken or protected (so investment costs are much higher than in the past and sometimes even higher than new technologies), but also the market in Europe lacks legislation and regulation. PHES are usually seen as electricity consumers and electricity generators, paying double tariffs in many EU countries for access the network. Investments requires a period of almost 10 years and the permits today are increasingly difficult to grant.

2.2.2 Compressed air energy storage (CAES)

The process of CAES is very similar to PHES, but instead of water, ambient air is compressed using off-peak electrical power by an electric engine into an underground reservoir, where it is stored under pressure. To convert compressed air into electricity again, the pressurized air is heated and expanded in a turbine driving a generator for power production. A diagram of this process is shown in *Figure 8*. There are five major components in this technology: a motor/generator, an air compressor of two or more stages, turbine train, cavity or cavern for storage and controls and auxiliaries.

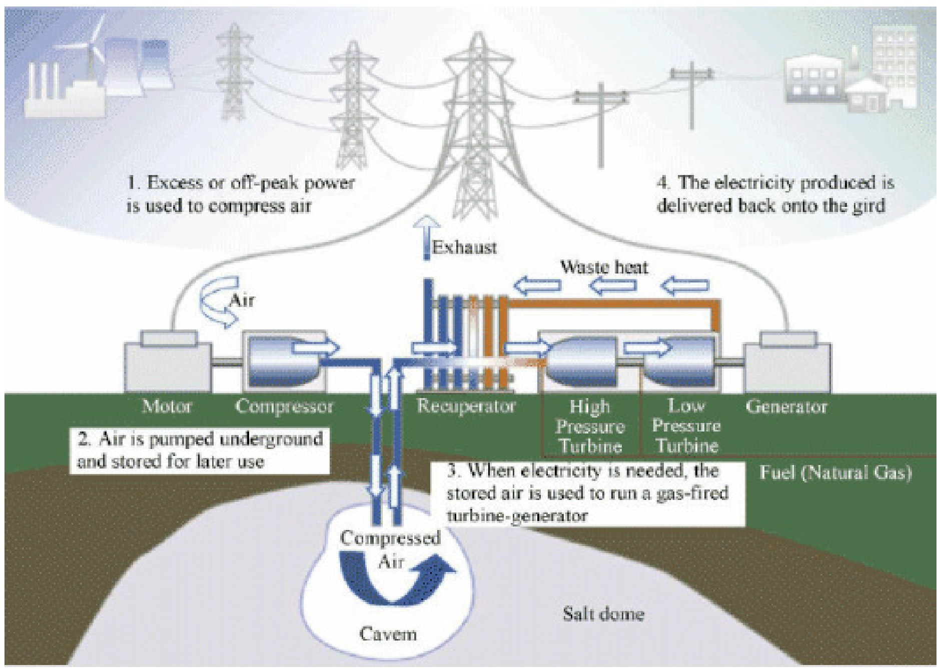

Figure 8: Diagram of a CAES unit (adapted from Mahlia et al (2014)

The capital cost depends on the required stored air volume and the construction of the reservoir. The reservoir could be manufactured, but at a very high cost, so CAES locations are usually decided by identifying natural geological formations that suit these facilities. These natural reservoirs can be hard rock cavern, salt cavern, depleted gas fields or an aquifer. Hard rock caverns are more expensive than the other types (e.g. more than 60% of the investment costs of salt caverns, Mahlia et al (2014)). On the other hand, aquifer cannot store high pressure, resulting in lower energy capacity. For these reasons, salt caverns have more advantages, having the capability to be easily designed as specific requirement by using fresh water to dissolve the salt. Yet, this strong geological dependence for the location of the caverns makes the investment costs higher when compared with other technologies.

CAES normally have very small losses due to leakage. Another advantage is that CAES have fast reaction time (less than 10 min) and are capable to undertake frequent start-up and shutdown, making this technology ideal for large bulk energy supply and demand.

However, the technology uses fossil fuel to operate. When the air is released from the cavern, it must be mixed with a small amount of natural gas before entering the turbine for heating. If there were no gas added, the temperature and pressure of the air could cause some issues in the process.

In the current days, an improvement in the technology is being studied. The advanced adiabatic-CAES (AA-CAES) systems utilizes thermal energy storage (TES) to absorb the heat from the hot compressed air (as the air naturally heats when compressed) and reuses the energy to reheat the air before expansion (the same way, air cools down when in expansion). This system enable CAES to run the turbine without added gas, making the process cleaner and with no GHG emissions (as no fossil fuel is needed). In this case, efficiency can be increased up to 70%, reaching similar performance of PHES.

From a thermodynamic point of view, the most efficient CAES should continuously subtract heat during the compression and continuously add heat during the expansion, keeping the air temperature at its ambient value. This is the principle of the Isotherm CAES and this technology can be used with a reciprocating engine (Hala, 2012).

Compressed air technology was introduced in 1970s to provide load following and to meet peak demand. The first plant was installed in 1978 in Huntorf, Germany, with a capacity of 290 MW and storage capacity to generate power for up to four hours. Second plant was installed in 1991 in McIntosh, Alabama with a capacity of 110MW for 26 hours. Enhancements were made in the technology as waste heat from turbines were used to preheat air from the cavern (Mahlia et al (2014); Hala (2012)).

In December 2012, a new facility of 2MW capacity was completed by General Compression. It is a near-isothermal CAES in Gaines, Texas.

After these investments, there are only a few projects in the pipeline for CAES. The so-called ADELE project, the first adiabatic CAES to be constructed in Germany, was postponed to 2016. Another project in Texas by Apex was delayed until 2017. Also in 2017, Storelectric Ltd has a plan to build a 40 MW 100% renewable energy pilot plant in Cheshire, UK, with 800 MWh storage capacity.

2.2.3 Flywheels energy storage (FES)

The basics of this technology is to accelerate a rotor (flywheel) to a very high speed, maintaining the energy in the system as rotational energy. The rotor floats on magnets inside a vacuum to reduce friction and let the rotor spin, based on the conservancy law. They are discharged with this same rotor acting as a generator to produce electricity. In *Figure 9*, the schematic of a FES is shown. The total energy potential of this technology is based on the size and speed of the rotor, while power rating is a function of the generator (Evans, 2012). Unlike batteries, flywheels do not use chemicals, but only mechanical energy. Also, a flywheel uses no water and has no emissions.

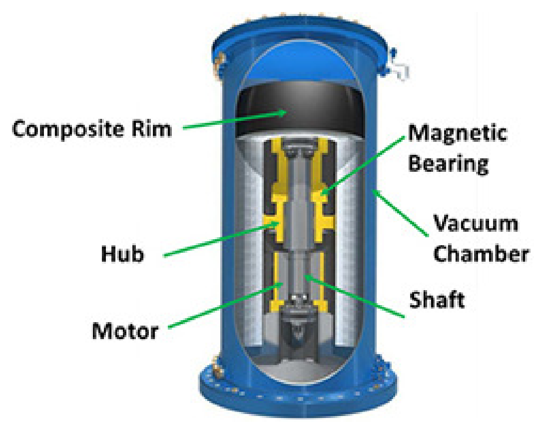

Figure 9: Flywheel device components (Bacon Power)

Based on the speed the rotor spin, FES can be divided in two categories: high speed FES and low speed FES. High speed has the advantage of giving a longer period time of storage, but on the other hand, it has lower power capacity. On the other way around works the low speed FES, with short period time of storage, but higher capacities. However, the price of low-speed FES can be up to five times lower than the cost of high speed FES (Kousksou et al, 2014).

The capacity of a flywheel as a storage system may be used as a separate energy storage, coupled with distributed generation assets or in a hybrid configuration with other storage, i.e. batteries (Mahlia, 2014).

In the 1950s, flywheel-powered buses, known as *gyrobuses*, were used in Yverdon (Switzerland) and Ghent (Belgium). The use of FES in vehicles is very promising and some people in the market believe it can replace batteries.

Another use for FES is the combination with wind turbines, storing energy during off-peak or during high wind speeds. The American company Beacon Power began testing their Smart Energy 25 at a wind farm in Tehachapi, California as part of a wind power/flywheel demonstration project being carried out for the California Energy Commission.

There are some small projects in operation using flywheels in US and Canada. In Europe, the first grid-connected hybrid flywheel project was announced in 2015 in Offaly, Ireland. The project is a collaboration between Schwungrad Energie Limited and the Department of Physics and Energy at the University of Limerick and comprises two flywheels of 160 kW capacity each and one valve-regulated lead acid batteries of a capacity up to 240 kW.

2.2.4 Supercapacitors and ultra-capacitors

A capacitor stores energy by an electrochemical reaction. It consists of two metal plates separated by an insulating material. Applying a voltage differential on the positive and negative plates charges the capacitor. A schematic process of a capacitor is shown in *Figure 10*.

Supercapacitor, also known as ultra-capacitor or double-layer capacitor, differs from a regular capacitor as it has higher energy density, making use of an electrolyte ionic conductor as insulating material in which ion movement is made along a conducting electrode with a large specific surface (Kousksou et al, 2014).

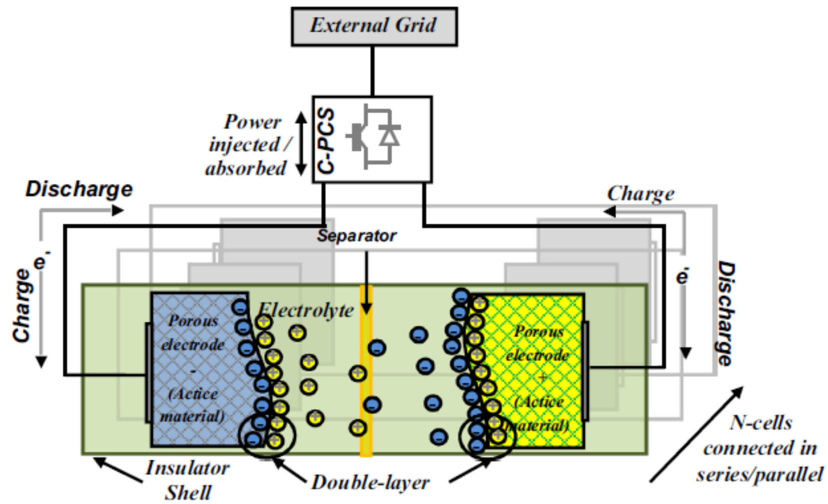

Figure 10: Capacitor storage system (Kousksou et al, 2014)

Supercapacitors are more used when a quick charge is needed to fill a short-term power need. Batteries are chosen to provide long-term energy. The combination of the two into a hybrid battery satisfies both needs and reduces battery stress, which reflects in a longer service life.

Future research has to concentrate on cost, manufacturing process and lowering internal resistance. Currently, researches to use Supercapacitors in the electric vehicle industry are being conducted with good results. It is believed that the use of supercapacitors in a hybrid system with batteries or hydrogen fuel cells can have longer lifetimes and better storage/power perform.

2.2.5 Superconducting magnetic energy storage (SMES)

The superconducting magnetic energy storage is a device that store electrical energy in a magnetic field, by flowing direct current into a coil made of superconducting cable and cooled to a temperature below its superconducting critical temperature. As there is no transformation to chemical or mechanical energy, the coils do not degrade with time so durability and reliability depend only on the power converters (Ferreira, 2013).

The system comprehend tree basic parts: superconducting magnetic coil, power conditioning equipment and refrigeration system. This storage technology has a very high efficiency and very fast response time, being suitable for power quality control. However, investments costs are very high due to the complex refrigeration requirements and the high cost of the cable.

SMES is an available and commercial technology used worldwide. It is mainly used in applications that require low-energy storage and shorter duration of power supply. In Europe, some small devices can be found, but not in a representative quantity.

2.2.6 Battery energy storage

The battery energy storage comprises a rechargeable battery system and a control and power conditioning system (C-PCS). Rechargeable batteries are electrochemical cells that use chemical reaction to convert electrical energy into chemical energy to be stored. When electricity is needed again, a redox reaction (reduction-oxidation) occurs and the electric current flows through the external circuit from the cathode to the anode. The C-PCS works as a voltage regulator to improve power quality, acting like an interface between the battery and the loads from the grid, regulating charge and discharge operations and charging rates.

An electrochemical cell has three basic components: the positive electrode (cathode), a negative electrode (anode) and the electrolyte (liquid or solid). The voltage of the battery is produced when the two electrodes are immersed in the electrolyte and usually a voltage from one cell is between 1V and 2V, many cells are connected in parallel or in series in order to increase the voltage. The basic components of a battery are shown in *Figure 11*.

Different types of batteries are being developed nowadays, with different electrodes and electrolyte. Some are already commercially available, but others are still in an experimental stage. For power system applications, the deep cycle batteries are most commonly used, with capacities of 17 to 40 MWh and efficiencies about 70 – 80% (Divya and Østergaard, 2009). Some of these batteries are briefly described below.

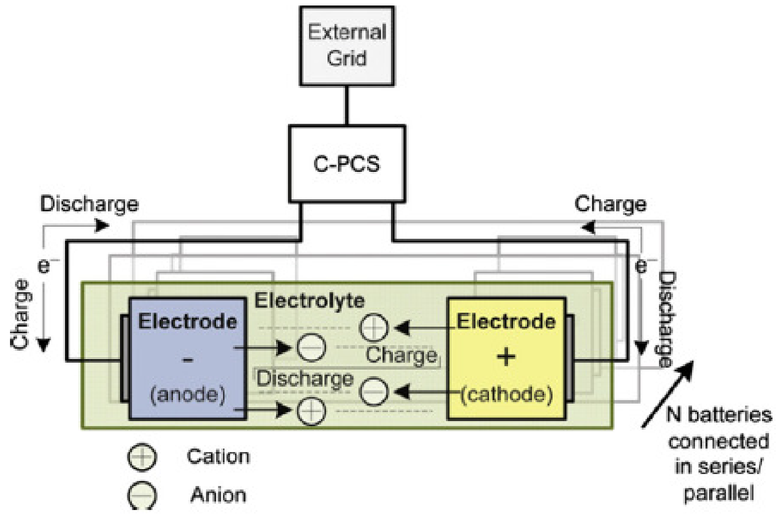

Figure 11: Basic components and operating process of a battery energy storage (Yekini Suberu et al. 2014)

Lead-acid batteries (Pb-acid)

The lead-acid battery was the first rechargeable technology available for households and industrial application. It is composed of a positive electrode of lead dioxide, a negative electrode of sponge metallic lead and the electrolyte is a sulfuric acid solution, having lead as the current collector. The reactions are as follows (right to left: discharge; left to right: charge).

Cathode reaction: $PbO_2 + HSO_4^- + 3H^+ \leftrightarrow PbSO_4 + 2H_2O$ (1)

Anode reaction: $Pb + HSO_4^- \leftrightarrow PbSO_4 + H+ + 2e^-$ (2)

It was largely used due to its low cost and mature technology, however today is losing space for other batteries types with higher efficiency and energy density. In addition, the use of heavy metal components, which are toxic and bring a high environmental impact if leaks occur, makes it not the favorable technology to be used as energy storage system. Nevertheless, some facilities still continue to use it as in Wittstock-Alt Daber, Brandenburg, Germany – an installation combining electricity generation from PV cells and battery storage of 2 MWh.

Nickel-cadmium (Ni-Cd)

The Ni-Cd battery uses nickel oxyhydroxide as cathode, metallic cadmium as anode and a potassium hydroxide as an alkaline electrolyte. The reactions are as follows (right to left: discharge; left to right: charge).

Cathode reaction: $2NiOOH + H_2O \leftrightarrow 2Ni(OH)_2 + OH^-$ (3)

Anode reaction: $Cd + 2OH^- \leftrightarrow Cd(OH)_2 + 2e^-$ (4)

This kind of battery was extremely popular on the 1990s due to its mature technology, more robust to deep discharge, longer life cycle, temperature tolerance and higher energy density than Pb-acid. However, it lost space to new technologies today, as the cadmium makes it extremely expensive. Also, another downside from this type of battery is the memory effect – it is the need of always fully charge and discharge the battery, otherwise it will “forget” the new charging state and “remember” to discharge based on its previous charging condition, reducing the available capacity (however, physically capacity is not reduced). Due to the high environmental impacts of the toxic metals used, the European Union has banned the use of this technology (except for medical uses), with the so-called "batteries directive" (2006/66/EC), but this technology is still largely used in US and Japan. One of the largest storage facilities using NiCd batteries is operated by the Golden Valley Electric in Fairbanks, Alaska, with a capacity of 27 MW and it helps to stabilize the grid.

Sodium-sulfur batteries (NaS)

This kind of battery works with a molten sulfur as the positive electrode and molten sodium as the negative one, separated by a solid beta alumina ceramic electrolyte, which only permits the positive sodium ions to go through it and produce with sulfur the sodium polysulfide, this reaction must be kept at high-temperature of 300°C.

Discharge reaction: $2Na + 4S \leftrightarrow Na2S4$ (5)

This technology has an excellent lifecycle and high energy density, however it shows some serious disadvantages as the high operational temperature and the fact that the isolating system must be extraordinary (sodium can explode when in contact with humidity of the air). In September 2011, an explosion at a facility in Tokyo using this technology caused the suspension of the production of this kind of battery by NGK – an important manufacturer in Japan.

Lithium-based (Li-ion)

Lithium batteries use lithium metal or lithium compound as cathode and a graphitic carbon with a layer structure as anode. The electrolyte is made of a solution of lithium salts dissolved in organic carbonates. When charging, lithium atoms in forms of ions run from the cathode to the anode, collecting electrons and being deposited as lithium atoms in the carbon structure, having the opposite movement when discharging. The reactions are as follows (right to left: discharge; left to right: charge).

Cathode reaction: $CoO2 + Li+ + e– \leftrightarrow LiCoO2$ (6)

Anode reaction: $LiC_6 \leftrightarrow C_6 + Li+ + e^-$ (7)

This type of battery is largely used today in portable devices such as laptops and mobiles as they offer high energy to weight ratio, do not show memory effect and have a low self-discharge. They are also likely to be set as dominant technology for electric vehicles application, which the large research and development driving costs down. However, prices can be the biggest obstacle of this technology for bigger systems to be used in power storage, although there are several grid energy storage facilities such as the battery storage power station in Schwerin, Germany with capacity of 5 MWh and an output of 5 MW to compensate for short-term power fluctuations. In Braderup, also Germany, the largest hybrid batteries system in Europe operates since July 2014, mixing a Li-ion battery storage with 2 MW power and a vanadium flow battery storage with 330 kW power. The system is connected to the grid and to the local community windfarm, storing the wind energy when needed. Another storage is located in Dresden, Germany with a peak power of 2 MW and it is in operation since March 2015. But, in September 2015 the largest battery energy storage project in Europe opened in Feldheim, Germany with capacity of 10 MW. The storage provides control of fluctuations to the power grid caused by wind and solar power plants. Many storage facilities using Li-ion batteries are also seen in UK, such as the 2 years project of 6 MW battery power plant at the Leighton Buzzard substation, northwest of London. The aim of the project is to explore ways to maximize the value from energy storage, by offering multiple benefits from the storage to both the local network and the wider UK system. Another important project in UK is in the UK's Orkney Islands that has a high penetration of renewable energy. The project started in 2013 and has the intention to demonstrate power supply stabilization in the region with a storage system with a power output/input of 2MW.

Flow batteries

Flow batteries differ from conversional batteries, as the energy is stored in the electrolyte solutions and it is based on the reduction-oxidation reaction between two electrolytes (which is reversible, allowing charge and discharge). It consists of two separated tanks containing the two electrolytes, which are pumped to circulate through an electrochemical cell with a cathode, an anode and a membrane separator. The amount of electrolytes (size of the tanks) determines the energy density, but the power density depends on the size active area of the cell (between electrodes). Flow batteries can release energy continuously at a high rate of discharge for up to 10 hours and have no self-discharge, as there is no reaction outside of the reaction chamber. Three different electrolytes form the basis of the existing designs of flow batteries currently in demonstration or in large-scale project development.

Polysulphide Bromide (PSB) is a regenerative fuel cell that promote a reversible electrochemical reaction between two salt solutions, sodium bromide and sodium polysulphide, separated by a polymer membrane that only allows sodium ions to go through. PSB has been verified in the laboratory and demonstrated at multi-kW scale in the UK.

Vanadium redox battery (VRB) stores energy by using vanadium redox couples in mild sulfuric acid solutions as electrolytes. During charge and discharge, ions from hydrogen are exchanged between the two electrolytes tanks. VRB has several potential applications in improved power quality, peak shaving and increased integration with renewable energy systems. This is the most researched flow battery technology in Europe, with projects in Germany, UK, Italy, Netherlands, Denmark, Spain and Portugal.

Zinc Bromine battery (ZRB) has a solution of zinc bromide as electrolyte and a carbon-plastic composite as electrodes, separated by a micro-porous polyolefin membrane. During charge, metallic zinc is deposited on one side of the carbon-plastic electrode, while zinc and brome combine into zinc bromide during discharge. ZRB offers the highest energy density among currently available flow batteries as two electrons are released per atom of zinc. However, the materials are expensive and the use of bromine can be dangerous.

From all the technologies presented, Lead-acid is the most mature and used in power system applications. Ni-Cd was developing quite fast, but the restriction in Europe made this technology less attractive for the energy storage market. Li-ion and NaS are today leading in use for high-power and density applications and Li-ion is the technology showing biggest potential for future deployment and optimization, as they offer small system size, low weight, high energy density and storage efficiency close to 100%, having its costs still the barrier to be overcome. An estimate of more than 100 projects in Europe, among Spain, France, UK and Germany, are being developed based on this technology (Divya and Østergaard, 2009).

Yet, flow batteries have the also promising development for long duration storages, due to its zero self-discharge characteristic. Researches are based on the future development of this technology with an increased power density, however the investment and running costs associated with the operation of a chemical plant need are still to be overcome.

2.2.7 Hydrogen storage

The main components of a hydrogen storage system include an electrolysis unit, the storage component and an energy conversion (re-electrification). The principle involved is to use off-peak electricity to produce hydrogen thought the electrolysis of water. The oxygen can be released or stored and the hydrogen is specially stored. Hydrogen is one of the most common elements available on Earth and it can actually be produced from many substances such as natural gas, oil, coal, biomass or water. Only a small amount of the world hydrogen production is based on water electrolysis, which is considered the only truly clean energy without any production of CO_2 and zero environmental impact, but currently most industrial methods use natural gas as resource.

When energy is needed again, the hydrogen is re-electrified, having electricity available to the grid again. (Hala, 2012; EASE website; Sharaf and Orhan, 2014).

A diagram of the process is shown in *Figure 12*.

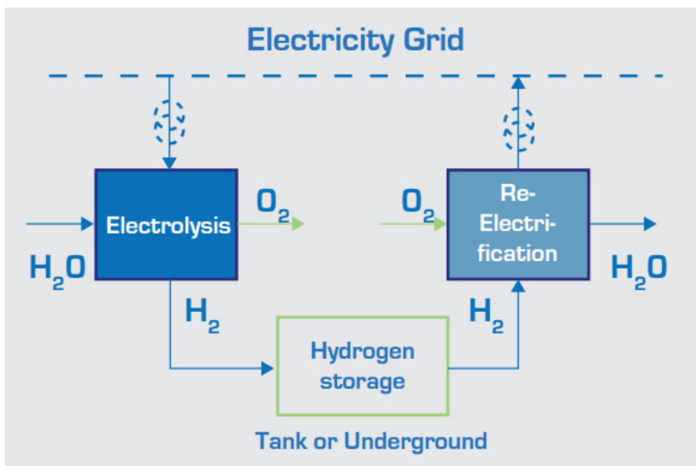

Figure 12: Diagram of a hydrogen storage plant (EASE)

Electrolysis unit

The electrolysis phase requires two electrodes made of an inert material (typically platinum, stainless steel or iridium) inserted in water. Connecting electric power to the system, a voltage will impose between the two electrodes and, as a result, hydrogen will be formed at the negative electrode (cathode) and oxygen will appear on the positive electrode (anode). The reactions involved are:

Cathode reduction	$2\ H^+ + 2e^- \rightarrow H_2$	(8)
Anode oxidation	$2\ H_2O \rightarrow O_2 + 4\ H^+ + 4\ e^-$	(9)
Overall reaction:	$2\ H_2O \rightarrow O_2 + 2\ H_2$	(10)

Electrolysis of pure water requires a big amount of energy to the system, as pure water has very low conductivity and the self-ionization necessary for the process is very poor. To increase efficiency in the system, an electrolyte (such as a salt, an acid or a base) is used, as well as electro catalysts to promote the ionization of water and continuous flow of the ions, increasing conductivity. Many techniques can be used, but two are the most available: alkaline and polymer electrolyte membrane (PEM). High temperature electrolysis is also being vastly studied, with some advances in research and development, but as the power input is mainly heat (electrical power can be used, but is not needed), it will not be discussed on this work.

Alkaline water electrolysis is the most mature technique for water electrolysis. The solution used as electrolyte is usually potassium hydroxide or sodium hydroxide, being the first one commonly used due to the higher conductivity. This technique increases the efficiency of the electrolysis by 75%, when compared with pure water, and typical temperatures for operation are between 80 - 100°C.

With PEM (Polymer electrolyte membrane) electrolysis, the electrolyte is a solid polymer electrolyte (SPE), precisely a polymer membrane that is responsible for the flow of ions between the electrodes. It has some advantages over the alkaline electrolyzer such high-pressure operation and high current density, which can be crucial for systems coupled with variable energy sources such as wind and solar, resulting in lower operational costs. Moreover, using PEM, the outcome is a more pure hydrogen due to its solid structure that act as filter for the gas – a high gas purity is important for storage safety. However, this technology is today available in MW-scale and in demonstration phase, still having high costs as the biggest disadvantage.

Storage component

Storing hydrogen is not an easy task. The storage must be completely safe as hydrogen is a very light and flammable gas, so any leak can cause a serious accident. Moreover, hydrogen has a large density – 11m^3 per kg at ambient temperature, which means that under normal conditions it will use 3,000 times more space than a gasoline storage, for the equivalent amount of energy stored (Hala, 2012).

There are mainly four technologies today for hydrogen storage: high-pressure tanks, absorption in metal hydrides, liquid hydrogen tanks and absorption on carbon nanofibers. The firsts two are most commonly used, as technology is more mature and developed. The last two are still being researched or under development phase.

With high-pressure tanks, hydrogen can be stored in a stable way. Steel tanks can storage the gas under pressures at 200 – 500 bar, but still with low ratio of hydrogen per unit weight. Tanks with aluminum liners and reinforced with composite materials can handle high pressures (up to 350 bar), increasing the ratio in 5%. Researches are working in new materials that can handle even higher pressures, which is key to reduce storage volume.

Metal hydrides storages are capable of absorbing hydrogen (on its proton form) and restoring it when needed in a safe and compact way (most have high volume absorption capacities), operating in low pressure (1 bar) and at room temperature. However, this technology requires a thermal control, as temperature of the system increases when hydrogen is absorbed (exothermic process) and decreases when it is released (endothermic process) (Hadjipaschalis, 2009).

Liquid hydrogen tanks have limited use due to the extreme temperatures that need to be reached to keep hydrogen in liquid form (-253°C) and the high cost of the thermal insulator needed for the tank. The storage is considered inefficient due to the high amount of energy that is needed to keep the storage cold.

Hydrogen can also be stored in carbon nanofibers under conditions of 12 MPa pressure and ambient temperature but this technology is still under research stage.

Energy conversion

The final energy conversion phase will depend of the final use of the hydrogen. Here, many pathways are possible and the versatility of this technology is one of its greater advantages, having the final uses combined or not, depending of the grid necessity.

For this last step, mainly three technologies are being used today: combined-cycle gas turbine (CCGT), hydrogen combustion engines and fuel cells.

Combined-cycle gas turbine (CCGT) is a mature technology to reconvert hydrogen into electricity again and currently is the most available solution. Special gas turbines are used that can burn hydrogen-rich gas. Hydrogen can be mix with natural gas, synthesis gas or biogas. The turbine is coupled with an electric generator, transforming the energy into electricity to the grid.

Hydrogen combustion engine is used only in the transport sector – electrical energy cannot be produced with this technology, only mechanical energy, working similar as the traditional combustion engine using gasoline. A mix of air and liquid hydrogen is added to the chamber to create an explosion that propels the pistols inside of the engine. It is estimated that the power output is 20% higher than a gasoline engine and the residue is only water vapor, as shown in the reaction (4). Therefore, it is considered a clean technology with zero GHG emission.

Combusting reaction: $2\ H_2 + O_2 \rightarrow 2\ H_2O$ (11)

However, this technology usually does not replace completely the use of fossil fuels, as the market is using vehicles with a hybrid system, using both traditional and hydrogen engine due to the low availability of H_2 station fills. In addition, the complexity of this engine type is very high, with many special valves, connections and materials, which makes it very expensive when compared with the traditional version.

Fuel cells are currently one of the technologies that are being most researched due to its versatility, as it can be used in the electricity market (returning electricity to the grid) and in the transport market, with the use of fuel cells vehicles. They differ from batteries in a sense that continues fuel and air input leads to a continuous process, whereas in a battery, the chemicals present in the battery react and when they are over, the process ends.

A fuel cell is, basically, a system to convert chemical energy from a reaction to electrical energy, by doing the reversal reaction of the electrolysis. The components are a fuel electrode (anode), an oxidant electrode (cathode), and an electrolyte. The hydrogen is oxidized in the anode, leading to the detachment of electrons (reaction (5). These electrons flow in an external circuit from the anode to the cathode, producing electricity. At the cathode, oxygen reacts with the positive hydrogen ions, production water (reaction (6)). The overall reaction is shown below:

Anode reaction: $H_2 \rightarrow 2\ H^+ + 2\ e^-$ (12)

Cathode reaction: $O_2 + 4\ H^+ + 4\ e^- \rightarrow 2\ H_2O$ (13)

$$\text{Overall reaction:} \quad 2\,H_2 + O_2 \rightarrow 2\,H_2O + W_{ele} + Q_{heat} \qquad (14)$$

The heat and the power must be continuously removed from the system in order to maintain the operation in an isothermal way. The power output is direct current (DC), which means that a transformer must be used to convert it to altering current (AC) and be connected to the grid. Fuel cells have a simple system and higher efficiency when compared to hydrogen gas turbines.

The fuel cells are categorized by the type of electrolyte it uses. There are many types today already available and others are in development phase. To mention, PEMFCs (Polymer electrolyte membrane fuel cells) is the one mostly used – same technology as the electrolysis phase. PEMFCs are extremely flexible, good efficiency rates and easy to operate, being vastly used in the transport sector and the fuel cell in vehicles. Downside is that is still too expensive, especially when compared to batteries for the electric cars (Sharaf and Orhan, 2014).

Alkaline fuel cells (AFCs) can also be used, however their lifetime is shorter due to CO_2 impurity (which contain in the air), so its use is more seen by NASA in space applications.

PAFCs (Phosphoric acid fuel cells), MCFCs (Molten carbonate fuel cells) and SOFCs (Solid oxide fuel cells) are also been used in the market, especially for combined heat and power applications in stationary power generation, as they operate in high temperatures with high efficiency, however the high temperature also reduces the lifetime of those fuel cells.

As said, hydrogen can be used in the transport sector (so called power-to-mobility) in fuel cell cars or a hydrogen combustion engine cars. It can be transformed again in electricity (power-to-power) using gas turbines or fuel cells, having the same advantages as all other energy storages; can also feed directly the natural gas grid (power-to-gas). In addition, a fourth option is to distribute the produced hydrogen to the industry to be converted into another chemical. A diagram with the different uses for hydrogen is demonstrated in *Figure 13*.

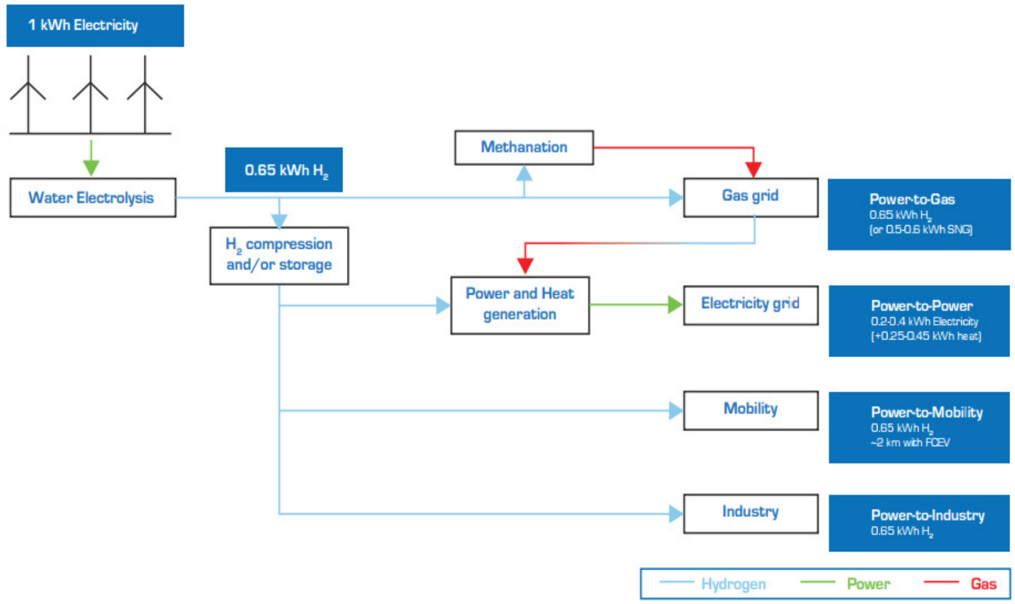

Figure 13: Different proposes for hydrogen use (EASE)

In Fusina, Italy, the first hydrogen power station inaugurated in 2010. The plant uses the hydrogen captured from refining operations at a nearby petrochemical installation into a combined-cycle power plant. It has a capacity of 16 MW.

In Germany, they first hybrid wind and hydrogen plant entered in operation in 2011. The plant is located in Prenzlau and has 500 kW electrolyzer. The hydrogen produced can be sold to the market or transformed in electricity again using a gas turbine.

Since 2012 the MYRTE project has been connected to the grid in the French island of Corsica. It combines solar power with electrolyzer, hydrogen storage and fuel cells with a developing technology called Greenergy Box™.

In the end of 2013, the INDRIG project led by McPhy started operation in the Apulia Region, Italy. The project is 39 MWh energy storage facility using hydrogen stored in solid-state form (as MgH_2). The plant will store energy from solar, wind, and biomass plants of the region, by producing hydrogen via electrolysis and when energy is needed again, a fuel cell power system.

Many other projects are in development in Europe for hydrogen storage integrated with intermittent renewable generation, from a size range of a few kW to some hundred MW. Most of them have the objective the use of hydrogen for mobility or direct use of the gas in the grid.

Hydrogen storages is a very promising technology for long-term storage due to its flexibility and versatility, allowing integrating energy storage with chemical production. However, it is still at an early stage of development and it is still difficult to predict when it will be commercially available in large volumes. Some experts estimate the market time line from 10 to 40 years.

2.2.8 Power to gas – methane (PtG-methane)

Power to gas technology is being established as one of the potential technologies on the pathway to energy storage. One part of the power to gas technology, called power to hydrogen, has already been described in the Hydrogen storage section 2.2.7 of this work. Hydrogen can be added directly into the natural gas grid (up to 10% of volume can be injected into natural gas – this is actually a huge quantity of hydrogen and the natural gas storage and distribution could be used for free) (EC, 2013).

Another pathway for the power to gas is the production of methane, happening in two steps: first, there is the production (and storage, if needed) of hydrogen through electrolysis of water, using technologies already discussed on section 2.2.7 of this work. Then, the idea of the PtG-methane is to use this hydrogen to produce methane that can be injected to the natural grid (at any quantity) or used as CNG motor fuel. A diagram of the process chain can be seen in *Figure 14*.

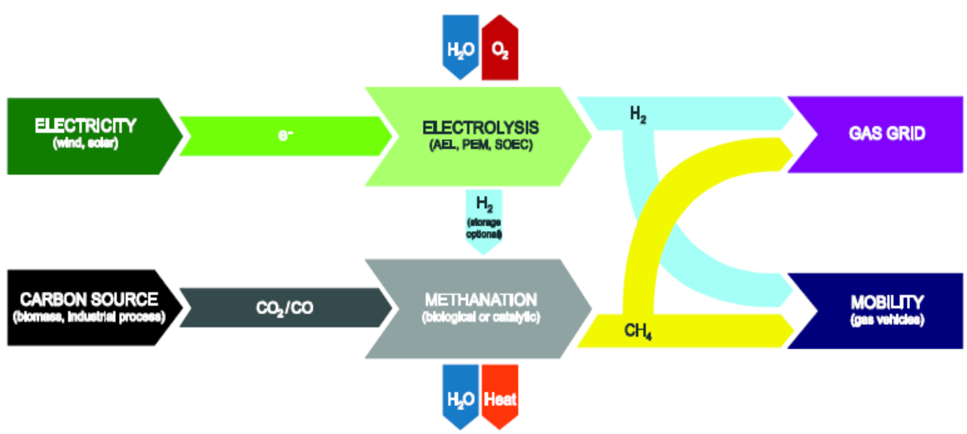

Figure 14: Diagram of PtG process chain (Goetz et al, 2015)

The methanation process is the reaction between CO_2 and/or CO with hydrogen, producing methane and water, as it is show in the reactions below:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O \qquad (15)$$

$$CO + 3\ H_2 \rightarrow CH_4 + H_2O \qquad (16)$$

The methane produced is called synthetic natural gas (SNG) and its properties must be similar to the natural gas, which has a concentration of CH_4 of more than 80%. Hydrocarbons as ethane, propane and butane are also important as they increase the calorific value of the mixture. The reaction is extremely exothermic, meaning a large quantity of heat will be produced, which can be recovered and used as thermal energy (Goetz, 2016).

The methanation can be done in a catalytic or a biological reactor. Catalytic reactors are typically operated at pressured from 1 to 100 bar and in temperatures between 200° - 500°C. The catalyst is metal, mostly nickel, ruthenium, rhodium or cobalt. Usually nickel is the most utilized as it has a high activity, good CH_4 selectivity and low price. There are many reactions in research for this process, as fixed-bed, fluidized-bed, three-phase and structured reactors. Each of these materials offers a different solution for removing the heat (essential to maintain efficiency).

Biological reactors are using methanogenic microorganisms as catalyst. The whole process is slightly more complex, but all done in one big reactor at ambient pressure and temperatures between 20° to 70°C. The first step is the hydrolysis of the biomass to simple monomers as amino acids and monosaccharide. Then, they are converted into acetate of smaller chains and CO_2, which is then transformed by microorganisms still into methane. To increase efficiency, hydrogen is injected in the mass, as the hydrogen concentration in water is lower than CO_2.

There are several pilot projects and demonstrations sites in Europe using both technologies. Some studies point the catalytic reactor as a preferential route as the size of the reactor can be smaller, efficiency is higher and the heat produced is used as a co-product. Nevertheless, research proved that the most costly factor of this technology is yet the hydrogen production (Goetz, 2016).

Audi e-gas, a project from ETOGAS for Audi AG, is the first industry-scale PtG-methane plant located in Werlte, Germany. The plant is using the CO_2 produced as waste from a close biogas plant and producing SNG that can be fed into the local gas grid or used in CNG vehicles.

In 2013, a demonstration project with 250kW electrical input power was put in operation in Stuttgart. The plant is running with the excess of renewable energy sources from wind and solar to produce hydrogen and methane to be fed in the grid. The project uses SolarFuel GmbH (now ETOGAS GmbH) technology.

The project HELMETH (Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion) started in 2014 with perspective to end in 2017. The objective of the project is the proof of concept of a highly efficient PtG technology by thermally integrating high temperature electrolysis with CO_2-methanation. A methane output of approximately 30 kW is targeted.

2.3 Comparison of different types of energy storage technologies

Table 3 shows the comparison between the different types of energy technologies described. The table was built compiling data collected from recent literature and empiric data.

Table 3: *Energy storage technologies comparison*

Tech.	Storage capacity (MW)	Energy density (Wh/kg)	Efficiency (%)	Response time/ availability	Self-discharge/ loss (per day)	Discharge time	Charge time	Lifetime (years)	Lifetime cycles	Capital cost ($/kW)	Maturity	Environmental impact	Advantage	Disadvantage	Suitable for
PHES	20 - 2100	0.5 - 1.5	75 - 85%	~1 min	15 - 25%	1 - 24h	hours	> 40	20000 - 50000	1000 - 2200	mature	medium - high	huge power capacity flexibility high round-trip efficiency	low available suitable locations environmental impacts	load management pick generation backup and reserves
CAES	20 - 350	30 - 60	50 - 80%	~10 min	negligible	1 - 24h	hours	20 - 60	> 13000	700 - 1200	available AA-CAES research	low (AA-CAES or Isotherm CAES) medium (fossil fuel needed)	high capacity	problematic to obtain sites for use	load management power quality
FES	0.25	5 - 130	< 90%	ms	100%	ms - 15min	minutes	15 - 20	20000 - 100000	600 - 1000	available	low	long time life low maintan. cost high efficiency	low energy density large standby losses dangerous failure modes	power quality
Supercapacitors	0.3	0.1 - 5	85 - 95%	s	20 - 40%	ms - 60min	seconds	10 - 20	unlimited	1000 - 2000	developing	low	performance at low temperature no need for maintenance fast response time extreme durable	high cost high self-discharge low energy density	power quality transport

Tech.	Storage capacity (MW)	Energy density (Wh/kg)	Efficiency (%)	Response time/ availability	Self-discharge/ loss (per day)	Discharge time	Charge time	Lifetime (years)	Lifetime cycles	Capital cost ($/kW)	Maturity	Environmental impact	Advantage	Disadvantage	Suitable for
SMES	0.1 - 10	0.5 - 5	95 - 98%	ms	10 - 15%	ms - 8s	minutes - hours	10 - 20	>100000	100 - 400	available up to 10MW	medium	high efficiency durability and reliability short response time low maintenance	high cost impact of magnetic field	power quality load management
BES Pb-acid	> 40	30 - 50	70 - 90%	ms	0.1 - 0.3%	s - h	hours	5 - 15	100 - 1000	200 - 650	mature	high	high availability (mature technology) low cost	weight low specific energy short cycle life	transport power quality bridging power
BES NaS	> 10	150 - 240	80 - 90%	ms	~20%	6 - 7h	hours	10 - 15	2500 - 4500	700 - 2000	available	medium	high lifetime cycle high energy density	high operational temperature Na explodes in contact with humidity	power quality peak shaving
BES Ni-Cd	> 40	50 - 120	60 - 91%	ms	0.2 - 0.6%	s - h	hours	10 - 20	2000 - 2500	350 - 1000	available	high	high storage capacity long life cycle	NiCd is highly toxic Memory effect	transport power quality bridging power
BES Li-ion	0.1	100 - 200	85 - 95%	ms	0.1 - 0.3%	0.2 - 4h	hours	5 - 15	1500 - 4500	700 - 3000	available / developing	medium	high power and energy density high efficiency	high cost Lithium oxide & salt require recycling	transport power quality bridging power

Tech.	Storage capacity (MW)	Energy density (Wh/kg)	Efficiency (%)	Response time/ availability	Self-discharge/ loss (per day)	Discharge time	Charge time	Lifetime (years)	Lifetime cycles	Capital cost ($/kW)	Maturity	Environmental impact	Advantage	Disadvantage	Suitable for
Flow batteries	> 15	60 - 80	70 - 80%	< 1 sec	negligible	few sec - 5h	hours	5 - 15	5000 - 10000	1000 - 2500	research / developing	medium	high capacity	Low energy density	power quality bridging power load management
H_2 (gas turbine)	0 - 50	-	50-85%	< 1 sec	negligible	hours	hours	5 - 10	-	1300 - 2700	research / developing	low	flexibility	high cost electrolysers with low efficiency	power quality load management bridging power
Hydrogen (fuel cell)	0 - 50	800 - 100000	50 - 85%	< 1 sec	negligible	hours	hours	5 - 15	20000	2000 - 4000	research / developing	low	flexibility versatility	high cost electrolysers with low efficiency	transport power quality load management bridging power direct use in gas grid
PtG-methane	0 - 100	-	55%	-	negligible	-	-	5 - 20	-	2600 - 4300	research / developing	low	flexibility versatility	still low efficiency	transport direct use in gas grid

Source: adapted from Evans et al (2012); EC (2013); Ferrera et al (2013); Mahlia et al (2014); Ponsot-Jacquin, Bertrand (2012); Kousksou et al (2014); Zakeri and Syri (2015); Chen et al (2009)

2.3.1 Key parameters for comparison

In order to better understand the comparison of the different type of energy storage technologies and have a clear evaluation where each technology can be applied, depending of the application, the key parameter used on this work are explained.

- *Storage capacity (W or MW)*

It is the maximum available energy per unit of time in the storage system after charging.

- *Energy density (Wh/kg)*

This is the usable energy content per unit of mass of the storage unit – it can also be seen per unit of volume. The higher the energy density is, the more energy may be stored for the same amount of volume or mass.

- *Efficiency (%)*

Efficiency can be simplified by the ratio between discharged energy (useful energy) and total stored energy. However, the whole system must be evaluated and for more than one cycle, as the useful energy of a storage system depends of charging, no load and self-discharge losses. Overall, good storage systems are the ones with higher efficiency (Ibrahim, 2008).

- *Response time/ availability*

It is the length of time that it takes for the storage device to start releasing power.

- *Self-discharge/ losses*

This represents the portion of energy that will be lost during loading, unloading or dissipated over non-use time.

- *Discharge and charge time*

Discharge time is the amount of time a storage technology can maintain its output. On the other hand, charge time is the time the storage needs to load to maximum capacity.

- *Lifetime*

This correspond to the total lifetime estimated for the storage until the efficiency still is at an acceptable level. After this period, it considers the ageing of the system and its degradation. The lifetime can also be represented in number of cycles, which represents the total number of charges and discharges the system can perform in its operational life with the same efficiency that it was designed for.

- *Capital cost*

As any project, the investment cost is always one of the most important parameters. The cost should be given by the capacity that the system is able to generate, in order to be comparable.

- *Maturity*

This refers to the maturity of the technology itself. Many technologies are vastly marketed today and many are still under development or not in large scale yet.

- *Environmental impacts*

Nowadays people are more and more conscious about the environmental impacts of all goods that are consumed, energy included. Even though this is not a criteria of storage system capacity, it is important to analyze the technology's impact and sustainability.

3 EU renewable policy and targets

A projection from the International Energy Agency (IEA) estimates that renewable energy will be the main source of electricity by 2035. This is a plausible statement when looking how many countries in the world today have a renewable energy support policies in place. In *Figure 15* below, it is possible to see the increase of policies for RES all over the world from 2005 to 2015. At the end of 2015, 146 countries in the world had at least some kind of renewable energy policy.

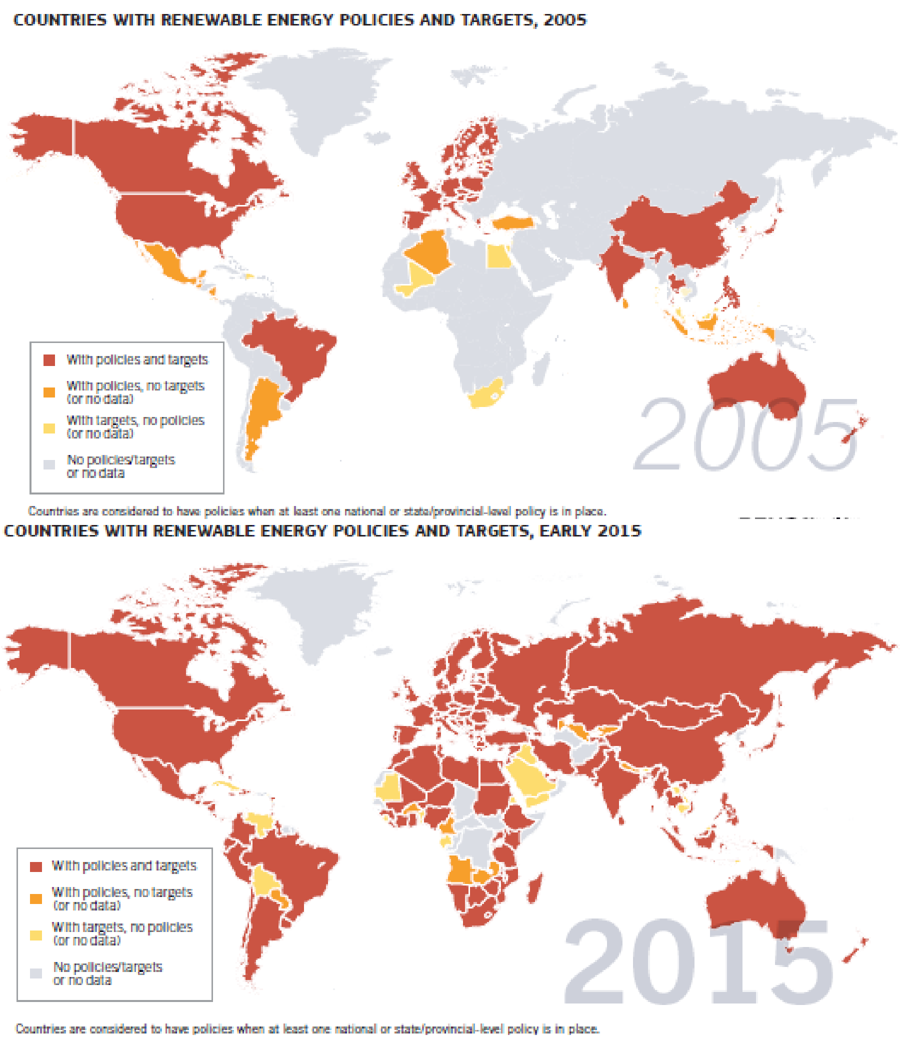

Figure 15: Countries with renewable energy policies in 2005 and 2015 (REN21, 2015)

In fact, those policies and targets were really the trigger driving the increase of the share of RES in the electricity generation mix seen today, especially in the European Union.

In the trajectory of the development of renewable energy technologies, environmental policies worldwide play one of the most important roles. In the subject of promoting global sustainable development and combating global climate change, a long run was accepted by society worldwide. However, the governments and policymaking organizations, together with the support of opinion makers, researchers and scientists, have the mechanisms to drive our economy and society to a low-carbon environment through political strategies, management, and leadership. Private sector and society are also making their part, but the effectiveness that renewable policies and targets have in all sectors, incentivizing new ways of thinking and concepts, is extremely positive.

Protocols and agreements discussed in a worldwide level have guided policies and frameworks adopted by each country in the world and those have developed new business and promoted market adjustments and regulations in order to achieve the sustainable targets proposed by each.

This also applies to electricity markets where many mechanisms are used to increase competitiveness, drive down the cost of electricity and provide a high quality service to consumers with lower tariff. Regulation and environmental policies act directly on the promotion of new technologies in order to achieve mandatory targets towards a low-carbon grid, in all energy chain (generation, transmission, distribution and end-users).

A review of the policy framework for renewable energy for European Union is given, as well as the prospects the European commission is foreseeing for the future.

3.1 EU policy framework for RES

In preparation for the *Third Conference of the Parties to the United Nations Framework Convention on Climate Change*, held in Kyoto in December 1997 - which resulted in the Kyoto Protocol, the European Union set the basis for the renewable energy policy in Europe in a document called *White Paper for a Community Strategy and Action Plan Energy for the future: Renewable sources of energy*.

This document proposed to double the share of RES in the EU gross energy consumption from 6% to 12% by 2010. In addition, some specific targets for the development of each renewable technology were set, for instance 135Mtoe of energy production from biomass, 40 GW installed capacity from wind energy, 3 GWp installed capacity from photovoltaic energy, 5 GWth for geothermal heat and 1 GW for geothermal electricity and 105GW for hydropower.

In 2001, the European Commission set the *Renewable Electricity Directive 2001/77/EC*, to promote an increase in the contribution of RES to electricity production in the internal market and to create a basis for a future framework in RES. The indicative target was 21% of total electricity to be produced from RES by 2010 for the EU Member States.

The results were promising. Yet, the indicative target of the 2001/77/EC was not achieved. The final share of RES in the gross energy consumption in Europe was 12.8% in 2010. The biggest success was the development of RES technologies and their fast deployment, attracting investors and consolidating as important generators in the market. The electricity generation capacity for wind was 84 GW by the end of 2010 (more than double the target). For solar, it was reached 29 GW of installed capacity (almost 10 times more than previewed) (Scarlat, 2015).

Also, an important contribution was the organization of the stakeholders in all Member-State in EU to discuss and set national frameworks and support schemes for renewables and the penetration of these technologies in the energy market. Incentives to promote RES development and deployment were settled, such as fix feed-in tariffs and/or price premium for RES generators.

Continuing the work and reaffirming the compromise from the EU with the climate change, the *Renewable Energy Directive 2009/28/EC* on the promotion of the use of energy from renewable sources, repealing Directives 2001/77/EC (and 2003/30/EC for biofuels) was set in 2009. This directive brings mandatory targets for each Member-State of the European Union to achieve 20% of gross final energy consumption by 2020. The targets for each Member-State vary according to its capability and availability, from 10% (Malta) to 67.5% (Norway), submitted in the

National Renewable Energy Action Plants (NREAPs), which was proposed by each Member-State. The evolution of this target can be seen in *Figure 16* and it is considered on track for the 2020 target for the full picture of European Union. However, looking at each Member-State, Sweden has by far the highest share, 52.6% in 2014, already overcoming its target of 49%, followed by Latvia and Finland (both with 38.7% but targets of 40% and 38% respectively), Austria (33.1% and a target of 34%) and Denmark (29.2% with a target of 30%). The countries with still need to work more on their shares to achieve their targets are United Kingdom (7% in 2014, short from a target of 15%), The Netherlands (5.5% , short from 14%), Malta (4.7%, short from 10%) and Luxembourg (4.5%, short from 11%).

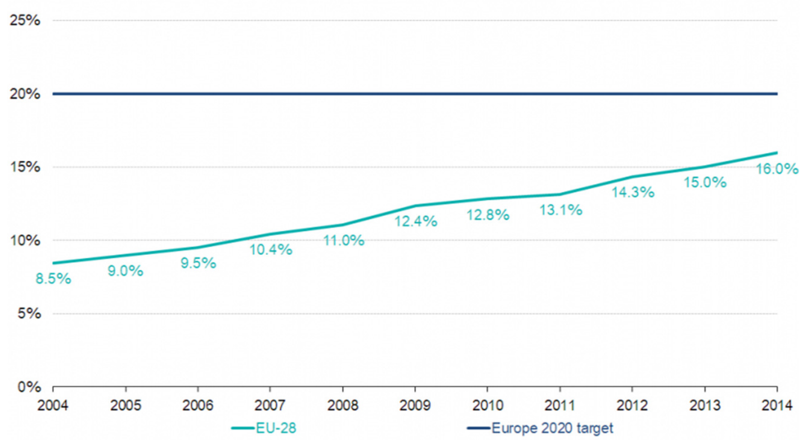

Figure 16: Share of energy from RES in gross final consumption of energy in EU-28 (Eurostat 2004-2014)

Besides, this directive also set a mandatory and equal share of 10% renewable energy source only in the transport sector by 2020 (including liquid biofuels, hydrogen or RES-electricity). In *Figure 17,* the share of each Member-State is shown in 2014. The average share in 2014 for EU-28 was only 5.9%, with Finland as most contributor (21.6%) and Estonia as the least (0.2% in 2014).

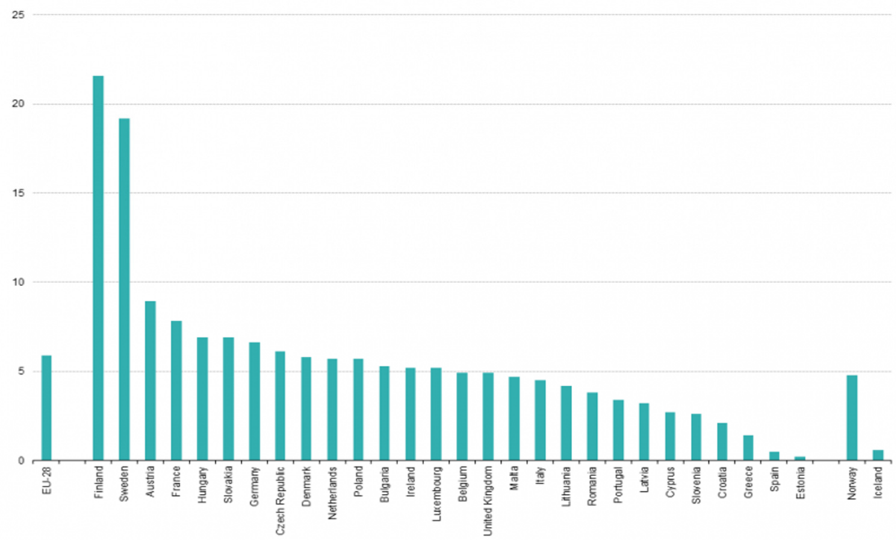

Figure 17: Share in % of RES on transport sector in EU-28 (Eurostat 2014)

As only biofuels that fulfil sustainability criteria stipulated by Renewable Energy Directive 2009/28/EC should be considered for the share – the main goal is GHG emission reduction - the biofuel sector has been hit, not being able to reach better targets. The consideration of the indirect land use change for the GHG calculation has penalized some biofuels and the so expected second-generation biofuels (the ones produced from waste, residues and lingo-cellulosic material) are still not largely available.

Nevertheless, the share of renewable energy in the transport sector is expected to grow in EU achieving 11.4% in 2020, above the target. This increase is justified by the estimated increase of the use of RES-electricity in the transport sector (with the electric vehicles) and the deployment of second-generation biofuels, which will impact with double counting for GHG emissions according to the RED 2009/28/EC.

This environmental package is part of the agreement the European Commission made in 2007 to reduce GHG emissions and limit global climate change to a maximum of 2°C increase the in world average temperature. All these policies are part of the EU 2020 Energy Strategy, which aims to reduce its GHG emissions by at least 20% (compared to the 1990 levels), increase the share of renewable energy to at least

20% of consumption in 2020 and achieve energy savings of at least 20% by 2020 compared to business as usual.

3.1.1 EU policy framework for energy storage

Today, in the EU policy framework, there is no reference to the use of energy storage as a combined generator and regulator (Anuta 2014). The Directive 2009/28/EC references on its Article 16 a support to energy storages:

"Member States shall take the appropriate steps to develop transmission and distribution grid infrastructure, intelligent networks, storage facilities and the electricity system, in order to allow the secure operation of the electricity system as it accommodates the further development of electricity production from renewable energy sources, including interconnection between Member States and between Member States and third countries […]".

However, there is no clear target or plans for an increase of storage capacities and incentives for new technologies, which can be attributed to the yet developing landscape of its knowledge.

As the development of energy storages is closely related to electricity market and policies, each Member-State have its own interests in the subject, with different stages of development (and as already said, mainly focus today is on PHES). Nevertheless, this development is very slow due to the economic challenge of making the investment attractive to investors.

In 2009, the Directive 2009/72/EC, called the Electricity Directive, was adopted for a better integration of the electricity market in the European Union. It guides common rules for the internal market in electricity for generation, transmission and distribution, also bringing definitions regarding all terms for the sector and permission or prohibitions for market players. The Directive misses energy storage systems as a separate component, giving free interpretation for the players. The result is that usually energy storage is treated as a generator.

This is what occurs to PHES that are today on operation in the electricity market. They are considered a traditional generator in the majority of the EU countries, not receiving any benefit for the flexibility services it can provide.

Gas storage facility is regulated in some markets in Europe for natural gas in order to regulate and control volatile prices in the international market. This regulation can be seen in countries like Austria, Ireland, Poland and Hungary. However, there is no mention on the regulatory framework about electricity storages.

Countries, which do not have any kind of regulation for storage (electricity or gas storage), are Belgium, France, Italy, Norway, Spain, Netherlands, Denmark and United Kingdom. In these places the existing electricity storage (many of them are PHES) are considered as a regular supplier.

Germany is the only country with some regulation for electricity storage. In Germany, the focus seems to be on large scale and centralized storage, differentiating gas and electricity, giving special inventive for PHES. The grid codes make no special requests on storage, but then again it must cope with requirements on load and generation. The aim is to use electricity storage for RES system integration and only for primary, secondary and minute reserve.

In Slovakia, the electricity storage is only covered by tariffing, mainly giving this privilege to PHES. On the other hand, in Czech Republic, there is no incentive scheme, nonetheless the access to storage capacity allocation is regulated and prices, market-based.

The European Union has developed the Strategic Energy Technology plan (SET-plan) with the objective to accelerate the development and deployment of low-carbon technologies by investing in research, innovation actions and development and demonstration. Electricity storage itself is not considered as one of the strategic areas in the plan. However, as it was identified that the main barriers for the deployment of energy storage are the insufficient performance of the technologies available and, consequently, its high costs, EU is supporting the research and development of those technologies under the initiatives of Smart Grids and Fuel Cells and Hydrogen.

3.2 Projections beyond 2020

To reinforce EU commitment to the low-carbon economy and, also, to show long-term compromise with its target, the European Commission launched in 2011 the *Roadmap for moving to a competitive low-carbon economy in 2050*. This document set out a cost-efficient pathway to make the European economy more climate-friendly, reducing its GHG emission to 80% - 95% when comparing to 1990 levels, and identify policy challenges, investments needs and opportunities in all sectors, as power generation, industry, transport, buildings, construction and agriculture.

To achieve the target, the document brings some milestones to be reached to a sustainable path, setting a cut of 40% in GHG emissions compared to 1990 levels through domestic reductions alone by 2030 and 60% by 2040. The share of low-carbon technologies in the electricity mix is estimated to reach 60% in 2020, 75 – 80% in 2030 and almost 100% in 2050 (Scarlat, 2015).

The Energy Roadmap 2050 COM/2011/885, issued in December 2011, is the official roadmap that detail the long-term European framework commitment with low-carbon energy system. Four main routes are explored in the document such as energy efficiency, renewable energy, nuclear energy and carbon capture and storage, in order to develop different scenarios with different shares of renewable energy.

Regarding energy storage, the document concludes that the costs are still be biggest barrier for storage technologies, being additional transmission capacity, gas backup generators and conventional technologies are today cheaper to the system. On the other hand, it recognizes that flexible facilities (as flexible generators, storage, demand management) are needed in the system to control of intermittent renewable generation and more will be needed in order to increase the share of VRE.

In 2014, the EU countries agreed on a new framework on climate change mitigation to 2030, endorsing a binding target of 40% reduction in GHG emissions by 2030 compared to 1990 levels, with at least 27% share of renewable energy in the EU energy consumption by 2030 and with at least 27% energy efficiency indicative target.

This framework will give fresh support to attract new investments in the renewable energy business and to the energy storage business as well. However, unlike as in the current framework RED 2009/28/EC, the European Commission decided (at least until now) not to set national targets via EU legislation, giving more flexibility to each Member-State to meet their national targets.

The Paris agreement, which was adopted at the Paris climate conference (COP21) in December 2015, set a commitment between rich and poor countries in the world to take action to mitigate climate change by limiting global temperature to rise to well below 2 degrees Celsius. It requires governments to elaborate and present national plans to reduce GHG emissions.

Until now, 62 parties that were accounting for almost 52 % of global emissions have ratified the Paris Agreement. With EU ratification, which happened in October 2016, it crossed the 55% of global emission threshold and the agreement should enter into force before the end of 2017.

With the Paris Agreement in place, a reformulation on the Renewable Energy Directive and the Energy Efficiency Directive should be expected.

4 Integrating energy storage and its possible impact on policies and market

The increase of the share of RES and new low carbon technologies in the electricity grid will bring some impacts on the conversional grid operation and in the performance of the transmission and distributions (T&D) networks. In an economy with a long-term strategy sustained by decarbonization, changes will be required on the current regulations and market operation in order to allow a 100% low carbon electricity grid, with (projected) 100% renewable energy sources, which will result in a very high share of intermittent energy sources.

Some discussion started within the European Commission in order to evaluate the best strategy that will permit the increase of VRE as targeted. The increase of energy efficiency is one of them, which consists of reducing energy consumption by increasing efficiency of the technologies and the system itself in order to deliver the same amount of electricity or service. In fact, targets for energy efficiency are already seen in the regulations such as the Energy Roadmap 2050.

Demand response with intensification of grid connection in T&D networks and introduction of smart grids can also minimize the difficulties of the increase of VRE technologies, with the shift of the consumption to match demand and supply by using backup generators in the grid. A long discussion here is expected, as the success of this pathway needs a perfect cooperation of all EU Member States and could be considered further the countries outside the European Union but still close geographically and/or important electric players. Not only that, it is also discussed the technologies to be used as backup generators – in a low carbon economy, low carbon and preferable renewable technologies would have to be applied (and also developed). Some technologies here in discussion are the use of biofuels, bioliquids, the production of energy from waste, geothermal and even hydropower, all technologies with good but limited potential in Europe (Steinke, 2013).

Lastly, there is energy storage, which can store energy by transforming electricity into other form of energy and retransforming again to electricity for later use. This is also an important pathway for increase RES integration and many discussions in the

European Commission are approaching this topic in detail for its development and deployment. The intention of this chapter is to highlight which challenges the energy storage system could bring to the grid regulation in European Union and to the European electricity market, and give some recommendations based on literature in order to allow the integration of energy storage system as an operator in the European electricity grid.

4.1 Challenges for energy storage

The challenges for energy storages that will be described here could be identified and classified as technological barriers, little or lack of support in regulation and difficulty to penetrate in the electricity market. Overall, the main challenge for energy storage development is making it economic available and attractive.

4.1.1 Technological barriers

The most important barrier for energy storages is the higher cost of implementation seen today when compared to conventional solutions for utilities, adding extra cost to the already expensive transmission and distribution grid. In addition, the limited operational experience in energy storages, except for some PHES, brings complexity and more costs for its integration (Anuta, 2013).

Moreover, an improvement in capacities and efficiencies of the existing technologies is extremely important to allow the deployment of those in the electricity market (EC, DG ENER 2013). As this paper presented, there are already some technologies commercially available, but the economical challenge is what makes them not to be widely spread and used and the improvement in their capacities and their system efficiency are crucial.

Many new technologies appear to be very promising for energy storage, as also described on chapter 3 of this work, but they are still at a very early stage of research and development and still cannot be considered for domestic or large centralized application, needing massive investment on research. A technological learning curve still needs to be overcome to drive costs down.

Another challenge that can be categorized as technological is the grid integration. Energy storage system can work as an actor in many kinds of grids and in many forms – connected to the electricity grid, in the transport sector, in the natural gas grid. The definition of where the storage is needed (generation, transmission, distribution or customer level) and the integration level have too high influence and can be a barrier for its deployment. As an example, one of the main challenges for the hydrogen use in the transport sector is the investment on charging stations, where they should be located and how they should be supplied. A whole package of integrated measures is still needed for large centralized and small-decentralized storages, promoting flexible generation and backup capacity.

4.1.2 Regulatory barriers

The regulation still does not have a holistic and systemic interpretation of the role of an energy storage system in the electricity market and this approach makes the energy storage system not attractive to the market and stakeholders. The difficulty in shaping and valuating the wide range of benefits among the electricity chain lead to an investment dilemma that delays the deployment of energy storage.

RES technologies were vastly implemented in Europe mainly due to subsidies. A big barrier for energy storage systems is the nonexistence of a compensation scheme in the legislation that would incentive the implementation and operation of energy storage, giving market premium or feed-in-tariffs for any service provided, such as power quality improvement, efficiency increase, demand response improvement, ancillary service or backup reserve. This is a key point for all stakeholders in the chain, transmission and distributors system operators (working usually in a regulated market) and for generator and consumers (acting in a deregulated market). Furthermore, energy provided from energy storage system is cannot be considered as renewable and count for the RES targets, even if the energy storage is loaded exclusively from RES energy (Papapetrou et al, 2013).

Renewable integration policies give high priority and financial compensation to renewable generators that control excess energy avoiding grid unbalance, promoting in a certain way the investment of energy storages close to the RES (before the meter) to improve intermittency (Anuta, 2014). In one side, this can be seen as an incentive for promoting energy storage systems and, in fact, do play an important role to develop some technologies. Yet, it may not be the optimal location on the grid to solve congestion problems.

Nowadays, there is an intensive discussion about the ownership of the energy storage system and if it should be considered to all stakeholders or not, as there is no clear rule for the asset classification. According to the Electricity Directive, TSO and DSO cannot have any type of control of an electricity generation facility and, in many cases, the energy storage systems are categorized as generators. Regulation also states that grid operators cannot participate in the electricity market, by means they could not benefit from the open market to bring more value to a possible energy storage system owned by providing services when it is not being used for grid support. This brings no incentive for grid operators to invest in energy storage systems, the ones who could benefit from it the most.

Regulation in each EU Member State determines which charges and taxes should be applied to generators and consumers. In many countries, energy storage systems are entitle for double taxation and there is a lack of transparency in the calculation of the charges for T&D. This uncertainty on how energy storage system must be treated in each EU Member State leads to insecurity for investors in the market.

Moreover, some regulations in practice today benefit some established and old technologies, not willing to open space for new technologies as energy storage due to the unwillingness of taking risk and innovate. This lack in standards and practices limits the expansion of new technologies.

4.1.3 Market barriers

The European Union decided to change the basis of the electricity and gas market from a monopole and regulated based to a liberalized one, while T&D networks are still regulated in many EU Member State. Unbundling of the power sector aim to keep the electricity prices for the final consumer as low as possible by increasing competition in the market and ensuring power supply.

There are many discussions about the market structure and the advance of energy storage systems. In one side, many believe that in countries with a vertical integration, the deployment of energy storage systems is easier as TSOs and DSOs can have the ownership and decide what the best operational setup to meet profit targets is. Others believe that the benefits provided by energy storage systems with competitive services are better comprehended in an unbundling market. However, none of the both structures currently incentivizes the development and deployment of energy storage.

The revenue on electricity market is based on the amount of energy loaded on the grid, which today is provided by renewable energy generators, with incentives as they have special rates. This penalizes energy storage systems as they are only paid as a capacity asset, so they have revenues only when they generate in demand peak needs, not being valued for the other serviced they provide, as frequency and voltage stabilization (Anuta, 2014). Ancillary services should have a higher commercial value.

Moreover, no facility is enabled to claim revenues for both providing reserves, flexibility and ancillary services. In reserves market, usually the facility is obliged to reserve capacity that it was contracted for, in any case and at any time, forcing energy storage system to choose one of the markets to operate, reserves market, balancing market or ancillary service market. Many studies, as from Wasowicz, B. et al. (2012), show that revenues increases significantly when energy storage systems are able to participate at the same time in both markets.

In a market where electricity price has its greatest value when demand is high, negatives prices can also be seen when demand is too low (or when the load from RES is too high), bringing a huge economic impact to all stakeholders. This happened in 2012, for example, when high wind power generation during a low demand period brought energy prices to negative levels during some hours in some Western European countries. Energy storage system could help the spot market to reduce price volatility, but instead big generators commit in bilateral markets to mitigate their risk in the market, leading to low liquidity on spot markets and increasing the risks for energy storage to operate.

The whole market operation is a limitation for energy storage as it can act as generator, regulator and consumer in the reserve market, ancillary market and spot market. A new view in the market has to take place to deploy the use of energy storage systems, understanding the concept of flexibility and giving it a value, otherwise the market will continue to penalize energy storage and limit its development.

In addition, a business model problem is seen for the old and traditional energy storage systems. Historically, large-scale energy storage facilities were developed manly for storing electricity during the night and supply it during daytime, being able to operate profitably from the spread between off-peak and peak prices. Market changed over the past few years and these spreads have been decreasing also due to the high generation of RES (wind blows more at night, the sun shines during the day) and the increase of grid extension. This have been reducing the revenue for electricity storage plants and a new business model must be applied to reverse this situation.

A review of all challenges described can be seen in Table 4 below.

Table 4: *Challenges and barriers for energy storage deployment*

Areas	Challenges and barriers
Technological	- High investment costs and limited operational experience - Improvement in capacities and efficiencies (for commercial available technologies) - Promising technologies still under R&D phase - Grid integration in different levels
Regularity	- No systemic interpretation of energy storage and its clear definition - Nonexistence of a compensation scheme for all services provided - RES policies not considering energy storage - No rule for asset classification and ownership - Double taxation and charges - Benefit for some established (old) technologies

Market	- Unbalanced revenues for all services provided - Limitation on more than one market participation - Low liquidity on spot markets - Market operation not considering flexibility as a value - Low spread between off-peak and peak prices

Source: EC and DG ENER (2013), EC Energy Roadmap 2050 (2009), Anuta et al. (2014), Garvey (2015), Papapetrou et al (2013)

4.2 Proposed action-plan

According to a technology roadmap developed by the International Renewable Energy Agency (IRENA) in 2015, some action-plan in order to promote energy storage system to facilitate the integration of renewables must take place now in many countries considering a transition towards a 2030 with a higher share of VRE, such as:

- Countries in which the share of VRE will exceed 30%, combined with further ambitions to increase renewables. In Europe, those are Denmark, Germany, UK and Spain.
- Countries in which the share of VRE will exceed 20% and have constrains in grid infrastructure. Italy and France, for instance.
- Island countries or islands without a good connection to the grid (considered as remote off-grid).

In all action-plan, indicators must be provided to track the process and compare the different applications and features of electricity storage systems. These indicators must focus in the technology development progress and others focus on tracking the benefits energy storage system are bringing to the entire system.

All stakeholders must be involved in the process, to ensure that all the process will cover the relevant aspects of the different technologies. Also, stakeholders of the non-energy market, such as the transport sector, gas sector and heat, as well as the industry, since storage systems have a cross-sector impact and requires integration (IRENA, 2015). The outcome must fulfill the following conditions:

- The discussion and results must ensure the operation of an open, fair and transparent market, with the outcome of a clear regulation of the use of energy storage system by each operator
- No technology can be discarded, the selection of the most efficient solution must come from the market analysis

Some steps towards the increase of energy storage are being done by the European Commission (EC). In May 2015, a high-level roundtable called *Strategic Contribution of Energy Storage to Energy Security and Internal energy Market* was held by the DG ENER (the Directorate-General for energy in the EC). The aim was to initiate a discussion between all stakeholders, such as operators, producers, regulators, consumers and academics, on challenges in the energy storage system and on required market rules. A proposed definition and principles for energy storage has been drafted by the EC on June 2016 showing the commitment of the entity to develop a more cost-effective energy system including energy storage.

Below the proposed action-plans identified in the literature for regulatory framework and electricity market are described and detailed.

4.2.1 On regulation and policies

The most important change in regulation is the creation of a new asset category encompassing energy storage and new rules and mechanisms in the market. The European Association for Storage of Energy (EASE) together with the European Commission released a draft on June 2016, which defines:

"Energy storage in the electricity system would be defined as the act of deferring an amount of the energy that was generated to the moment of use, either as final energy or converted into another energy carrier"

However, this is not in the regulation yet and they are still under discussion.

These new rules for this new asset must cover the dual characteristic of energy storage in flexible generation and demand role, enabling more accurate and fair tariff charge and compensation scheme based on all services and benefits the facility is providing, not only a single service (e.g. kWh). With clear rules and responsibilities regarding technical modalities and financial conditions, energy storage systems would become more cost effective and attractive for investment in both T&D networks – recognizing the benefits for system security, loss reduction and ancillary service provision; and by the unbundled operators who are prohibited from operating in generation.

However, the impact of implementing many energy storage technologies on the grid, with many services to be controlled, needs to be understood by all stakeholders (policy makers and market players) and this will require a learning curve also in the operation side. For this to happen, continue research and evaluation of energy storage schemes for pilot operation in generation, balancing and T&D networks must be supported by the European Commission. According to Anuta (2014), only this experience will enable to standardize methods for evaluation, connection, operation and maintenance of energy storage in the electricity grid.

Another important recommendation of many studies is to have an integration of energy storage in RES policies and targets, aligning the use of energy storage systems as a base technology for the increase of RES, reducing intermittency, balancing supply and demand and providing ancillary services, also considering as a decarbonization provider for the electricity grid. A combination of direct and indirect methods applied for the RES technologies should also be considered to support the development and deployment of energy storage technologies.

Anuta (2014) states that primarily direct methods of support would be more effective in order to provide new investments in energy storage facilities, by creating subsidies or tax incentives in all Member-States. However, the EC already stated its wishes to have incentives mechanisms based on market value, rather than subsidies. It is important to make clear that this framework must be technological neutral, not selecting one technology as the most suitable and enabling a fair competition between all new technologies.

Furthermore, renewable energy policies should be updated in order to provide two different tariffs for the RES owners providing intermittent energy and dispatchable energy utilizing energy storage, as it is current in practice for island power system in Greece (Anuta, 2014).

In addition, Papapetrou et al (2013) consider that the provision of some kind of support when the facility is storing renewable excess would be extremely beneficial, granting priority dispatch to this stored renewable energy, similar to the priority that RES has according to the Article 15 (3) of the Electricity Directive. This would promote a decarbonization of the electricity grid, enabling the increase of the share of renewable in the entire energy mix in EU and helping the renewable targets.

A roadmap for energy storage must be designed by the European Commission, as an addendum of the Energy Roadmap 2050. Targets, plan and milestones must be underlined and addressed to each Member-States. This would reduce uncertainties of investors and motivate the market and the governments.

Anuta (2014) also brings another view for the use of batteries used in electric vehicles, the European Union could create a mechanism to promote the reuse of those batteries again in the electricity grid as a smart solution of storage, involving consumer in order to reduce investment costs and also incentive the use of electric vehicles in the transport sector.

4.2.2 On the electricity market in EU

The reward of energy storage based on more than one application will claim for a new position and comprehension of the electricity market as well. Energy storages can be used in the wholesale market being measured for all benefits it provides in the balancing and ancillary services and capacity market, providing flexibility, security and decarbonization of the grid. Simultaneous operation of energy storage systems in all markets would enhance the revenues of the operation and accelerate the full return of investments, generating economic viability for energy storage.

It is important that the electricity market can change its mechanisms in order to create a fair competition between energy storage technologies, or also other new technologies entering in the market, and established generation technologies. Garvey et al (2015) propose that the revenues for generators in the grid should be based on the MWh of low-carbon energy supplied with a multiple of the energy value at that time, not only based in a fix value for the MWh. This could be a formula to promote low-carbon technologies in the grid.

Also, the EC, through the DG ENER, already investigated a possible introduction of a time component in the grid tariffs, when an energy storage system is using the grid during off-peak it should not generate grid investment than with it is using peak periods. With this, ancillary services could be better remunerated.

The peak increase issue can be addressed with enabling energy storage at different levels in the system, such as centralized energy storage as reserve systems, decentralized energy storage for demand management and demand response systems. The market must make sure there is fair and equal access to any energy storage facility, not depending on its size and location in the chain.

A recommendation from Papapetrou et al (2013) is the consideration of common rules to be applied across the EU Member States about transmission access fees and system fees and the integration and role of energy storage systems in order to deploy this technology in an equal way in all countries of the European Union. In addition, these fees should be calculated with a method that takes in consideration the real impact of the electricity storage on the grid. In this way, energy storage would be benefit from the relief of congestion problems, increasing their viability.

Additionally, the development of a forward services market in which the services could be purchased in future could be a relevant tool to incentive investment decision in resources that can provide needed balancing and flexible services (Papapetrou et al, 2013).

A better market design, integrating the EU market as one, is key aspect for the development of energy storage, removing barriers related to accessing cross border market (within the EU) and trading. Clear rules should provide transparency towards all market players, covering all diversity it has, not penalizing any Member-State and introducing financial instruments to be used to control investment risk.

The proposed key action-plans reported are summarized in the Table 5.

Table 5: *Key action-plans for the development and deployment of energy storage systems*

Areas	Possible action-plan
Technological	- Mapping storage potential - Integrate energy storage as a key area in the SET-plan - Financial support for research, development and demonstration
Regularity	- New asset class for energy storage in EU regulation - Include energy storage in the RED Directive, providing some support and priority when storing renewable excess energy - Enable more accurate and fair tariff charge and compensation scheme based on all services and benefits provided, including flexibility and decarbonization - Standardize methods for evaluation, connection, operation and maintenance of energy storage - Roadmap for energy storage included in the 2050 vision - Reuse of batteries from EV in the grid
Market	- Legal framework for energy storage at EU level with a new restructure of the electricity market - Energy storage operators should be able to operate in all markets having revenue based on all the service provided - No discrimination between technologies - Integration with other sectors for energy storage (e.g. power to gas, hybrid electric vehicles, heat storage)

Source: EC and DG ENER (2013 and 2016), EC Energy Roadmap 2050 (2009), Anuta et al. (2014), Garvey (2015), Papapetrou et al (2013), IRENA (2015)

5 Conclusions

The global power sector is face to face to a difficult era. The demand for electricity in the world is growing every day. Traditional power plants with usual technologies as well as transmission and distribution infrastructure are getting older and obsolete in some cases. The guideline towards a low-carbon economic brought the increase of variable renewable energy into the grid, with its environmental and economic benefits but difficulties for grid integration and distribution. In addition, the public opinion is concerned about climate change, adding pressure to the market and to the policy-makers around the world to meet environmental targets and to have a more sustainable society.

Integration of energy storage systems can provide technical, economic and environmental benefits to the power system, as already discussed in this paper. However, due to its unconventional characteristic of acting in the generation part and being a consumer in the grid at the same time, also providing support to generators and managing network operators, this technology is not well interpreted since there are some gaps in defining and regulating it on current EU directives. The current regulatory framework and the market structure must be reviewed otherwise the integration of energy storages into the EU electricity grid will fail.

In the time being, some discussions in the European Union are seen about what should be the focus of the EC in order to enable the increase of the share of RES in the electricity grid, but keeping safety and reliability. Demand side management and extension of the grid connectivity can also contribute to the integration of renewable energy (specially the VRE) into the grid and stimulate the increase for share of RES on the same. However, only energy storage systems have the potential to be a technology that can be 100% managable and reliable, giving to the grid operator full control of the balance of supply and demand. Demand side management depends on uncertainties as socio-economic situation and profile of the users and willingness to drive to a low-carbon economy.

Energy storage systems can provide flexible generation, balancing services and ancillary services to the grid, as well as increase energy security and facilitate integration of renewable energy sources. Moreover, the technology can comply with low-carbon rules, storing only renewable energy excess and promoting decarbonization of the electricity grid. This variety of services, if adequately rewarded, would enable the business case for energy storage to succeed.

Another advantage of energy storage is the flexibility to promote the energy production and management in loco in certain regions in a decentralized way, but also promote large energy production in a centralized way, all depending of the technology applied. Flexible solutions will be required in all levels of the electricity grid and an integration of the power industry, the transport sector and the gas and heat networks will bring many benefits for the European Union.

As described in this paper, many interesting technologies are available today, such as pumped hydro, CAES and batteries, and some others, still under research and development such as hydrogen and power-to-gas, also have a lot of potential that will enable the integration of new renewable energy technologies as generator in the grid. As an example, offshore wind farms can be more explored and deployed with the use of energy storage system, as hydrogen or power-to-gas technologies.

Regulatory changes and a new design for the electricity market are required, as showed in this paper. Only with this transformation and modernization, the energy storage systems can really develop and deploy in Europe. Ensuring a stable regulation and market structure for energy storage can provide a better economic scenario for investors to advance in research in technology and facilitate the penetration of energy storage in the grid.

Energy storage should be integrated into all current and future EU energy and climate change regulation and targets. Policies must give a clear indication to technology developers, industry and consumers about the role of energy storage systems in the electricity grid of the European Union. A new asset class creating is necessary, promoting the optimization of the power system and the synergies between all elements in the market. The consideration of energy storage as a facilitator for the realization of decarbonization targets is key element to be considered in the new regulation for energy storage.

In addition, it is crucial the increase of interests of energy storage investments and for this a structural change in the market is needed for the calculation of the revenues of those technologies. They should be entitled to have fair tariffs for all services they provide to the grid system, simultaneously, being able to act in all markets, as described on this work. Only enhancing fairly the profit for energy storage systems will enable the market to these technologies attractive for investment and motive its deployment.

Cooperation of all stakeholders such as governments, industry, TSOs, DSOs, consumers and others, is extremely necessary to vison a long-term commitment for this necessary change. The leading role belongs to the European Commission, which should promote more roundtables for discussions and alignments with the objective to find realistic proposals for enhancements in the regulatory framework and electricity market, promoting integration and decarbonization, as a low-carbon energy system appears to be cheaper with energy storage facilities than without them.

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