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# Energy storage systems: state of the art and economic evaluation criteria

Relatore: Prof. Federico FRATTINI

Tesi di Laurea di:

Tomaso Torriani
Matr. 799415

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# Abstract

In the last decade the spread of the Renewable Energy Sources (RES), in particular of the Variable renewable electricity sources (VRES), has deeply changed the landscape and consequently the way it is managed the electric grid. Before the development of the RES, the managing authority of the electric grid had to deal with the variability coming only from the demand side of the electric grid. Nowadays, beside the demand variability, it has to face the instability of an increasing share of the supply side of the grid.

The reason behind this is that VRES are intermittent and unpredictable. Sun power and wind power cannot be neither controlled nor predicted with the accuracy of seconds, because its regularity of supply is interrupted by stochastic elements as weather conditions; nevertheless consumers need electric energy to be reliable and of good quality.

In this scenario, the Energy Storage System (ESS) can provide a valuable solution to this problem, absorbing the variability at any stage of the electric power supply chain. Energy storage systems allow fluctuating renewable energy sources to be as stable as conventional systems(Nair & Garimella, 2010) and also provide a mean to decouple generation of electricity from its use (Houseman, 2005), minimising supply and demand related issues(Nair & Garimella, 2010). There is still one strong barrier that limits the spreading of ESS: its economical feasibility. The problem of assessing the economic profitability of ESS has not simple solution though. This complexity is due to the multitude of variables involved in this issue.

These usually refer to:

i. Different political, environmental and social backgrounds (which determine the national energy strategy, the as-is national energy production mix, the energy consumption profile etc.);
ii. Different kind of actors who could get involved in this investment (e.g. the owner of a renewable energy power plant; the company that manages the electric grid; a private householder etc.) whose return has to be identified and analysed case by case;
iii. The wide range of technologies that can be used as a ESS (e.g. Batteries, Compressed Air Energy Storage, Pumped Hydro Storage, Fuel Cells etc.);
iv. The diverse yardsticks used to determine the economical feasibility, since there is not a method that fits every scenario.

Through a review of the academic literature on the topic, the purpose of this work is: (i) to make order in the techno-economic landscape of ESS, giving the reader the necessary tools to comprehend the matter; (ii) to discover the different economic evaluation methods implemented in the academic literature; (iii) to suggest an economic evaluation framework that shall be used in order to develop a complete economic analysis according to the context of application of ESS.

This dissertation is based on a review of the literature on this topic: 103 different thesis were analysed in order to understand which evaluation methods have been used. Particular attention was given to the specific yardstick employed to define the economic return. Every work has been classified according to the economic yardstick exploited. After a definition of the different areas of application of ESS, it was assessed paper by paper whether there was a connection between the areas of application and the economic yardstick. It was found that there were no clear correlation between these two variables. Every area of application should be assessed in a specific way: what was found is a disparity among the different evaluation methods within the same area of application. This difference concerned economic yardsticks, voices of income and the target of the economic analysis: for these diversities is difficult to compare the different economic evaluations without having a common structure of evaluation.

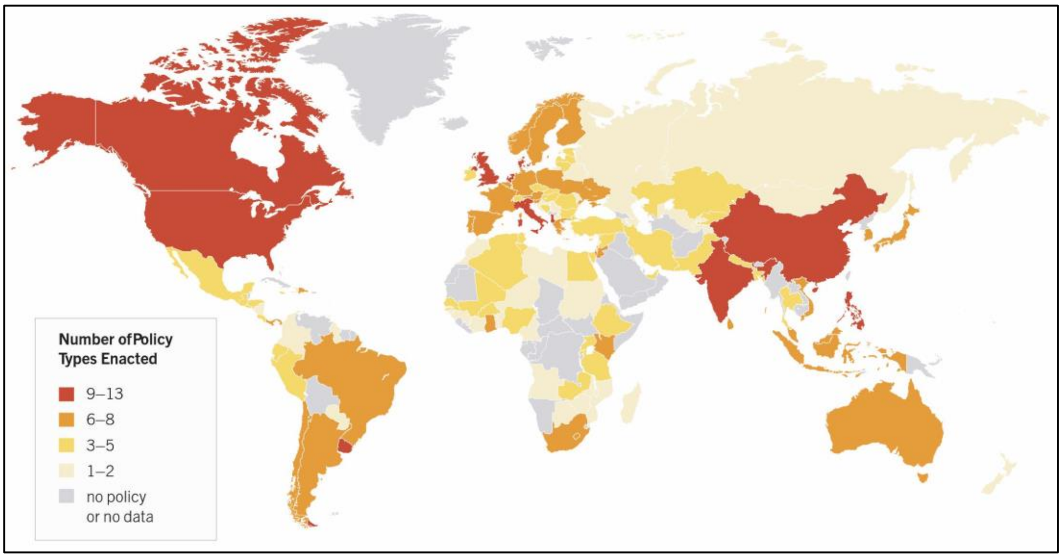
# 1. Overview of VRES – policies and current development

ESS are closely linked with renewable energy sources. In this starting chapter, it is going to be assessed the current landscape of worldwide renewable energy sources. The focus of the chapter is on the VRES, which are the category of RES that gain from the use of ESS. Here it's given an overview of the major policy instruments that are active on the VRES world, and the current development of solar and wind energy. As the VRES world and market dynamics are very close to the development of ESS, it has been chosen to make an introductive analysis of the status of development of these categories.

Policies and government subsidies have a great influence on the RES world. This is due to the fact that power generation from RES has been and generally is more expensive than power generated from traditional energy sources, in terms of financial expense. In fact, the costs of installing a RES power generation unit regards mainly the starting investment, with few running costs. Vice versa costs related to power generation from fossil fuels is in majority due to the costs of fossil fuels. Thus if investors are not stimulated in investing in RES, they won't do it spontaneously. Government subsidies often are  subdued to supranational policies and related politics. Here it follows a review of the most relevant milestones on renewable energy worldwide and European policies. In 1992, the United Nations Framework Convention on Climate Change defined a fixed level as the goal of greenhouse emissions. Based on this, the European Union defined a temperature target to limit global temperature increase to 2 C° or below (1939th EU Council meeting, 1996). A fee years later, this target was adopted on a global level by the United Nations (UN, 2010). According to the Intergovernmental Panel on Climate Change (2007), this would entail a reduction of $CO_2$-equivalent emissions between 50% and 80%. The electricity sector in particular is been recognised in having a large potential for emission reduction, with utopic scenarios of up to 100% electricity production from renewable energy sources (Pleßmann, Erdmann, Hlusiak, & Breyer, 2014)(Spiecker & Weber, 2014).

A very important role is the one played by governments, which have the power to give the economic support in order to reach the best collective solution, for the energy sector. These subsidies must be spent in order to achieve the best outcome nationally and globally. The European countries are very active on this side, as it's displayed in the next paragraph and in Fig. 1.

**Figure 5: country with renewable energy policies, early 2014 (RENEWABLES 2014 GLOBAL STATUS REPORT)**




## 1.1 Europe 2020 targets

Focusing on the 2020 EU objectives, the European Council agreed on binding RES targets for Europe in March 2007: the share of RES in overall energy consumption should increase to at least 20% by 2020 (Presidency of the council of the European Union, 2007), and the share of biofuels in total transport consumption to at least 10%. The RES Directive 2009/28/EC which was effective in June 2009, translates these binding targets into a legislative structure that could be implemented in every single country. The European target of 20% RES in the gross final consumption of energy is broken down into binding national targets for the EU-27 member states; the biofuels target is translated into a 10% RES target in the final consumption of transport energy that applies to each member state individually. (Klessmann, Held, Rathmann, & Ragwitz, 2011). Another target for the 2020 sanctioned by the EU regards the total consumption of energy. Europe aims to achieve 20% primary energy savings in the period 2005–2020. For discussions related to the interpretation of the quantities involved, please refer to (Harmsen, Wesselink, Eichhammer, & Worrell, 2011).

The third and last target for the European 2020 strategy for "Climate change and energy sustainability" regards the lowering of the greenhouse gas emission of the 20% in respect of the values of the 1990.

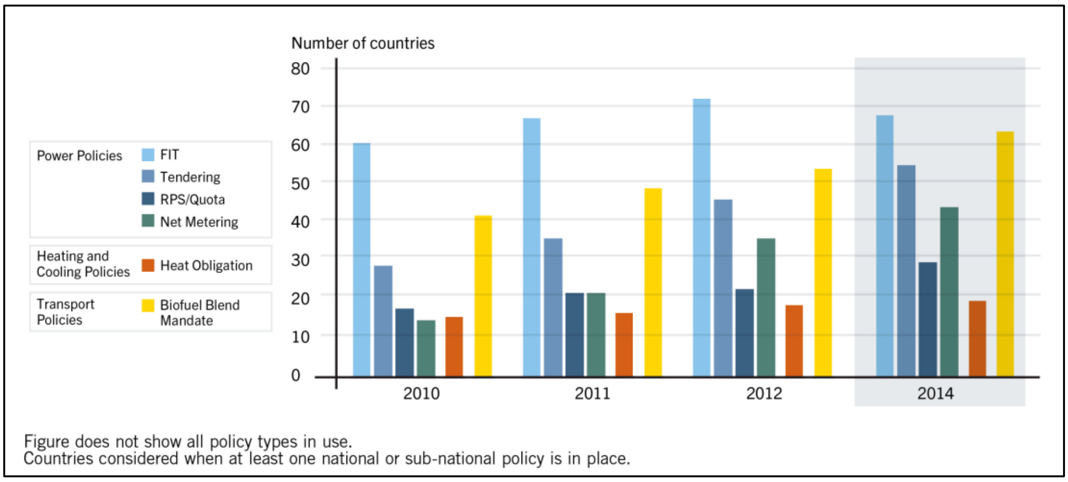
## 1.2 Subsidies mechanisms

National Support mechanisms are necessary because the EU 27 energy markets and the social and political system of the Member States still call for policy driven specific systems to counterbalance barriers on the existing markets in a way that suits best the political model and promotion schemes of the given country. Major support mechanisms in the electricity sector are mostly two: first feed-in systems (FiT) and tradable green certificate systems (TGC). The explaining of the mechanisms is in the

following lines. In a TGC system, a target for RE penetration is set by public authorities seeking to minimise cost for achieving this target. The certificate price is set by the market. In these systems a defined member of the electricity supply chain, be it consumer, generator or supplier, has to present a fixed minimum quantity of certificates each year, as set by a public authority. The certificates originate per MWh of RE electricity generated. An obligated party thus may generate himself or purchase certificates on a certificate market. The obligated party may pass on the cost of certificates to the consumer, in order to grant the profitability of its own business. The principle behind the quota mechanism is that a RE producer should receive a financial return from the selling of certificates on the market. The target of RE under the TGC system is set by the government and the certificate price is determined by the market. If the certificates generated are more than the ones required by the target, the price will fall to close to zero, and the investments in RE will have to rely on the revenue collected from electricity sales only. The risk of this mechanism is related to the presence of a demand-supply market that could follow dynamics not completely steerable by the regulator of the system.
In the FiT systems the basic principle is that any national generator of renewable electricity can sell its electricity at a fixed tariff for a specified time period under specific conditions depending on location, technology and other variables. Public authorities set a price varying per respective technology and application, and generally do not the power capacity installed. The tariff remains constant for the pre-defined period, and in general for new connections in subsequent years it could be offered a lower price level . Alternatively the RE producer receives a fixed premium in addition to the electricity market price. In FiT systems there is often a combination with priority grid access, so that it can be used and sold the most. The costs of FiT payments are in general passed on to the electricity consumers (Fouquet, 2013).
Other mechanisms include tendering. Tendering systems use government-supervised competitive processes that have the aim to meet planned power production targets by making long-term power purchase agreements with renewable energy generators firms. The price and the production RE projects that could be eligible for government support at the specified price are chosen through a competitive bidding process; in this auction bidders submit project proposals with the price they are able to offer (Wiser, Hamrin, & Wingate, 2002) (Sequeira, 2006).
The last spread subsidy mechanism refer to the Net Metering. Net Metering is an electricity mechanism which allows utility customers who own a small PV plant or another small RE power system, to balance some or all of their electricity consumption and their local production. The distribution power grid is the counterpart of the operation. This mechanism works by utilizing a meter that is able to spin in two directions, showing and counting either the net consumption or the net production during a period of time. This excess generation or net consumption is then valued at the end of the period usually at the retail rate. This policy promotes distributed generation because the retail rate paid to the PV system owner is higher than what would be received by a conventional generator for the same electricity.

The retail rate that the PV system owner receives also sometimes includes the payment for the distribution infrastructure, implicitly becoming a subsidy for distributed PV development (Watts, Valdés, Jara, & Watson, 2015).
Fig. 2 displays what mechanism are more widespread worldwide.

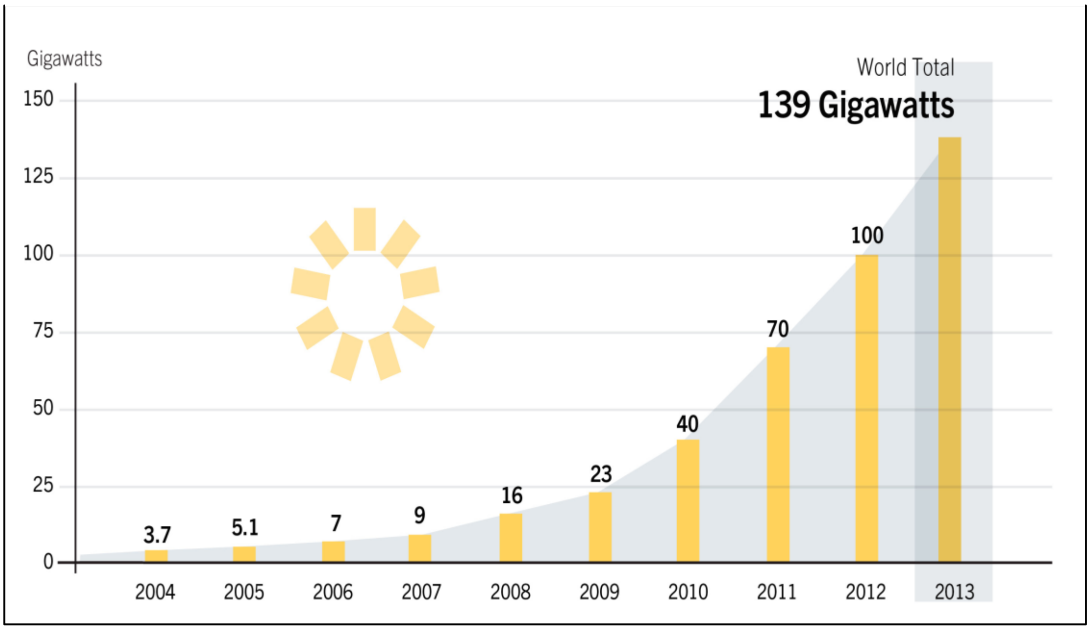
**Figure 6: Number of Countries with Renewable Energy Policies, by Type, 2010–Early 2014 (RENEWABLES 2014 GLOBAL STATUS REPORT)**




## *1.3 Overview of variable renewable energy sources*

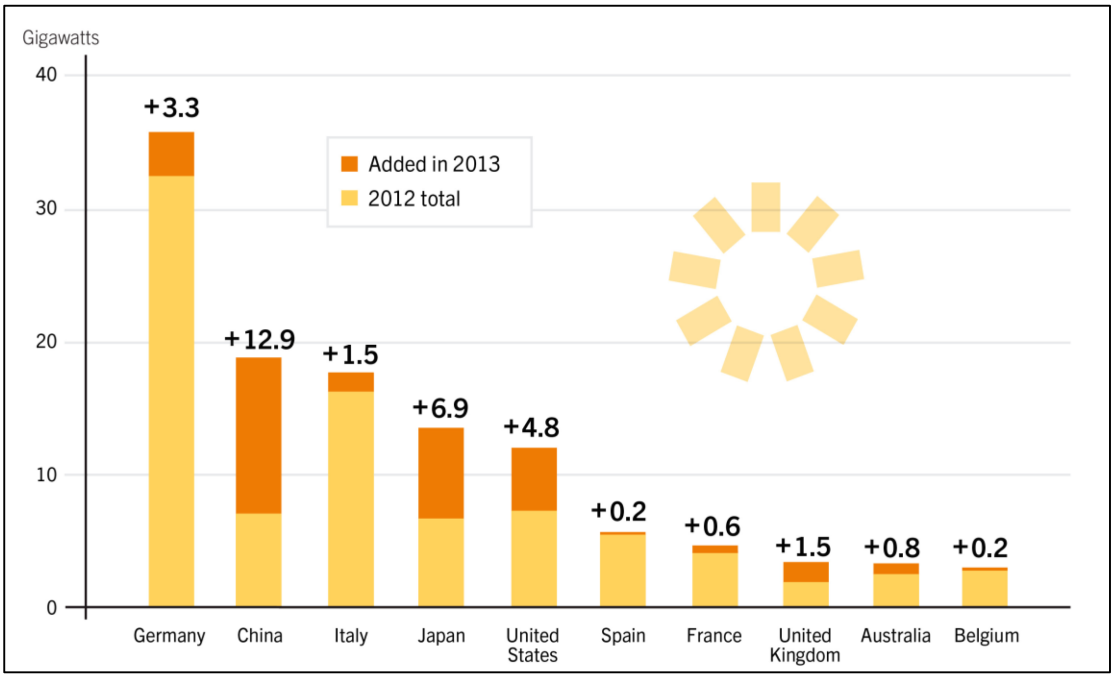
### *1.3.1 Solar PV*

**Figure 7: Solar PV Total Global Capacity, 2004–2013 (RENEWABLES 2014 GLOBAL STATUS REPORT)**



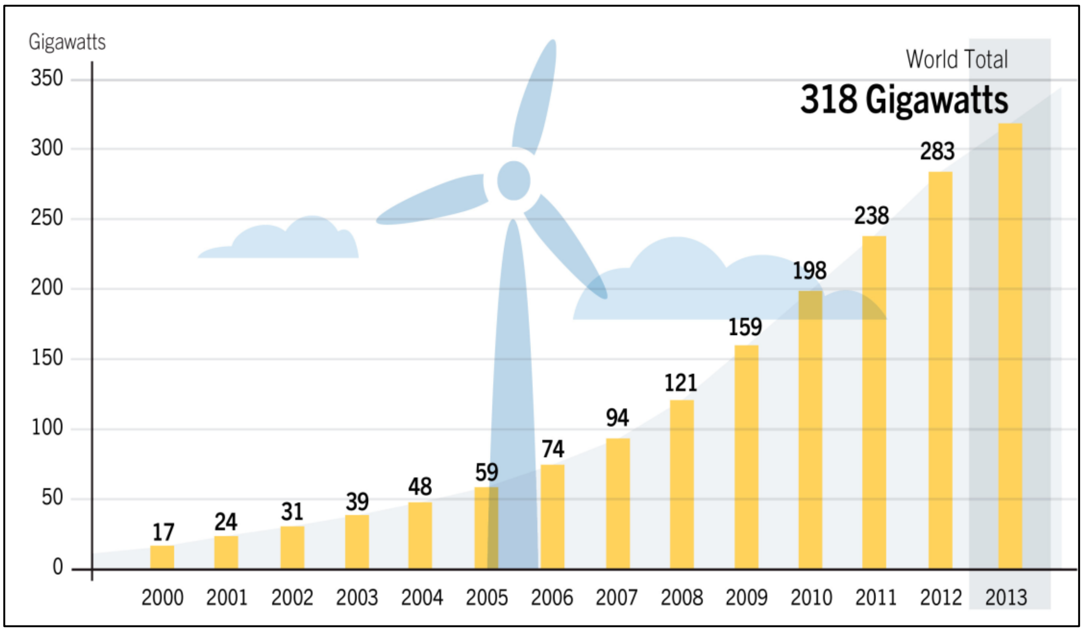

The global solar PV market had a record year in 2013 after a brief slowdown, installing more capacity than any other renewable technology except perhaps hydropower. More than 39 GW was added, bringing total capacity to approximately 139 GW (see Fig. 3) (Masson, 2014). Almost 50% of all PV capacity in operation today has been added in the past two years, and 98% has been installed since the beginning of 2004 (see figure 3). The year saw a major shift geographically as China, Japan, and the United States became the top three installers, and as Asia passed

**Figure 8: Solar PV Capacity and Additions, Top 10 Countries, 2013 (RENEWABLES 2014 GLOBAL STATUS REPORT)**



Europe – the market leader for a decade – to become the largest regional market (see Fig. 4). China's spectacular growth shined even more as Europe had a significant market decline, and hid the slower-than- expected development in the United States and other promising markets. Nine countries added more than 1 GW of solar PV to their grids, and the distribution of new installations continued to broaden. By 2013's end, 5 countries had at least 10 GW of total capacity, up from 2 countries in 2012, and 17 had at least 1 GW. The leaders for solar PV per inhabitant were Germany, Italy, Belgium, Greece, the Czech Republic, and Australia.
According to Anie Energia, in 2014 Italy has installed 385 MW of solar photovoltaic capacity, as compared to almost 2,000 MW in 2013.
More specifically, a total of 50,571 solar plants were put on stream last year, most of which are residential. Some 123.6 MW of the newly-added capacity was in the 3 kW-6kW range, while 97.98 MW correspond to PV systems with capacities of between 20 kW and 200 kW. At the end of 2014, Italy's installed solar capacity amounted to 18,325 MW.
About the solar photovoltaic industry, after a two-year recession, in which oversupply drove down module prices and many manufacturers reported negative gross margins, there was a growth and some signal of recover during 2013. It wasn't the best year ever, particularly in Europe, where shrinking markets left installers, distributors, and other players still in bad waters. Consolidation continued among

**Figure 9: Wind Power Total World Capacity, 2000–2013 (RENEWABLES 2014 GLOBAL STATUS REPORT)**




manufacturers, but, mostly in the last part of the year, the strongest companies were selling panels above cost. The rebound did not apply lower down the supply-chain unfortunately. Poly-silicon makers have had hard times recovering. Low module prices also continued to challenge many thin film companies and the concentrating solar industries, which have struggled to compete. On the stock market there was a strong recover. The BI Global Large Solar Energy Index of 15 manufacturers of the industry slumped 87 percent from the February 2011 peak through November 2012; but now has regained 55 per cent of its value in the 2013. The technology-dominated Nasdaq Composite index reached its post-bubble low in October 2002 and regained 37 percent of its March 2000 peak value in the next year, according to data given by Bloomberg.

*1.3.2 Wind power*

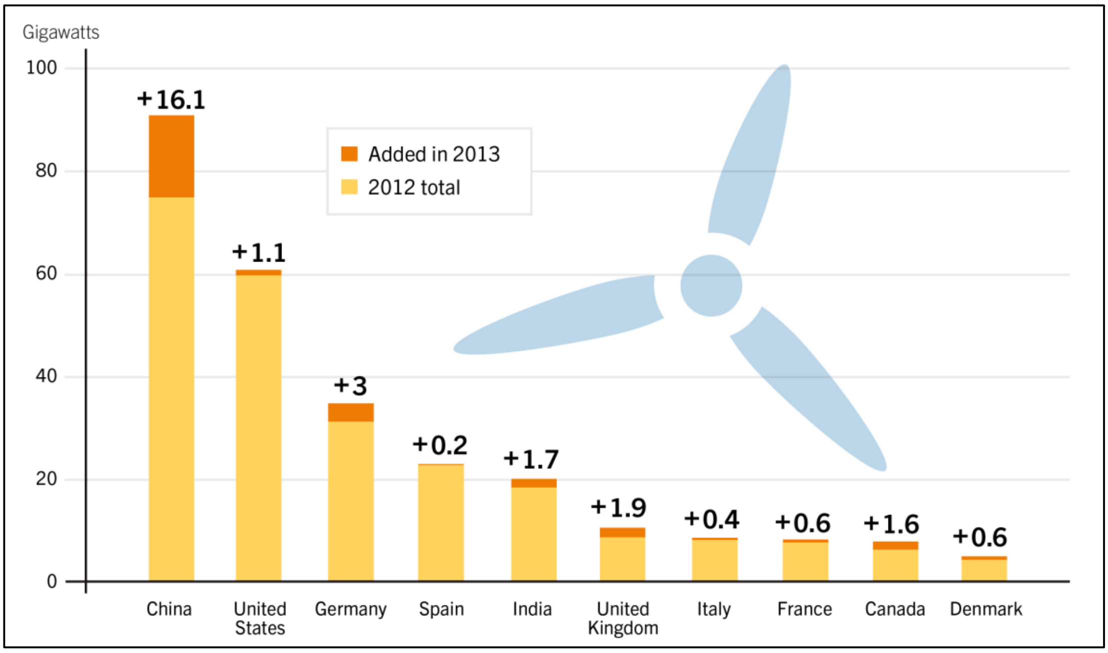
More than 35 GW of wind power capacity was added in 2013, bringing the global total above 318 GW (See Figure 5) (Fried, Sawyer, Shukla, & Qiao, 2014). Following several record years, the wind power market declined nearly 10 GW compared to 2012, reflecting primarily a steep drop in the U.S. market. The top 10 countries accounted for 85% of year-end global capacity, but there are dynamic and emerging markets in all regions. By the end of 2013, at least 85 countries had seen commercial wind activity, while at least 71 had more than 10 MW of reported capacity by year's end, and 24 had more than 1 GW in operation. Annual growth rates of cumulative wind power capacity have averaged 21.4% since the end of 2008, and global capacity has increased eight times over the past decade.

Asia remained the largest market for the sixth consecutive year, accounting for almost 52% of added capacity. It is followed by the EU (about 32%) and North America (less than 8%). Non-OECD countries were responsible for the majority of installations, and, for the first time, Latin America had a substantial share (more than 4.5%). China was the leader of the market, followed distantly by Germany, the United Kingdom, India, and Canada. Others in the top 10 were the United States, Brazil, Poland, Sweden, and Romania, and new markets continued to emerge in Africa, Asia, and Latin America (see figure 6). The countries that had the most wind power capacity per inhabitant were Denmark (863 W per person), Sweden (487.6), Spain (420.5), Portugal (412), and Ireland (381). Regarding the European situation in 2014, 12,819.6 MW of wind power was installed across Europe, of which 11,791.4 MW was in the European Union. Of the capacity installed in the EU, 10,308.1 MW was onshore and 1,483.3 MW offshore. In 2014, the annual onshore market increased in the EU by 5.3%, and offshore installations decreased by 5.3% compared to 2013. Overall, EU wind energy annual installations increased by 3.8% compared to 2013 installations. Investment in EU wind farms was between €13.1 billions and €18.7 billions. Onshore wind farms attracted around €8.9bn to €12.8bn, while offshore wind farms accounted for €4.2bn to €5.9bn. In terms of annual installations, Germany was the largest market in 2014, installing 5,279.2 MW of new capacity, 528.9 MW of which (10% of total capacity installed in Germany) offshore. The UK came in second with 1,736.4 MW, 813.4 MW of which (46.8%) offshore, followed by Sweden with 1,050.2 MW and France with 1,042 MW. The next countries are significantly behind: Poland with 444.3 MW and Austria with 411.2 MW (Pineda, Corbetta, & Wilkes, 2014).

In Italy in 2014 there have been installed 107 MW of wind power. There have been a tremendous slump after 2013, showing a downfall of 76% from 2013. People working in the industry has fallen from 37.000 in 2012, to 34.000 in 2013 and 30.000 in 2014. This crisis is the effect of the fading subsidies coming from the Italian Government (data coming from ANEV, the national association of wind power).

Let's take a look to the wind power industry. Over the past few years, capital costs of wind power have declined, primarily through competition, while technological advances—including taller towers, longer blades, and smaller generators in low wind speed areas—have increased capacity factors. These developments have lowered the costs of wind- generated electricity, improving its cost competitiveness relative to fossil fuels. Despite these largely positive trends, during 2013 the industry continued to be challenged by downward pressure on prices, increased competition among turbine manufacturers, competition with low-cost gas in some markets, reductions in policy support driven by economic austerity, and declines in key markets. In Europe, market contraction led to industry consolidation, with manufacturers Bard and Fuhrländer (both Germany) filing for insolvency in late 2013, and Vestas (Denmark) cutting its staff by 30%. European turbine makers also experienced a decline in market share within China, where domestic suppliers constituted over 93% of the market in 2013, up from 28% just six years earlier.

**Figure 10: Wind Power Capacity and Additions, Top 10 Countries, 2013 (RENEWABLES 2014 GLOBAL STATUS REPORT)**



# 2. The power grid and VRES

## *2.1 The power grid*

The electric power supply chain is composed of four different stages: production, transmission, distribution and retail. The first stage is the one where the electric power is produced from different means of conversion (from traditional sources, as gas and coal, through thermal power plants; from RES through wind, solar, hydroelectric power plants etc.). Transmission refers to the high and very-high voltage power lines that allow the transportation of electricity from the power plants to the electrical substations located near demand centres. Distribution is the third stage of the delivery of electric power, it carries electricity from the transmission system to individual consumers. Retail is the final stage in which the electricity is made available for the final consumer. The electric grid refers to the second and third stage of the electric power supply chain, that connect supply with demand of electric power.

Characteristics such as duration, cycling occurrence, power, and market value can be used to define the nature of electric grid services that are provided by the firms that manage the power grid. Within the industry nomenclature, these services are referred to depending on market definition and system operation with terms such as ‘‘regulation’’ and ‘‘reserves’’ (Pearre & Swan, 2014). From one side this category of services is very site-specific and depends on the generation, transmission and distribution lines. The common characteristics of this services are:

1. Duration: the length of time over which a service is provided. Duration is defined by natural time that can be load variation, generator start-up period, and renewable resource (Pearre & Swan, 2014).
2. Cycling occurrence: it defines the number of times a specific service is called upon service within a period of time, as a year. Note that the availability to provide a service for this category of system (the power grid) may be continuous; the actual implementation of these services could be sporadic (Pearre & Swan, 2014).
3. Power: the power provision is a peculiar characteristic that depends on the size, features, and interconnectivity of the local grid. In order to have the necessary requirements to provide this kind of services, the storage system requires to be able to both absorb and deliver power from and to the grid. (Pearre & Swan, 2014)
4. Market value: it refers to the price paid for delivery of the service, in accordance with capacity, time and location necessary for the electricity grid. (Pearre & Swan, 2014)

In addition to these common characteristics, services can be categorized depending on the stage of the supply chain of electricity where are implemented. These services are classified as: generation side and transmission/distribution side as presented in table 1 and table 2:

**Table 1: Grid services – generation side**

| Generation side | |
|---|---|
| Time shifting | Transfer of electricity from periods of low load to periods of high load. This enhance a major use of electricity produced by VRES |
| Peak/valley limiting | Power to clip peaks and fill valleys of load |
| Regulation (load following, ramp compensation, frequency control) | Power to solve normal variations in load an generation as: load following (generation dispatched to address inter-hour load variation), slow regulation, fast regulation |
| Reserves (spinning, non spinning and supplemental reserves) | Power to address unexpected deviations in load and generation |
| Emergency | Power to restart system after extensive fault |

**Table 2: Grid services – T&D side**

| Transmission and distribution side | |
|---|---|
| Power factor correction (VAR support) | Reactive power support to address line voltage excursions |
| Deferred upgrade/maintenance | T&D infrastructure is size for a certain peak load. Upgrade and maintenance of the power grid can be achieved by power averaging |

The activity of the power grid operator consists in providing services that assure that the power grid works properly. This activity involves often the management of some issues. There are three ways to address these "power quality issues" (Perrin, Saint-Drenan, Mattera, & Malbranche, 2005)that can affect the power grid*:*

1. Power quality concerns (Voltage sags, flickers, reactive power consumption etc.)
2. Dispatchment concerns; demand and supply of electric energy always need to be instantly equal. This issue is faced by the company that manages the transmission lines, which is responsible for matching demand and supply for the national grid.
3. Issues relating to compliance with grid requirements (power flows limited by the thermal capacity of the lines, avoidance of over-voltage on the distribution line, etc.)

The spread of  variable renewables energy sources have made the management of the power grid more difficult and expensive. In the next paragraph it is assessed this topic.

## *2.2 Characteristics of VRES*

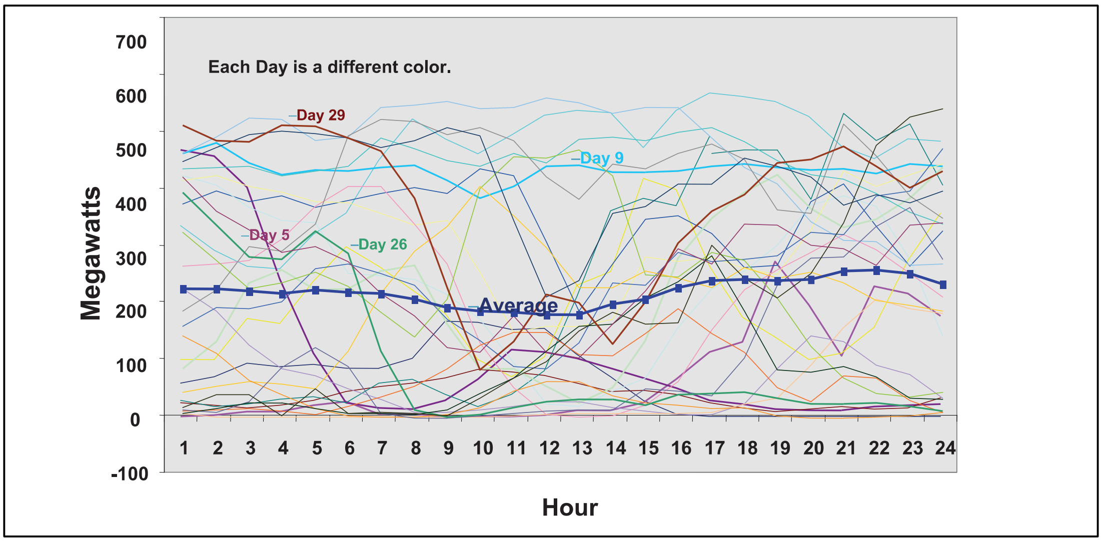
In this paragraph there are shown the peculiarities that make VRES a difficult to manage for grid operators. There are three distinct aspects that create different challenges for generation owners and grid operators in integrating VRES into the power grid (Icrp, 2009):

### *2.2.1 Non-controllable variability*

*Variability* in the context of wind and solar resources refers to the fact that their output is not constant (see Fig. 7). It means that even if they were perfectly predictable, the sudden drop or increase of power supply need to be faced and properly solved. There are few *ancillary services* that address this problem and operate to solve it:

- Frequency regulation: occurs on a seconds-to-minutes basis, and is done through automatic generation control (AGC) signals to generators;
- Spinning reserves: generators available to provide power typically within 10 minutes. These reserves are used when another generator on the system goes down or deactivates unexpectedly;
- Non-spinning reserves: these generators serve the same function as spinning reserves, but have a slower response time;
- Voltage support: generators used for reactive power to raise voltage when necessary;
- Black-start capacity: generators available to restart the power system in case of a cascading black-out.

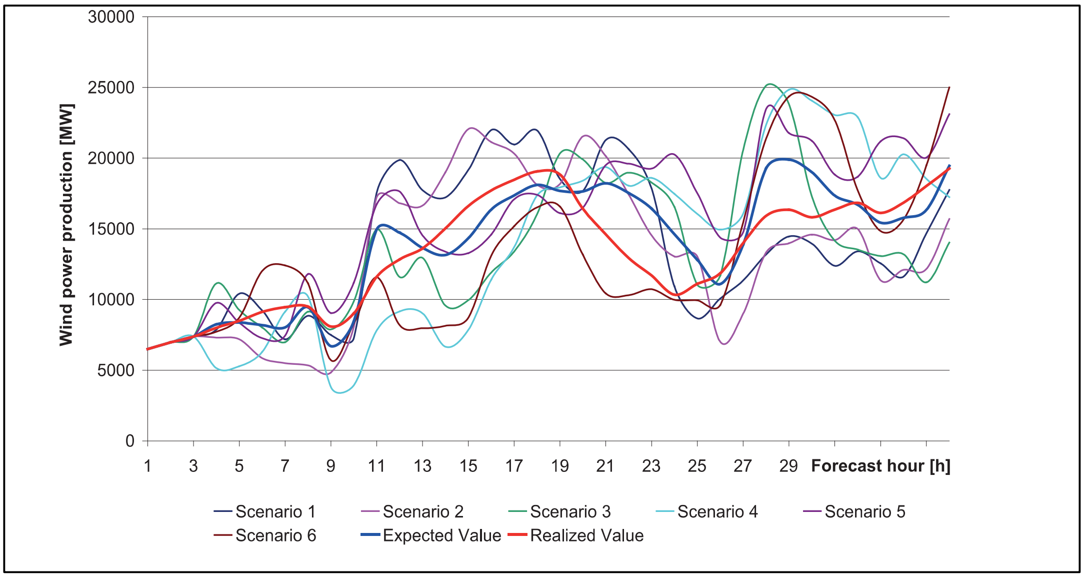
**Figure 11: Hourly wind power output on 29 different days in April 2005 at the Tehachapi wind plant in California** (Hawkins & Rothleder, 2006)




*2.2.2 Partial unpredictability*

Partial unpredictability, also called *uncertainty*, refers to our inability to predict with exactness whether the VRES will be generally available for energy production an hour or a day from now (see Fig.8). This hour-to-day uncertainty is significant because grid operators manage the great majority of energy on the grid through "unit commitment", the process of scheduling generation in advance, generally hours to a full day ahead of time, in order to meet the expected load.

**Figure 12: Examples of a day-ahead forecast scenario tree for the wind power forecast for PJM region of the United States** (Erik Ela, Milligan, Meibom, Barth, & Tuohy, 2010)




### *2.2.3 Locational dependency*

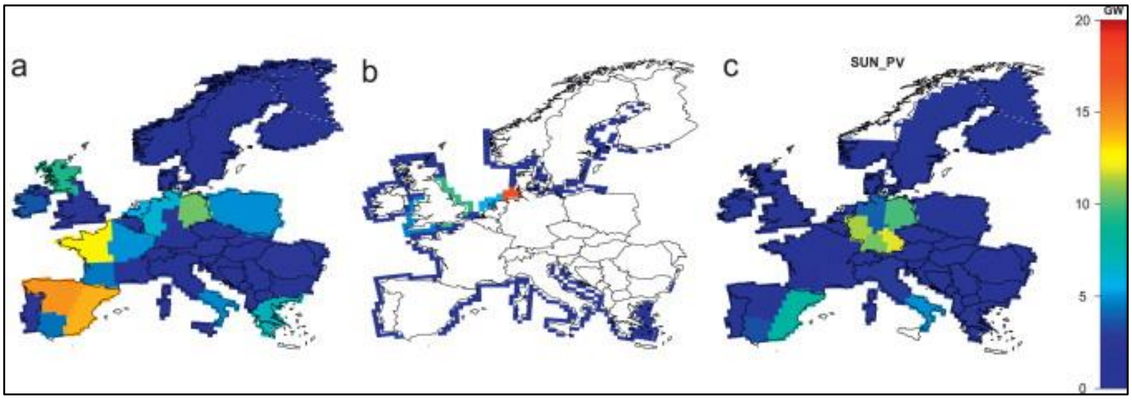
Beyond the day-to-day management of the grid is its long-term planning, specifically the siting and utilization of new transmission lines. VRES generation plays a significant role and introduces new challenges. Because wind and solar resources are often located in remote locations, far from load centers, developing sufficient transmission to move RE to markets is critical to their integration. New transmission lines built out to RE generation resources will carry primarily renewably generated, variable and partially unpredictable electricity, so technical needs arise regarding the transmission technology to be used.

## *2.3 Effects of VRES on the power grid*

VRES timescale variations can be categorized as micro-scale, meso-scale, and macro-scale. Micro-scale variations have a major effect on regulation (seconds to minutes), while meso-scale variations affect the load following timescale (minutes to hours), and macro-scale variations modify the unit commitment timescale (hours to days) (Beaudin, Zareipour, Schellenberglabe, & Rosehart, 2010). In micro-scale, more regulation reserves and frequency control features may be required according to the power system characteristics. For example, a study conducted for Ontario Power Authority stated that integration of 10,000 MW wind power capacity into the Ontario system which presents a 26,000 MW peak load, would require more or less an 11% increase in regulation requirements (Van Zandt et al., 2006). In meso-scale, VRES variations determine a mismatch within the balance between the supply and demand, and thus, may require a significantly increased amount of operating reserves (Doherty & O'Malley, 2005). The same study for the Ontario Power Authority shows that a 47% increase in operating reserves would be needed in order to deal with meso-scale variations of wind under a 10,000 MW wind integration scenario in Ontario (Van Zandt et al., 2006). In macro-scale, VRES variations impact unit commitment and the day-ahead scheduling of traditional sources generators; unpredictable variations may cause significant economic costs. For example, in Germany system start-up costs could boost by up to 227.2% caused by day-ahead wind power forecasting errors (Musgens & Neuhoff, 2006). Broadly speaking, large variations of VRES, wind in particular, have originated some serious operational difficulties in some cases. On 26 February 2008 an unexpected 1400 MW slump in wind power generation corresponded with an unexpected load increase and a conventional generator failure in Texas (E Ela & Kirby, 2008). These events forced the Electric Reliability Council of Texas (ERCOT) to take emergency steps and cut 1100 MW firm load in order to restore system frequency. In addition, wind generators were dispatched down three times in 2008 in the Irish power system for security reasons (Ackermann et al., 2009)(Beaudin et al., 2010).

If we look at the future potential development of VRES in Europe, there can be made predictions regarding the amount of power capacity to be implemented before 2020. (Schaber, Steinke, & Hamacher, 2012) make a prevision based on previous studies and on the National Renewable Energy Action Plans of the European Member States. The forecasted new installment of VRES are displayed in Fig. 9, divided by category of VRES.

**Figure 13: Capacities of variable renewable energies for 2020 in GW** (Hekkenberg & Beurskens, 2011)**. Total European capacity per VRE technology is indicated in brackets. (a) Wind onshore (152 GW), (b) wind offshore (66 GW), (c) solar PV (92 GW).**




All of the above mentioned problems regarding VRES and the power grid could be solved with the help of ESS. In the next chapter is presented this topic.

# 3. Characteristics and typology of Energy Storage Systems

An ESS can be introduced as a buffer between the electric power generation from RES and the power grid. There is not a unanimous classification of the services that can be provided by ESS. Some classifications define the services depending on two variables: energy and power applications. The first requires ESS with prominent storage capacity in terms of energy (kWh) and provide stable exchange of power for long periods (many hours); the latter requires systems with large power capacity (kW) and define exchanges of large amounts of power (available within fractions of seconds) for short periods (seconds/minutes). In this study we use the classification provided by (Castillo & Gayme, 2014) that is later presented.
The features and characteristics of ESS depend on the specific technology that forms the storage system. Thus it's important to define the nature of the various technologies in order to assess what can be the application of these systems. Below it's summarized a classification of the main features of Energy Storage Systems, and later on a description of the different technologies. (Energy&strategy Group Politecnico di Milano, 2013).

## 3.1 Features of ESS

The different features of ESS can provide a range of services that can help different players that belong to different stages of the supply chain of electric power. These can be producers of power (mainly from VRES), managers of the transmission and distribution grids and consumers of energy.

### *3.1.1 Technical characteristics*

There are some characteristics that are useful to define the technical aspects of ESS:

- **Energy storage capacity** [kWh]: is the quantity of energy that the storage can stock.
- **Energy density** [Wh/L]: the nominal storage energy per unit volume, the volumetric energy density
- **Power output** [kW]: the maximum power dischargeable by the system
- **Power density** [W/L]: the maximum power dischargeable per unit volume
- **Charge/discharge duration** [s]: the time needed for the storage to sully charge or discharge
- **Response time** [s]: the time that passes between the need for services and the providing of services
- **Lifetime** [years or cycles]: measures the useful lifecycle of the storage. It can me measured in years or in cycles. A cycle is defined as a complete charge/discharge round. Some technologies have a fixed number of cycles before passing through heavy losses of performance
- **Roundtrip efficiency** [%]: the ratio between the quantity of discharged energy and the charged energy within one operating cycle

- **Capital cost** [€/kW or €/kW h]: the upfront investment costs of a storage technology per unit of power discharge [€/kW] or energy storage capacity [€/kW h]

*3.1.2 Services*

These are the services that ESS are able to provide, as (Castillo & Gayme, 2014) define.

**Power quality**: support utilization of electric energy without interference or interruption. Generally power quality refers to maintaining voltage and frequency levels within bounds

**Transient stability**: help to maintain synchronous operation of the grid when the system is subject to sudden (potentially large) disturbances

**Ancillary services**

- Regulation: correct short-term power imbalances that might affect system stability (generally frequency synchronization)
- Spinning reserves: provide on-line reserve capacity that is ready to meet electric demand within 10 min
- Non spinning reserves: provide reserve capacity that has a higher response time than spinning reserve
- Voltage control: provides the ability to produce or absorb reactive power, and the ability to maintain a specific voltage level

**Energy services**

- Time-shift: refers to using power that is produced during off-peak hours to serve peak loads, i.e. energy storage charges during off-peak times and discharges during peak times in order to provide load levelling/load shifting
- Load following: refers to adjusting power output as demand fluctuates in order to maintain power balance in the system
- Firm capacity: provide energy capacity to meet peak power demand
- Congestion relief: reduces network flows in transmission constrained systems either by increasing the capacity of the lines or providing alternative pathways for the electricity

**Upgrade deferral**: refers to deferring either generation or transmission asset upgrades by for example, using energy storage to reduce loading on the system

## *3.2 Technology*

An energy storage system can be implemented using a wide range of different technologies. The technology used is a key component of the ESS evaluation. It effects the functionalities and therefore the areas of application of ESS; moreover the specific technology is the main driver that influences the costs of the storage system. This chapter has been built using the useful information provided by (Luo et al., 2015). There are many suitable methods to make a categorization of the different EES technologies, such as, in terms of their functions, response times, and suitable storage durations (Chen et al., 2009)(International Electrotechnical Commission, 2009). One of the most commonly used approach is based on the physic form of energy that the system is able to store. This classification refers to: mechanical energy (pumped hydroelectric storage (PHS), compressed air energy storage (CAES) and flywheels (FES)), electrochemical energy (conventional rechargeable batteries and flow batteries), electrical (capacitors, supercapacitors and superconducting magnetic energy storage (SMES)), chemical (hydrogen storage with fuel cells) and thermal energy storage (Luo et al., 2015).
Here it is a classification of the above mentioned technologies.

### *3.2.1 Batteries*

A battery is an electrochemical system which allows the reversible conversion of chemical energy into electrical energy. It is generally composed by two half - cells separated by a porous septum. The two cells contain an internal metal electrode (anode and cathode) immersed in an electrolyte solution (which typically contains ions of the same metal) . What is commonly called a " battery " is nothing more than a combination, in parallel and/or in series, of a variable number of electrochemical accumulators . The operating principle of an "ideal" battery that allows an electrochemical accumulator to release and store electric power refers to the redox and electrolysis reactions. In the first reaction the electrode (anode) is oxidized , giving off electrons, while the other electrode (cathode) is reduced, acquiring the electrons lost by the first: through a conductor, this flow of electrons is intercepted, thereby obtaining electric current. The second reaction, electrolysis, allows the system to return to the initial status: the application of an electric field converts the chemical stored energy into electric power. The different categories of electrochemical batteries that exist (as we will discuss later in this section) are at a different stage of technological development and are characterized by the material that compose the electrodes and the electrolyte solution, as well as the constructive characteristics.

**Batteries – Lead Acid**

The most widely used rechargeable battery is the lead–acid battery (Chen et al., 2009). The cathode is made of $PbO_2$, the anode is made of Pb, and the electrolyte is sulfuric acid. Lead–acid batteries have fast response times, small daily self-discharge rates (<0.3%), relatively high cycle efficiencies (63-90%) and low capital costs (50–

600 $/kW h) (Chen et al., 2009)(Beaudin et al., 2010). Lead–acid batteries can be used in stationary devices as back-up power supplies for data and telecommunication systems, and energy management applications. Also, they have been assessed as power systems for hybrid or full electric vehicles. Anyway, there are still few installations around the world as utility-scale EES, primarily due to their relatively low cycling times (up to 2000), energy density (50–90 W h/L) and specific energy (25–50 Wh/kg). Moreover, they perform poorly at low temperatures; thus a thermal management system is normally needed, which increases the cost.
The research and development of lead–acid batteries is currently focused on:

1. innovating materials for performance improvement, such as extending cycling times and enhancing the deep discharge capability;
2. implementing the battery technology for applications in the wind, photovoltaic power integration and automotive sectors.

**Batteries – Lithium ion**
In a Li-ion battery, the cathode is made of a lithium metal oxide, such as LiCoO2 and LiMO2, and the anode is made of graphitic carbon. The electrolyte is generally a non-aqueous organic liquid that contains dissolved lithium salts, such as LiClO4. The Li-ion battery is considered suitable for areas of application where the response time, small dimension and/or weight of equipment are critical (milliseconds response time, 1500–10,000 W/L, 75–200 W h/kg, 150–2000 W/kg) (Hadjipaschalis, Poullikkas, & Efthimiou, 2009)(Chen et al., 2009). Li-ion batteries also have high cycle efficiencies, up to 97%. The main drawbacks are:

1. the cycle depth of discharge can affect the Li-ion battery's lifetime
2. the battery pack usually requires an on-board computer to manage its operation, which increases its overall cost.

The current R&D investigation for the Li-ion battery include:

- increasing battery power capability with the use of nano scale materials;
- enhancing battery specific energy by developing advanced electrode materials and electrolyte solutions.

Different firms have experience in using Li-ion batteries in the utility-scale energy market. For a list of grid-connected projects that involve Li-ion batteries please refer to Chapter 4 and to our source of data (Luo et al., 2015).

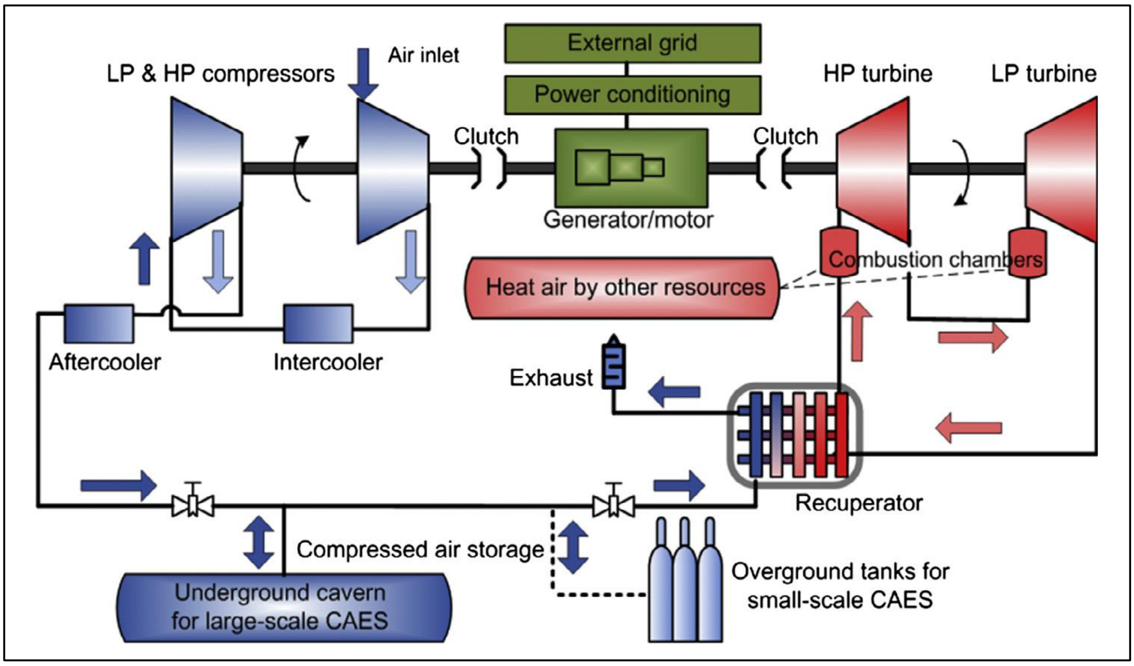
**Batteries – Sodium Sulfur (NaS)**
A NaS battery is based on molten sodium and molten sulfur that serve as the two electrodes, and makes use of beta alumina as the solid electrolyte. The reactions generally require a temperature of 574–624 K to ensure the electrodes are in liquid states, which leads to a high reactivity (Taylor et al., 2012). The useful properties of NaS batteries include high energy densities (150–300 W h/L), almost null daily self-discharge, higher rated capacity than other categories of batteries (up to 244.8 MW h) and high pulse power capability (Kawakami et al., 2010). The battery uses cheap, non-toxic materials that have a high recyclability (99%) (Díaz-González, Sumper,

Gomis-Bellmunt, & Villafáfila-Robles, 2012). The downsides are high annual operating cost (80 $/kW/year) and an extra system required to assure its thermal conditions.
The research and development efforts are mostly focused on improving the cell performance indexes and decreasing the high temperature operating limitations. For instance, Sumitomo Electric Industries and Kyoto University developed a low temperature sodium battery – the novel sodium – that contains material that melts at 330 K (Sumitomo Electric, n.d.). The inventor claimed that the new battery can achieve an energy density as high as 290 W h/L. Furthermore, the ‘‘Wind to Battery’’ project led by Xcel Energy was recently presented in (Tewari & Mohan, 2013): it displays empirical results and analyses the potential and the value of NaS battery EES toward integrating wind energy sources.

**Batteries - Other**
Batteries can be based on several other technologies, as Nickel – cadmium (NiCd), Nickel–metal Hydride (NiMH), ZEBRA, Flow Battery energy storage, $ZnMnO_2$, For an exhaustive analysis on these other technologies please refer to (Luo et al., 2015). We have chosen not to distinguish between these other technologies for purpose of synthesis, and because most of the revised papers that have analysed battery technologies were focused on the Lead-acid, Lithium-ion and NaS technologies.

### *3.2.2 Compressed air energy storage (CAES)*

**Figure 14: Schematic plant of a CAES plant/facility** (Luo et al., 2015)




CAES is a type of commercialized EES technology that can provide power output for more than 100 MW of with a single unit. During the charge periods, the

electricity drives a reversible motor/generator unit in turn to run a chain of compressors for injecting air into a storage container, which is either an underground cavern or over ground tanks. The energy is stored in the form of high pressure air. During periods of discharge, the stored compressed air is released and heated by a heat source which can be from the combustion of fossil fuel or the heat recovered from the compression process. The compressed air energy is in the last stage intercepted by the turbines. The waste heat from the exhaust can be recycled by a heat recuperator. For a schematic representation of a CAES facility refer to Fig 10.
The world's first utility-scale CAES plant, the Huntorf power plant, was installed in Germany in 1978 (Raju & Kumar Khaitan, 2012). It uses two salt caves as the storage vessel and it runs on a daily cycle composed by 8 h of compressed air charging and 2 h of discharge at a rated power of 290 MW (Succar & Williams, 2008). This facility provides black-start power to nuclear units, back-up to local power systems and extra electrical power to fill the gap between the electricity generation and consumption load. For other examples of CAES facilities please refer to (Luo et al., 2015).
CAES system can be built to have large power capacities; CAES technology can provide the discrete speed of responses and good partial-load performance. The practical uses of large-scale CAES plants involve grid applications for load shifting, peak shaving, and frequency and voltage control. The major barrier to implementing large-scale CAES plants is finding appropriate geographical sites that determine the main investment cost of the plant. Relative low round trip efficiency is another barrier for CAES compared to PHS and battery technologies.
Currently, the newly developing Advanced Adiabatic CAES (AA-CAES) is attracting attention. AA-CAES technology is normally integrated with a thermal energy storage subsystem, which has no fuel combustion involved in the expansion mode (Succar & Williams, 2008). The world's first AA-CAES demonstration plant – ADELE – is in the development stage, at Saxony-Anhalt in Germany. The plant will have a storage capacity of 360 MWh and an electric output of 90 MW, aiming for 70% cycle efficiency (Rwe Power, 2010). Because of the particular compression process that will be powered by wind energy, the ADELE plant emits no CO2 in a full cycle.
Recently, researchers have attempted to study other geological structures that can be used in underground CAES technology, other than salt caverns. A 2 MW field test program has used a
concrete-lined tunnel in an abandoned mine in Japan (Succar & Williams, 2008)(Rutqvist, Kim, Ryu, Synn, & Song, 2012). In Italy, Enel was operating a 25 MW porous rock based CAES plant in Sesta, but the test was stopped due to a disturbed geothermal issue (Succar & Williams, 2008).
Above ground small-scale CAES is has a rapid development. It can be used as an alternative to batteries for industrial applications, such as Uninterruptible Power Supplies (UPS) and back-up power systems. In addition, the guideline study for the efficient design and sizing of small-scale CAES pressure vessels considering

minimizing its cost was reported in (Proczka, Muralidharan, Villela, Simmons, & Frantziskonis, 2013).

*3.2.3 Pumped hydroelectric storage (PHS)*

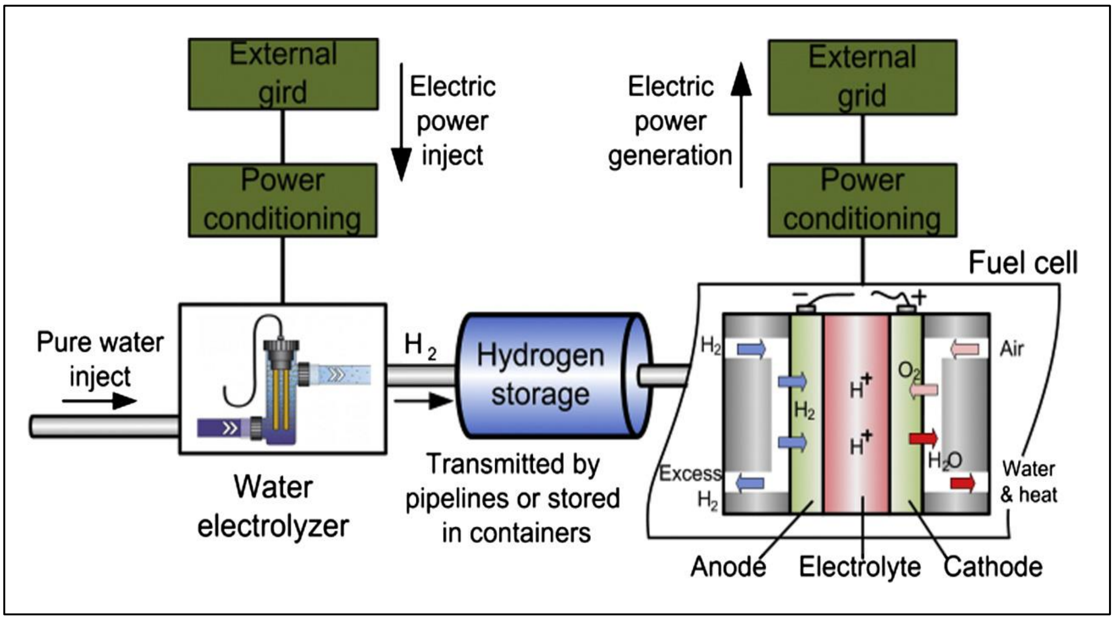
PHS is an ESS technology with a long history, maximal technical maturity and large energy capacity. As explained in chapter 4, there is a worldwide storage installed power capacity of 145658 MW**,** 97,5% of which is given by Hydroelectric power plants. A typical PHS plant uses two water reservoirs, separated vertically. During charging periods, the water is pumped into the higher level reservoir; during discharging periods, the water is released into the lower level reservoir. In the discharging process, the falling water powers turbines that move the electrical generators, and produces electric power. The quantity of stored energy depends on the difference of height between the two reservoirs and the total volume of water stored. The rated power of PHS plants depends on the water pressure and flow rate through the turbines and rated power of the pump/turbine and generator/motor units (Figueiredo & Flynn, 2006).

PHS plants have power ratings ranging from 1 MW to 3003MW, with approximately 70–85% cycle efficiency and more than 40 years lifetime (Chen et al., 2009)(Lacal-Arantegui, Fitzgerald, & Leahy, 2011). The properties of PHS make them feasible for applications that involve time shifting, frequency control, non-spinning reserve and supply reserve. The downside of this technology regards the restriction of site selection, for which PHS plants suffer long construction time and high upfront investment. Recently this field has been effected by some developments: PHS plants that use flooded mine shafts, underground caves and oceans as reservoirs have been planned or are in operation. One example refers to the Okinawa Yanbaru project in Japan, a 300 MW seawater-based PHS plant in Hawaii, the Summit project in Ohio and the Mount Hope project in New Jersey. PHS can be coupled with wind or solar power generation, and this could enhance the adoption of renewable energy in isolated or distributed networks. The R&D development trend of PHS regards the implementation of hydroelectric facilities with higher speed and larger capacity as regards to current applications. Other features involve the installation of centralized monitoring and the use of intelligent control systems (International Electrotechnical Commission, 2009) (Intrator et al., 2011).

*3.2.4 Fuel cell*

Hydrogen energy storage systems use two separate processes for storing energy and

**Figure 15: Scheme of a hydrogen storage and fuel cell** (Luo et al., 2015)




producing electricity. The use of a water electrolysis device is a common way to produce hydrogen that need to be stored in high pressure vessels and/or transmitted by pipelines to different areas (Díaz-González et al., 2012). The system that is necessary to transform the stored hydrogen in electric power is the fuel cell, which is the key component of an hydrogen ESS (see Fig. 11).
Fuel cells can convert chemical energy in hydrogen (or hydrogen-rich fuel) and oxygen (obtained from air) to electricity  (Díaz-González et al., 2012). The chemical reaction that is involved in the process is (Mekhilef, Saidur, & Safari, 2012):

$$2H_2 + \ O_2 \rightarrow 2H_2O + energy$$

Electric power and heat are produced during the process. Depending on the choice of fuel and electrolyte, there are six major groups of fuel cells, which are: Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Proton Exchange Membrane Fuel Cell (PEMFC) and Direct Methanol Fuel Cell (DMFC) (Mekhilef et al., 2012). For further information on the reactions and processes please refer to (Luo et al., 2015).
Some of the upsides of electricity generation by using fuel cells are that produces less noise and almost null pollution. Other interesting properties are easy scaling (potential from 1 kW to hundreds of MW) and compact design (Nakken, Strand, Frantzen, Rohden, & Eide, 2006). Fuel cells combined with devices for hydrogen production and storage can provide stationary or distributed power (primary electrical power, heating/cooling or backup power) and transportation power (potentially replacing fossil fuels for vehicles). Such hydrogen ESS systems, due to

the separate processes of production of $H_2$ – storage – electric power generation can offer capacity and power independence. It is worth mentioning that after the useful life-cycle of the fuel cell, it must be implemented a strategy to recycle and dispose of the toxic metals that are involved in the system as electrodes and catalysts. (Luo et al., 2015)
Stationary power applications are relatively mature. In 2012 nearly 80% of total investment in the global fuel cell industry was made by the U.S. companies.

*3.2.5 Flywheel energy storage (FES or Flywheel)*

A Flywheel system is made of five primary components: a flywheel, a group of bearings, a reversible electrical engine/generator, a power electronic unit and a vacuum chamber (Pena-Alzola, Sebastián, Quesada, & Colmenar, 2011). Flywheel devices use electricity to accelerate or decelerate the flywheel. The stored energy is transferred to or from the flywheel through an integrated motor/generator. For reducing air fraction and energy loss from air resistance, the flywheel system need to be placed in a high vacuum environment. The quantity of stored energy is dependent on the rotating speed of flywheel and its inertia.
The equation for stored kinetic energy is:

$$E = J\omega^2$$

where $\omega$ is the rotor angular velocity and $J$ represents the moment of inertia which is defined as

$$J = \frac{1}{4}kmr^2$$

where m is rotor mass (kg), r is rotor radius (m), and k is an inertial constant depending on the rotor shape. (Ramli, Hiendro, & Twaha, 2015).
Flywheel systems can be classified into two categories:

(1) low speed FES: it uses steel as the flywheel material and rotates below $6 \times 10^3$ rotations per minute (rpm);
(2) high speed FES: it uses advanced composite materials for the flywheel, such as carbon-fiber, which can run up to $\approx 10^5$ rpm.

Low speed Flywheel systems are generally used for short-term and medium/high power applications. High speed FES systems use non-contact magnetic bearings to mitigate the wear of bearings, thereby improving the efficiency. The application areas of high speed FES are continuously expanding, mainly in power quality and ride-through power service in traction and the aerospace industry (Díaz-González, Sumper, Gomis-Bellmunt, & Bianchi, 2013). The specific energy of low speed flywheels is ≈ 5 Wh/kg; the high speed rotor can achieve a specific energy of up to ≈100 Wh/kg. The high speed FES is generally much more expensive than conventional metal Flywheel. The advantageous characteristics of FES are high cycle efficiency (up to ≈95% at rated power), relatively high power density, no depth-of-discharge effects and easy maintenance(Pena-Alzola et al., 2011) (Hadjipaschalis et al., 2009).

In June 2011, a 20 MW modular plant built by Beacon Power was put into commercial operation in New York, which was the largest advanced ESS facility operating in North America ("Beacon Power inaugurates 20MW flywheel plant in NY," n.d.). It employs 200 high speed flywheel systems that provide fast response frequency regulation services to the grid, providing ≈10% of the whole state frequency regulation demand. The main problem of FES is that flywheel devices suffer from the idling losses during the time when the flywheel is on standby. This can lead to relatively high self-discharge, up to ≈20% of stored capacity per hour (Hadjipaschalis et al., 2009).
Currently, the R&D in Flywheel's applications moves towards the material of the flywheel for increasing their rotation speed capabilities and power densities, high speed electrical machines, high carrying capacity of the bearings and the flywheel array technology. (Luo et al., 2015). Another interesting development in FES technology is represented by the High Temperature Superconductor (HTS) bearings which is a promising option for improving bearing performance.

*3.2.6 Energy storage technology – Other*

There is a wide range of technologies - other than the ones already mentioned - that are considered feasible for storage applications. These technologies make use of other physical means of storing energy and they broadly refer to: Thermal Storage, Capacitors, Supercapacitors, Superconducting magnetic energy storage (SMES), Power to gas (PTG).
For more detailed information about these technologies please refer to:
**Thermal storage**: (Hessami & Bowly, 2011), (Rodrigues, Godina, Santos, Bizuayehu, & Contreras, 2014), (Comodi et al., 2014), (Luo et al., 2015)
**Capacitors**: (Bradbury, Pratson, & Patiño-Echeverri, 2014), (Luo et al., 2015)
**Supercapacitors**: (Luo et al., 2015), (Ren et al., 2012), (Hittinger, Whitacre, & Apt, 2012)
**SMES**: (Bradbury et al., 2014), (Zakeri & Syri, 2015), (S.M. Schoenung & Hassenzahl, 2003), (Luo et al., 2015), (Ren et al., 2012)
**PTG**: (de Boer, Grond, Moll, & Benders, 2014)
**Organic chemical hydride**: (Obara, Morizane, & Morel, 2013)

## *3.3 Matching between features and technologies*

Not all the technologies can provide every type of service. See Table 3 what technologies can provide certain features, according to (Castillo & Gayme, 2014) for large-scale projects. The reasons that explain why certain technologies can provide some services originate from the diverse characteristics of the technology as:

- energy density
- length of the life-cycle
- modularity
- roundtrip-efficiency

- response time
- variable cost

**Table 3: Services that can be provided by specific technologies**

| Service | L/A battery | Li-ion battery | NaS Battery | Flywheels | PHS | CAES | Fuel cell |
|---|---|---|---|---|---|---|---|
| Power quality | | | X | X | X | | X |
| Transient stability | X | | | X | | | |
| Regulation | | X | X | X | | | |
| Spinning reserve | X | X | X | | X | X | X |
| Voltage control | | X | X | X | | | |
| Time-shift | | | X | | X | X | X |
| Load following | X | X | X | X | X | X | X |
| Firm capacity | | | | X | X | | |
| Congestion relief | X | X | X | | X | X | |
| Up-grade deferral | X | X | X | X | X | X | X |

It's necessary to comprehend what means of storage can be used in order to provide some services and gain from them.

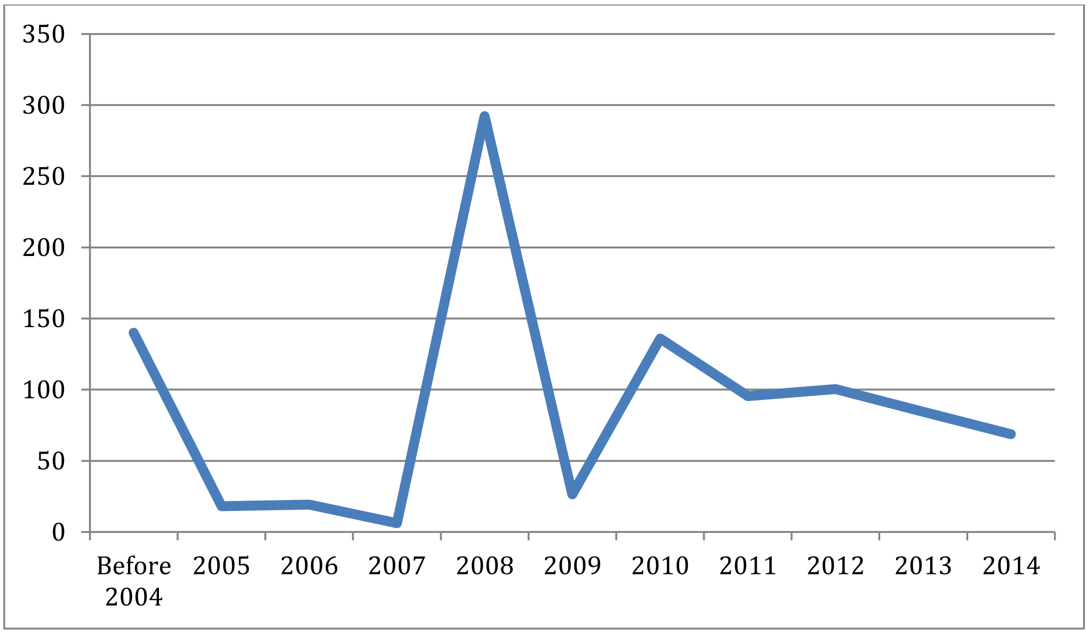
# 4. Global energy storage projects

In order to evaluate the development of ESS it's been assessed the size and magnitude of current and under development ESS. When estimating the number of projects around the world that have the purpose to storage electric power, first of all we have to choose the area of investigation between the different technologies that are involved in this matter.

This assessment in based on the data provided by the Department of Energy of the United States of America, named "DOE Global Energy Storage Database". (http://www.energystorageexchange.org/ ) This database provides up-to-date information about grid connected energy storage systems from all over the world. This collection of data has been chosen as all the information included into the database is vetted through a third-party verification process. On one side this site discloses the projects of ESSs classified by the technology used, the country where are installed, the size, the service provided by the ESS and other categories. On the other side it displays the policies that have regard to ESS of various countries around the world.

The first fact that we need to point out regards the hydropower plants. In the past century hydropower plants were the most important and reliable power sources for the national electric grids. Nowadays hydropower stations have a great importance as they provide the power supply for the peak-load of the electric system when needed, because of their almost null inertia in generating electric power. All over the world there are **145658 MW** of

**Figure 16: Number of MWh of electro-chemical ESS installed globally, before 2004 – 2014 (DOE Global Energy Storage Database)**




operational grid connected energy storage: **142115 MW** of which regard pumped hydro storage (97,5% of the total). This is due to the fact that big hydropower plants can be referred to as pumped hydro energy storage systems.

In order to make an investigation on how is developing the market and the projects of energy storage systems we choose to focus only on the electro-chemical storage – or battery energy storage systems (BESS) – as the most promising type of technology for the future applications, and being the type of ESS that most drive the attention of the academic world.

### *4.1 Global development of Electro-chemical ESS*

Fig. 12 shows the MWh of installed global BESS. Through the last ten years this sector has been interested by a huge development of this systems.

Figure 17: Operational electro-chemical ESS MWh, by country (DOE Global Energy Storage Database)

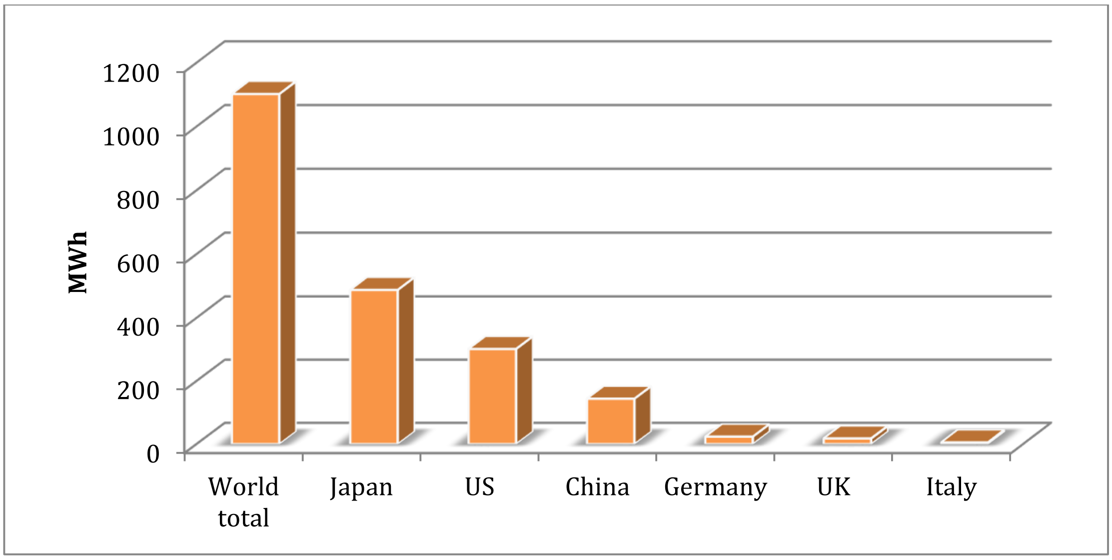
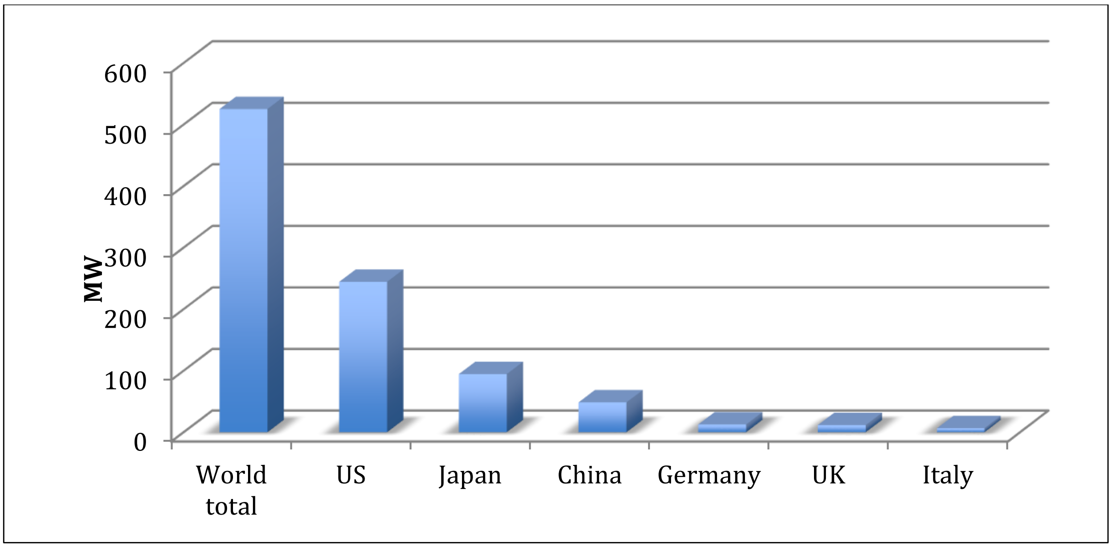
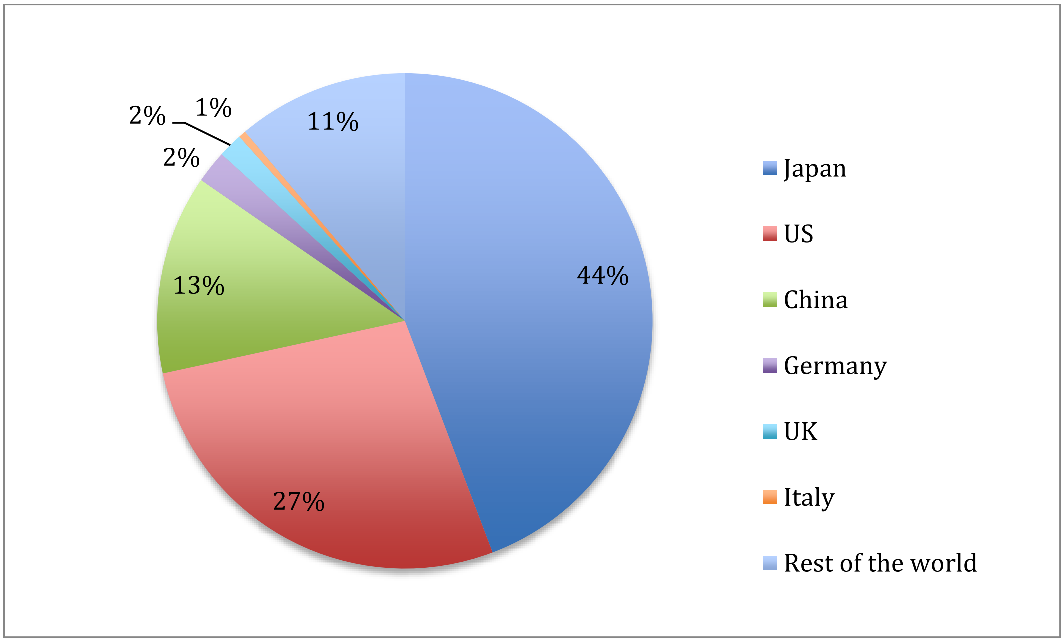



Figure 18: Operational electro-chemical ESS MW, by country (DOE Global Energy Storage Database)



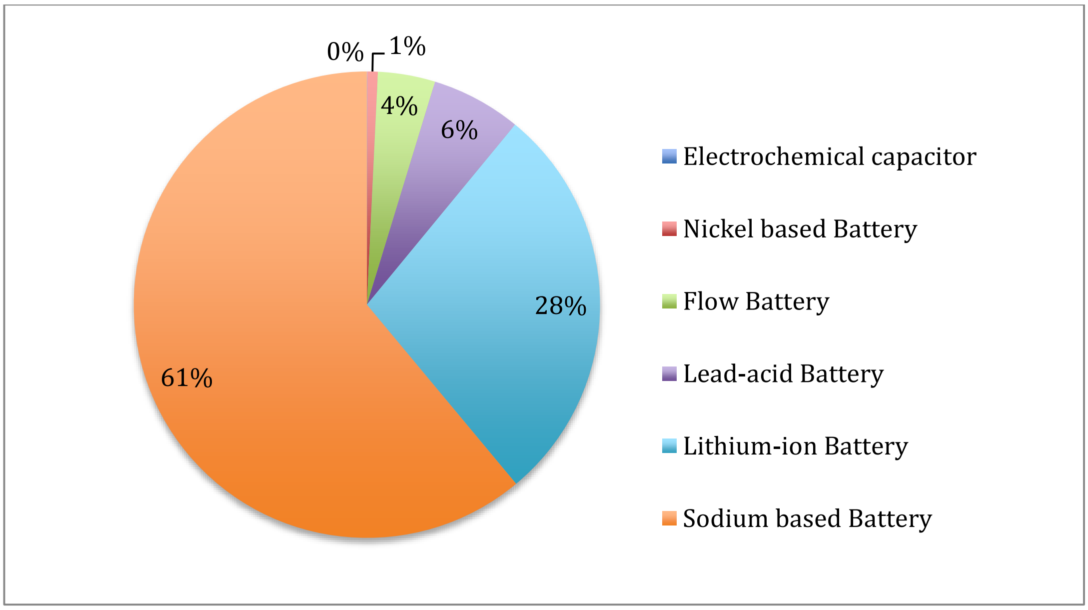

Let's see an analysis by country of installation. Six countries have been chosen as the most interesting for this study: United States, Japan, China, Germany, United Kingdom and Italy (see Fig. 15). The world total operational (defined as currently operative) electro-chemical ESS amount to

Figure 19: Operational electro-chemical MWh divided by country (DOE Global Energy Storage Database)




525121 kW of rated power (see Fig 14). The size of ESSs can be assessed taking under consideration the rated power or the capacity to storage energy. The last method is measured in kWh or MWh (depending on the size of the storage) and it's equal to the hours of duration at rated power that the energy storage system is able to provide multiplied by the rate power of the ESS. The rated power determinate the maximum power that the system is able to provide; the energy capacity measures the amount of energy that can be stored in the system (see Fig. 13 and 14). This two numbers can differ strongly since there are technologies that can provide a very high rated power for a very short period (as supercapacitors, capacitors, SMES etc.), and other technologies that can provide a relative smaller rated power for a much longer period (as PHS, Batteries..). The average duration of hours at rated power of global ESS is 2,5 h. In figure 16 the installed systems are divided by group technology. As we can see the leading technology is the Sodium based Battery, followed by the lithium-ion battery. These two technologies differ in the size of the avarage

**Figure 20: Operational electro-chemical ESS MWh, by battery technology (DOE Global Energy Storage Database)**




system, peculiarity highlighted Fig. 17. In Fig. 13 we can see the global installed ESS evaluated in MWh: the situation is slightly different from the rated power one and the first country for installed capacity is Japan, followed by the US and China. The installations that refer to the rest of the world are United arab emirates (4,3 %) and South Korea (2%).

Figure 21: Average project size, in MWh, by battery technology (DOE Global Energy Storage Database)

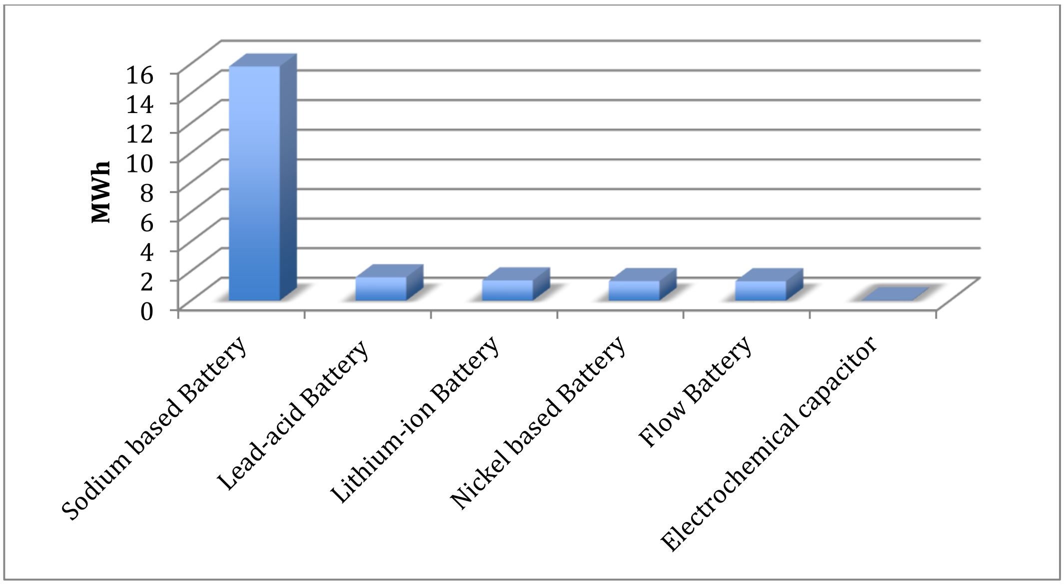
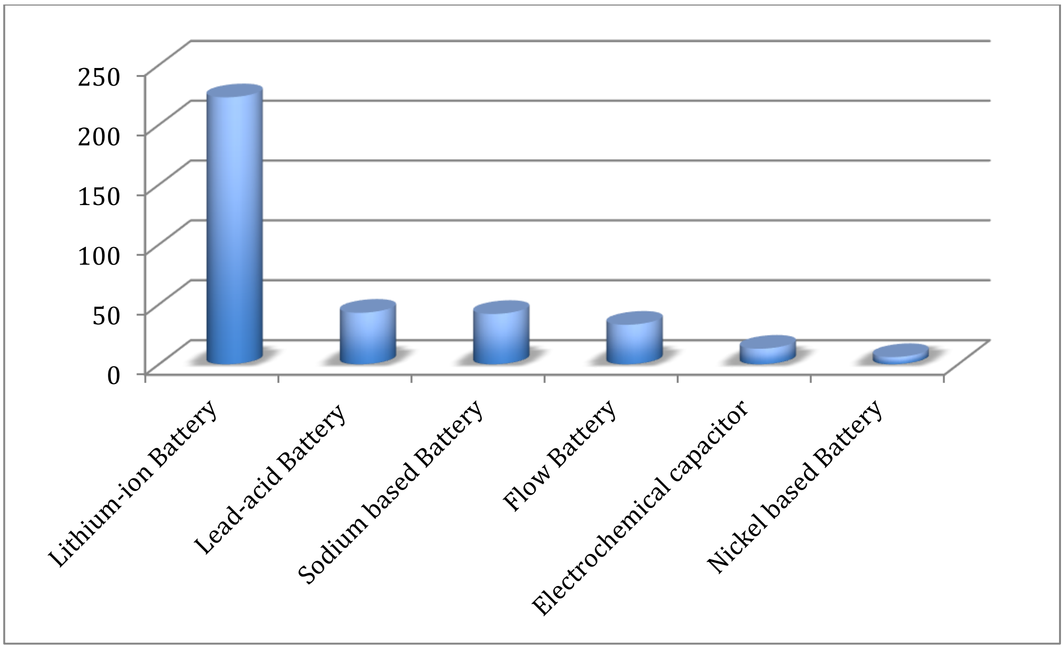



Figure 22: Number of operational projects, by battery technology (DOE Global Energy Storage Database)




Considering the future development of electro-chemical ESS we have to take into account the projects that have been listed in three different categories: the projects that have been announced but not yet contracted, the ones contracted but not under construction yet and the ones that are under construction. Since we cannot be sure whether the projects that are announced are going to be actually implemented, in this assessment we rely totally on the estimation given by the DOE thus ignoring other sources (see Fig. 19). Between the countries listed in the “Rest of the world”, the most important refer to France and Portugal (both 1%). In Table 4 there is the number of MWh under development in the countries assessed and the total in the world.

**Figure 23: Under development battery MWh, by country (DOE Global Energy Storage Database)**

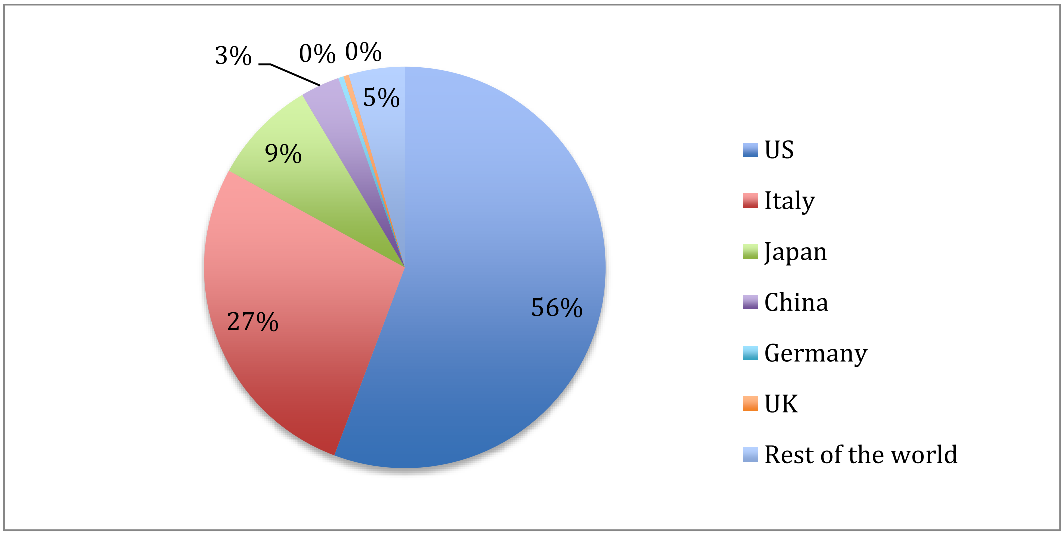
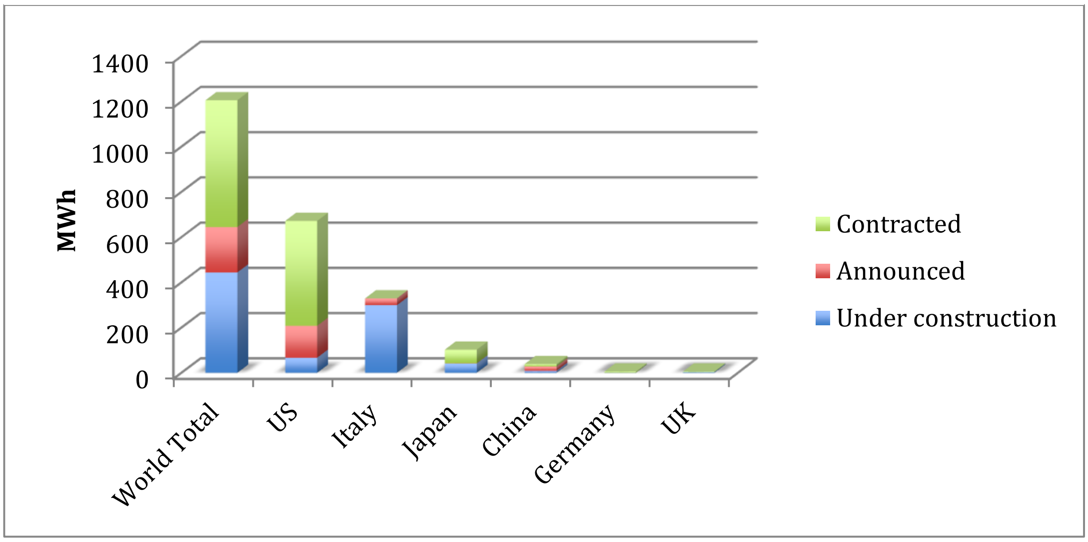



**Table 4: Under development battery MWh, by stage of development, by country (DOE Global Energy Storage Database)**

| Status | World Total | US | Italy | Japan | China | Germany | UK |
|---|---|---|---|---|---|---|---|
| Under construction | 443,465 | 66,252 | 298,740 | 40,9 | 8,15 | 0,204 | 3 |
| Announced | 200,723 | 141,16 | 30,031 | 1 | 20 | 0 | 0 |
| Contracted | 560,700 | 463,924 | 0 | 60 | 10 | 5 | 2,2 |
| Total Under Development | 1204,88 | 671,33 | 328,77 | 101,9 | 38,15 | 5,204 | 5,2 |

**Figure 24: MWh of electro-chemical ESS under development, divided by stage of development, divided by country (DOE Global Energy Storage Database)**




As you can see the US is the country leader in setting up new systems of energy storage. One peculiar case is the one regarding Italy. At the moment there are a few installations operational on the territory, but thanks to the effort of the transmission operator of the national grid (Terna) and the first distributor of electric power (Enel Distribuzione) Italy is the first country in the world for electro-chemical energy storage systems under construction.

### *4.2 Country situation and market analysis*

When assessing the markets drivers for the national markets, it's necessary to distinguish between the different actors and potential buyers of this type of technology. The reason behind this is that every different "consumer" has its own specific motivations for buying a BESS. A Prosumer has a different return from implementing a BESS  than a TSO for example, as explained in the previous chapters. But in a general sense, there are some drivers that can move the market towards a wider implementation of BESS, or that can weaken the potential expansion. This general drivers are:

- Increasing penetration of Variable Renewable Energy (VRE)
- Price of electricity
- Constraint in transmission/distribution infrastructure
- Emerging of micro-grids
- Increasing need for high power quality

(Status and Outlook of the Energy Storage Market, James A. McDowall)

In this chapter we will assess the operational and under development projects in six countries: Italy, United States, Japan, China, Germany and United Kingdom.

We will also give a brief analysis of the market in the United States and in Italy

*4.2.1 Italian BESS*

Currently in Italy there are 13 operational projects; nine of them are developed by Enel, the Italian former monopolist of the electric power generation/ transmission/sale market and actual leader in the distribution sector (with a share of more than 80%) and most important utility in the Italian electric power market. There are 23 projects under development in Italy up to now, 21 programs are realized by Terna and two by Enel. The most used technology is the lithium-ion battery (12 projects), followed by sodium-based batteries (7 projects). Terna is the only TSO for the Italian national grid, and one of the most active companies in the ESS area in the worldwide TSO sector. The average size of under developement BESS is 14,294 MWh

Terna states that the use of these systems is to be found in the frequency regulation, the transmission congestion relief and secondly in the capacity reserve (spinning). Enel's new installations have the aim to defer the distribution upgrade; other applications regard time-shifting and ramping. All new projects are situated in isolated areas, where the transmission and distribution grid is not developed as in the rest of the country. Installations are often matched with high penetration of wind power. the biggest system that is going to operate on the national grid is a BESS plant in the southern part of Italy. The global project consists in a 70 MW NaS battery that will be able to operate at rated power for 7 hours of discharge. The actual stage of the project consists in half of the rated power (35 MW) and an estimation of the costs is roughly 100 million euros.

**Table 5: Residential electricity price, divided by country, divided by voice of cost, 2013, in U.S. dollar cents/kWh (U.S Energy Information Administration EIA)**

| | Italy | EU 28 | US | Hawaii | Alaska |
|---|---|---|---|---|---|
| Base rate | 20 | 18 | - | - | - |
| Taxes | 11,5 | 8 | - | - | - |
| Total | 31,5 | 26 | 12 | 37 | 18,5 |

As we analyse the market drivers for the Italian market, we see that:

1. The price of electricity in Italy is higher than the average in Europe. For household consumers is the fourth highest in Europe and is the highest in Europe for industrial consumers (see table 5 and 6).
2. The total production from renewable energy sources has reached in 2012 almost the 33% of total electricity generation. But ESS is relevant to the unpredictable and intermittent RES, thus the important information is the one regarding only wind and solar production. The total electric energy generation in 2012 is 281029 GWh, and RES production was 91804 GWh. The amount generated from VER is 32269 GWh, which is 11,5% of the total net generation of electricity. Up to now there is a high penetration of VER in the national grid. Looking at the future development of VER, the

government's subsidies on RES are fading, so the expected number of RES new instalments is slowing down.

3. The national TSO and the market leader in the DSO market put a great effort in upgrading the national grid, as was highlighted in current paragraph.

**Table 6: Electricity price for industrial consumers in early 2014, divided by country, €/kWh (Eurostat)**

| | Italy | Germany | UK | France | EU 28 |
|---|---|---|---|---|---|
| Price | 0,172 | 0,159 | 0,129 | 0,096 | 0,123 |

As a conclusion we can say that the Italian market is quite promising and potentially interesting subject to a reduction in the price of kW of BESS, as they say the experts in the area.

*4.2.2 United States BESS*

In the US there are currently 157 operational projects with regards to battery energy storage systems. It's the world leader for installed MW and second for energy capacity installed, with 301,452 MWh. As we look at the future prospects, it's the country that is running more under development projects with a total of 671,33 MWh under development projects. Looking at the technology of the BESS the most common operational application are 29 lead-acid battery projects, 93 lithium-based systems and 16 sodium based systems. The state with more applications in California (49), followed by Hawaii and New York (13). Forty-five systems are applied to a renewable energy source and 48 have the aim to improve the power quality of a component of the electric system (transmission/distribution grid, consumer usage).

**Figure 25: Tehachapi wind farm California. The figure shows the wind farm with 6300 square feet facility at South California.**

The most important system already operational is the Tehachapi Wind Energy Storage Project. Southern California Edison (SCE) is positioned to demonstrate the effectiveness of lithium-ion battery and smart inverter technologies to improve grid performance and assist in the integration of variable energy resources. This project is sited at the Tehachapi Wind Resource Area, one of the largest wind resource areas in the world, where as much as 4,500 MW of wind resources are expected to come online by 2015. An existing SCE substation located approximately 100 miles north of Los Angeles, California, will host the demonstration. The Tehachapi Wind Energy Storage Project (TSP) Battery Energy Storage (see Fig 21) consists of an 8 MW-4 hour (32 MWh) lithium-ion battery and a smart inverter system that is cutting-edge in scale and application. The goal of this application was to:

- Validate the performance and effectiveness of lithium-ion technology
- Demonstrate the integration of intermittent resources
- Gain practical knowledge to develop a smarter, more efficient electrical grid
- Advance market readiness of utility-scale storage

The project duration is roughly six years with a total project value of $54,856,495 (Subburaj, Pushpakaran, & Bayne, 2015).
With regard to the market drivers we can see that:

- The price of electricity is very different from one US state to another but we can notice that the country average for the industrial sector is very low (6,67 dollar cents per kWh in November 2014) and also for the residential sector the price is quite low compared with the average of the European Union 28 countries (12 US dollar cents vs average 26) as displayed in table 5.
- RES penetration in the US is 12,5%, and penetration of VRE is 3,5%. On the overall electricity production we can see that a very small share is given by VRE, which makes the US market not so interesting by this point of view.
- The peculiarity of the US market is that is very different one state from another, and cannot be treated as a whole.

Considering the US as a whole for the BESS market is a mistake, since the difference between a place and another is remarkable in terms of general drivers. Thus the most relevant states to implement a BESS are the ones with a higher price of electricity: Hawaii and Alaska (see table 5). In the other states the application of BESS can be related to power quality reasons, because the price of energy is quite low and application for time-shifting are less valuable.

#### *4.2.3 Japan BESS*

Japan is the first country for energy capacity BESS installed so far with 487,493 MWh. The most important technologies involved in the operational BESS are lithium based batteries with 10 projects and 5,417 MWh and sodium based batteries with 11 projects and 447,68 installed MWh. As mentioned in the introductive paragraph, the technology most suitable for big installations are based on sodium based technology. The company that has provided most of the systems is the NGK Insulator Ltd, which is specialized in NaS batteries.
309,039 MWh of installed BESS refer to the smoothing of RES most of which not on-site. Another use of these systems concerns Electric bill management, that is included in the wider area of the energy time-shift.

Figure 26: Rokkasho-Futamata Wind Farm with storage facility

One of the most important instalments in Japan in the Rokkasho-Futamata Wind Farm (see figure 22). This is the largest combined wind generation (51 MW) plus battery storage (34 MW) plant in Japan and one of the world's largest sodium sulfur battery assemblies. 17 sets of 2-MW NaS battery units (each battery unit consists of 40 50-kW modules) are monitored and integrated with the Rokkasho wind farm in a control centre. The company that provided the energy storage technology is NGK Insulators. The BESS under development will be capable of storing 101,9 MWh. There are at the moment 8 projects that are going to be developed in the near future, most of all applied to RES.

*4.2.4 China BESS*

In China there are currently 143,599 MWh of operational BESS in 53 different projects . The most common technology is lithium-ion batteries, with 45 projects and 122,529 MWh energy capacity. The size of the average instalment of lithium-ion batteries is 2,722 MWh. Sixteen of these projects have the aim to operate in addition to a renewable energy power system. Seven are related to the ability to shift the energy load profile. But most of these projects are related to grid services as frequency regulation, voltage support and load following (22 out of 45).

There are a few BESS under development in China: six projects with an energy capacity of 38,15 MWh. Four of these projects use a lithium based battery and the other two a vanadium redox flow battery. 4 of the projects under development have the goal to balance the power from renewable energy sources.

The largest BESS announced is the Changsha 10MW/20MWh BESS. This facility is able to provide a power of 10 MW for a duration at rated power of two hours. Relying on the advanced Fe battery technology, this ESS technology uses a modular, flexible design and can be easily tailored to meet a diverse set of customer needs.

*4.2.5 Germany BESS*

Figure 27: “The energy self-sufficient district of Feldheim” says the signboard. This village has raised the attention of the green community from all around the world for its in-dependency from traditional energy sources.

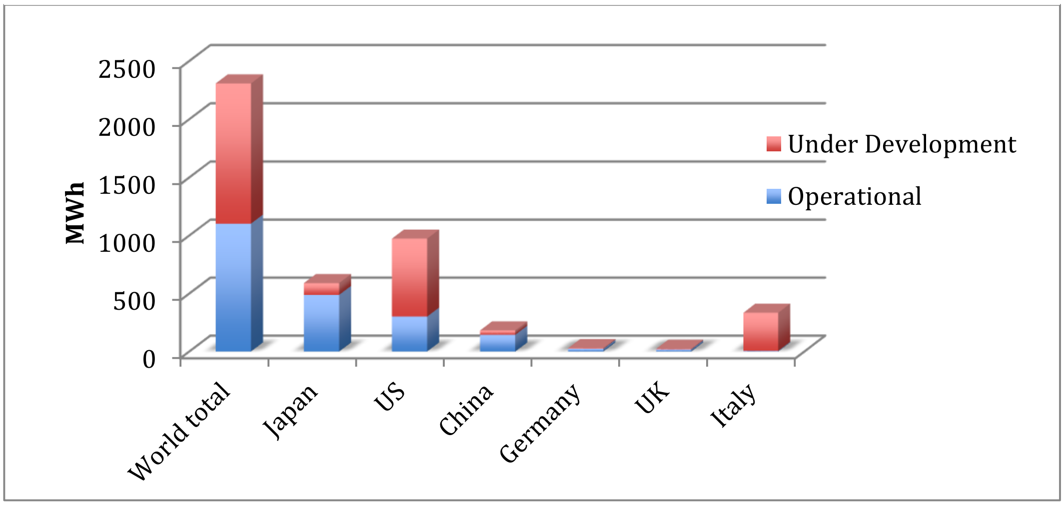

In Germany there are currently 23,388 MWh of BESS installed, developed in 18 different projects. The average size of the instalment if 1,299 MWh. There are 11 projects that use lithium-ion batteries (with an average size of the system of 0,749 MWh) and three systems that make use of redox flow batteries. The purpose of the projects is in most cases to provide grid services (8 projects) and secondly to manage renewable energy sources (6 projects). Most of these instalments have been introduced recently, 12 out of 18 have been developed in the last three years.
There are just a few projects under development (4), none of which of huge size. The most used technology is lithium-ion batteries and the aim of the projects often is to provide grid services. The most interesting project under development is the Regionale Regelkraftwerk Feldheim (figure 23). This innovative storage facility for renewable energy is being built in the energy self-sufficient village of Feldheim and functions as a ‘regulating power station’ at regional level. The first unit will go online in 2014, the second in 2015, when the full 10 MW of output will then be reached. The project is being financed by a venture capital company in which interests are held by Energiequelle, Enercon and a number of other partners. Grant support is also provided by the State of Brandenburg and the European Union.
LG Chem is the company that supplies the lithium-ion modules for the storage complex. (http://www.energiequelle.de).

*4.2.6 Unites Kingdom BESS*

The energy storage systems based on electro-chemical technology available at the moment in the United Kingdom consists in 17 projects that sum up 17,685 MWh. The most employed technology is lithium-based batteries with 16,471 MWh of installed capacity in 10 projects. There is also a moderate presence of lead-acid batteries in 6 different projects. There is a remarkable spread of lead-acid technology also because the related instalments are not very recent: those projects were developed between 2006 and 2009, in the late years the technology has shifted towards lithium-based (for small to medium instalments) and sodium-based batteries (commonly big and huge projects). The purpose of the operational systems is in 9 projects to provide grid services (voltage support, transmission congestion relief) and in 7 circumstances to improve the management of different renewables energy sources.
There are 4 projects under development at the moment, one will use a battery based on the redox-flow technology and two will use lithium-ion batteries.

Between the overall projects, the two companies that have provided the battery technology in most of the projects are Rolls Battery LTD and NEC Energy Solutions. The largest under development project is the AES Kilroot Station Battery Storage Array. AES company plans to build a 100 MW energy storage system at its Kilroot station in Northern Ireland. The ESS will be connected to a large windfarm as well as a coal-fired generation plant. It will serve to store wind energy for later use. The company has applied for a permit from the System Operator of Northern Ireland and projects the system to begin operation in 2015. It's not specified yet the duration of the system at rated power, but this project would be the largest BESS in all Europe. In figure 24 there is a resume of the operational and under development ESS from

**Figure 28: MWh of electro-chemical ESS, divided by country, divided by operational status (DOE Global Energy Storage Database)**




the assessed countries and from the world.

# 5. Industry

In this chapter it's given an assessment of the industry related to battery energy storage systems. We will focus primarily on the Italian market. As we will see in this chapter, in the industry related to ESS most of the operators of the upstream stages, those companies that provide highly technical devices, are not Italian. On the other side the portion of the value-chain that concerns the design and implementation of storage solutions it is definitely more national. Understand the supply chain of a market that has not totally manifested yet is not an easy task, since many operators are waiting to see if it is worth to enter the market.

## *5.1 General definition of the supply-chain of BESS*

In order to understand what are the categories of players belonging to the value chain of ESS, first it is necessary to resume the classification of the key components that constitute this kind of systems, which are:

- The storage device, eg the battery that stores and provides electricity, with attached the operating system that manages the operational side of the battery (Battery Management System);
- The management system of the storage device. This is the computer system that controls the operation of the storage device using management algorithms optimized for the specific of the single (for example it can be connected to a household energy management system or to a management system of a "smart" grid in the case of applications to the power grid);
- Electronic power devices, ie inverter for the DC / AC conversion;
- All other components, as the electromechanical devices (such as power and signal cables, switchgear and protection, electrical panels) for the connection of the various components of the accumulation system itself or between the ESS and the power grid.

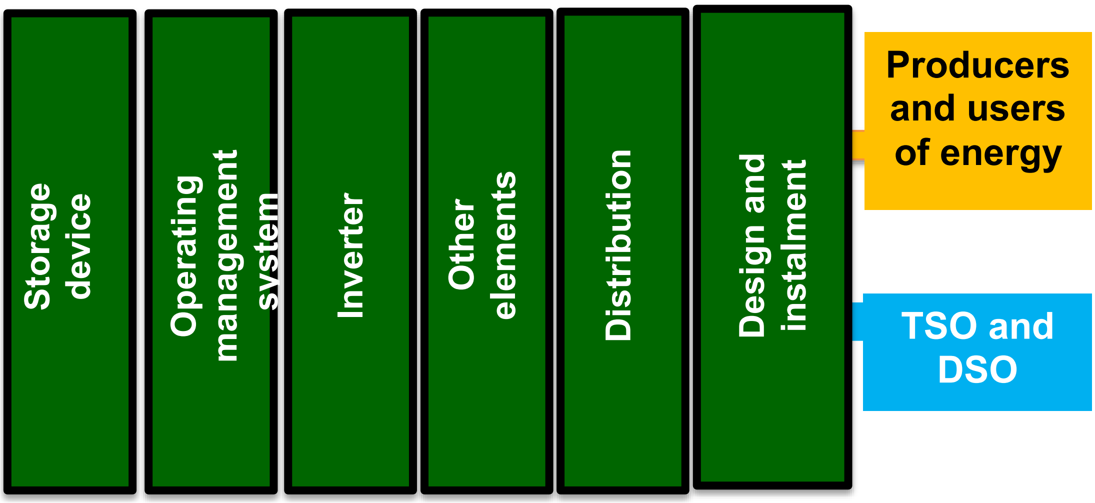
Each of these key components can be associated with a set of operators.
These components refer to the suppliers of the different components of a BESS. In order to complete the mapping of the supply chain we will also have to consider the distribution and installation stages.
The stage of development of the market and the corresponding supply chain of BESS in Italy is not developed yet, thus, it is premature to break down the turnover and the trend of profitability of the different stages of the supply chain. Anyway it should be noted that on the overall value of an ESS, the weights of the different stages are very different from each other. The dominant role, with a share of even 60-80% of the total investment costs for a large size plants (rather variable depending on the specific technology used ), is played by the storage device. The share of the investment cost due to the storage device comes to a 30-50%, with reference to a small size system.
Figure 25 shows two "markets":

- The first one is named “producers and users of energy” and includes the areas of application in CHAPTER 8 that consider a production system of a consumption load;
- the power grid operators, both transmission and distribution side.

The differences between these two "markets" are remarkable:

- Different market potential: the “power grid operator” is considered much smaller than the “producers and users of energy” one;
- The different "size" of the investment, which is obviously bigger for the power grid operators with investments of millions of euro (for plants of the size of Megawatt / Megawatt hours of storage systems). On the other side the prosumer would potentially need thousands of € to meet its storage needs. (iii)
- The number of potential customers, considering that the grid operators in Italy are currently 143 (1 manager of the transmission grid - eg Terna - and 142 operators of distribution grids - of which the main ones are Enel, Acea, A2a, and Iren Dolomiti Energia), while several thousand of plants based on RES are currently installed or are going to be installed in the coming years.

**Figure 29: Supply-chain of the BESS industry (reinterpretation from** (Energy&strategy Group & Politecnico di Milano, 2013)**)**




It’s interesting how these two different "markets" are associated with different supply chains, peculiarity that is explained in the next two paragraphs.

*5.1.1 The ESS supply chain related to the producers and users of energy*

With regards to the first segment of the market, which as mentioned before refers to the players that couple the BESS with a VRES or a load (of different sizes depending on the specific context of application) the companies involved in the supply chain can be divided into:

- operators that historically have operated in the business of energy storage (obviously focused on areas different from the production of electricity, such as the industrial, automotive, and electronics), and they see in the storage of electricity produced from renewable sources (and to a lesser extent also from traditional source) an interesting opportunity to expand its business portfolio
- operators in the industry of renewable energy (and PV in particular), who consider the storage systems as a useful/necessary complement to their traditional range of products/services on the market.

The actors of the upstream stages of the supply chain are, as anticipated before, the traditional operators of the storage system's market (and related management system battery - BMS).
Table 8 shows the main operators that currently offer an ESS on the Italian market (or they think to approach in the short term this market), giving specific attention on the category of potential clients served (as mentioned above closely connected with the size of the device).

**Table 7: Companies in the Italian battery market (reinterpretation from** (Energy&strategy Group & Politecnico di Milano, 2013)**)**

| Name | Industry of origin | Country of origin | Size of the devices | | | Technology |
|---|---|---|---|---|---|---|
| | | | P | MG | VER | |
| BYD | Batteries for automotive and electronics | China | X | X | X | Lithium-ion |
| Bosch | Automotive components | Germany | X | | | Lithium-ion |
| Dispatch Energy | Batteries for storage and automotive | Germany | X | | | Lithium-ion |
| FAAM | Industrial batteries | Italy | X | X | X | Lithium-ion |
| FIAMM | Batteries for automotive | Italy | X | X | X | Lead Acid, Sodium/nickel chloride |
| Full river | Industrial batteries | USA | n.d[1] | | | Lead Acid |
| General Electric | Hi-tech company | USA | | X | X | Sodium/nickel chloride |

[1] From the information collected we presume that the application are small sized, prosumer like.

| | | | | | | |
|---|---|---|---|---|---|---|
| Gildemeister | Machine tools | Germany | | X | X | VRB |
| Hoppecke | Industrial batteries | Germany | X | | | Lead Acid |
| Midac Batteries | Batteries for automotive and industrial | Italy | n.d. | | | Lead Acid |
| Moll Batteries | Batteries for automotive | Germany | X | | | Lead Acid |
| NGK | Products for the power grid | Japan | | | X | Sodium/sulfur |
| NEC | Battery for electronics | Japan | X | X | X | Lithium-ion |
| SAFT | Batteries for automotive | France | X | X | X | Lithium-ion |
| Samsung SDI | Batteries for automotive, consumer and industrial | South Korea | X | X | X | Lithium-ion |
| Sanyo/ Panasonic | Electronics devices | Japan | X | X | X | Li-ion |
| Siemens | High-tech company | Germany | X | X | X | Li-ion |
| Toshiba | High-tech company | Japan | X | X | X | Li-ion |
| Varta | Batteries for automotive, consumer and industrial | Germany | X | | | Lithium-ion |
| Vipiemme | Batteries for automotive | Italy | X | X | | Lead Acid |

The size of the devices is defined as follows: with the initials P (prosumer) are mapped the storage systems able to store a few kWh of electricity; with the initials MG (micro-grid) are defined ESS capable to accumulate tens or hundreds of kilowatt hours of electricity; the initials VER ( plants powered by renewable unpredictable-intermittent sources) refers to storage systems that can store MW of electrical energy.

As we see in the table, 7 of the 20 major operators identified on the Italian market are Germans, compared with only 4 that have their headquarters in Italy.  14 (4 of which aim exclusively this market) out of 20 offer a solution that is sized for prosumers; 12 (of which only one "exclusive") operators have a portfolio of solutions for systems

VRES or greater size. Nine operators can serve all three markets. The number and characterization of the actors at this stage of the supply chain shows a potential of supply that is assorted and significant. Appears clearly that this part of the chain is "ready" to develop the market. The technology of the devices currently offered or to be offered soon in the market refers to three types: lead-acid, lithium-ion and sodium-based. It 'clear that from the technological point of view, the operators aim specifically on lithium (present in 11 of 20 portfolios). This is even more interesting considered that this technology today presents higher initial investment costs (30-50% more with the same battery capacity) than the lead acid solutions. According to the operators, the reason behind this is that they have the goal to maximize the performance of the storage solution in the medium and long term, in respect of the belief that the a market is considered sufficiently "mature" (in terms of skills) in order to assess the advantage.

The players of the **inverter market** that populate the supply chain of ESS for the market of producers and users of energy, come from the world of renewable energies in most cases, precisely from the photovoltaic industry (see TABLE 4.2 ).

**Table 8: Companies in the inverter BESS industry (reinterpretation from** (Energy&strategy Group & Politecnico di Milano, 2013)**)**

| Name | Core business | Country of origin | Size of the device | | | Category of Technology |
|---|---|---|---|---|---|---|
| | | | P | MG | VER | |
| AROS | Inverter | Italy | X | | | n.d. |
| Convertitori Statici | Inverter | Italy | X | X | | Lithium |
| Danfoss | Inverter | Denmark | X | | | n.d. |
| Elettronica Santerno | Inverter | Italy | | X | | Lead Acid |
| Enerconv | Inverter | Italy | X | | | Lead Acid |
| Fronius | Inverter | Austria | X | | | n.d. |
| Layer electronics | Inverter | Italy | | X[2] | | Lead Acid, sodium |
| PowerOne[3] | Inverter | USA | X | | | Lithium |
| Selco Energy | Inverter | Italy | X | | | Lead Acid |
| SMA | Inverter | Germany | X | | | Lithium |
| Western Co | Inverter | Italy | X[4] | | | Lead Acid |

[2] For off-grid applications
[3] The 22 of april of 2013 it was communicated the acquisition of Power One from ABB group, for approximately one billion dollar.

The Italian component here is far more significant and reflects the development that has taken place in the market of the photovoltaic systems which currently focuses the offer for the size of the prosumer. The supply chain at the stages of distribution, design and installation is not very defined, also due to scarcity of the current installations. The providers of storage devices - that is worth to remember have the *lion's share* of the total value created in the supply chain - are clearly able to reach the final market using the "traditional" distribution channel of storage systems, that are reconfiguring themselves in order to point to this potential new market. It is worth mentioning at this regard the cases of **Uflex**, mainly focused on the storage for traction applications, **Alchemy Italy**, primarily focused on applications for traction (eg forklifts and electric vehicles), and **ENERPOWER**, which deals primarily batteries for industrial applications, special ignition and related products (battery chargers and inverters for renewable plants).
The final stages of the supply chain are design and installation. Some actors from the photovoltaic supply chain show some interest (in particular those shown in table 4.3) who offer a portfolio of storage " turnkey " solutions for small photovoltaic systems .

**Table 9: Major operators of the photovoltaic sector operating in the Italian market that offer storage systems ((reinterpretation from** (Energy&strategy Group & Politecnico di Milano, 2013)**)**

| Name | Core business | Country of origin | Size of the device | | | Category of technology |
|---|---|---|---|---|---|---|
| | | | P | MG | VER | |
| Albasolar | PV modules/ distribution | Italy | X[5] | X | | n.d. |
| Conergy | Distribution | Germany | X | | | Lithium |
| Energy Resources | Installation | Italy | X | X | | Lithium |
| Enerpoint | Distribution | Italy | X | | | Lithium |
| IBC Solar | Distribution | Germany | X | | | Lead acid; Lithium |
| Solarworld | Distribution / Installation | Germany | X | | | Lead acid |
| Solon | Distribution / Installation | Germany | X | X | | Lead acid |
| TecnoSun | Distribution | Italy | X | | | Lead acid |

[4] For off-grid applications
[5] Per applicazioni *off-grid*.

*5.1.2 ESS supply chain related to power grid operator market*

The supply chain related to the market of grid operators is definitely less crowded than the producers and users of energy for two main reasons: first because there are few - and large - potential customers, second because the storage systems necessary to meet customer needs are much more complex. The manufacturers of storage systems that can compete in this market are just a few and they come from the storage industry for other types of applications: we refer, in particular, to **BYD**, **Enersys**, **FAMM**, **FIAMM**, **General Electric**, **Gildemeister**, **NGK**, **Saft**, **Sanyo / Panasonic, Samsung, Siemens SDI** and **Toshiba**. There are other companies that play an important role, as the manufacturers of connection components - in particular the Italian company named Selta provides; "turnkey" automation systems, control and supervision services on the grid and production facilities, transmission and distribution of electricity - which represent a critical challenge between the grid and the storage systems.

In this market, customers are making the rules regarding the installation and design operations[6].

Terna (the only transmission operator of the Italian power grid) believes that the battery is the part of the whole system that brings most of the value: for this reason the tender notice for the batteries (in particular, the orientation is towards technology sodium / sulfur for energy-intensive applications, lithium ion and sodium / nickel chloride for power intensive applications) is separated from the one for the other components of the system[7]. Enel Distribuzione on the other side, which is the main national DSO, as well as the most active (like ACEA) on storage, requires the presence of a system integrator who is concerned to define the optimal configuration of the entire system. The companies of the industry, consequently, adapt. Two emblematic cases refer to ABB and Siemens. Their positioning in this customer segment allows them to provide both "turnkey" plants (e.g. that include every component of the storage system, along with the storage device) as well as every component of that system individually.

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[6]Sometimes they adopt solutions " alternative" to storage. Within the Dolomiti Energia Group, the company SET Distribuzione SpA engages in the distribution of electricity in the province of Trentino . This company is the successor to Enel Distribuzione in the management of the facilities and service of electricity distribution in the province of Trento from 1 July 2005. SET Distribuzione decided in the recent years to make investments to improve its grid infrastructure, which is an alternative to storage systems in certain cases, in a context where the spread of RES requires it, considering this solution more efficient in both technical and economical terms.

[7]There are now only six operators " qualified " within the standards of rule IEC 61850 - Standard defined by the International Electrotechnical Commission ( IEC ) for the design of automation systems for electrical substations – that can participate in tender notices for the transmission operator regarding storage systems ( e.g. electronic and electromechanical components, in addition to the necessary civil works, beyond the storage device): ABB , Alstom , Col Giovanni Paolo, Ducati Energia , Selta and Siemens .

## 5.2 The competition on the two markets: business models compared.

Although it's difficult to define a complete market for storage systems in Italy, it is also true - and this chapter proves it - that different companies (even big players) are preparing in order to have a range of storage solutions to offer in accordance with the developments that are forecasted for the near future. The absence of a defined market, anyway, causes an unclear game pattern and two different business models very different one to the other.

One again it's useful to separate the two markets, to highlight a different feature of the context:

- the power grid operators, which is clearly a market "regulated". In this case the customer of the storage systems market acts in response to an input from the Government, which can make profitable investments that are inconvenient at the origin;
- the producers and users of energy market, which is primarily driven by the laws of the market. The Government can intervene sanctioning the obligation to provide some specific services for the benefit of the power system. Requirement that the individual could meet (for the whole or in part) due to the realization of a storage system.

For the grid managers (particularly transmission side) the market today strictly concerns pilot projects. In the near future there are many under development projects implemented by Terna and Enel; all of these projects are for R&D purposes. Although some uncertainty still remains about the actual inalienability of storage systems: as what concerns the transmission system operator (Terna) the orientation by the government is clear, thus storage systems are "grid assets" and therefore not transferable or operable by a third party. For the managers of the distribution grid seems possible the situation where the storage systems are installed and managed by third parties with the goal of providing services for the Ancillary Services Market[8].

Quite different is the market of producers and users of energy. In particular , the analysis of current market dynamics ( not only in Italy ) reveals some models that is worth to mention. We are referring to those segments that are coupled with a VRES power plant, as is presented in chapter 8 and beyond.

A new paradigm is emerging, especially in the US, that is called "microgrid-as-a-service". This model involves the construction and operation of a micro-grid by a company (or a pool of companies) which takes the burden of the initial investment on itself and as a reward sales the electric (and thermal) energy and network services to the customers of the same micro-grid.

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[8] For example, in the perspective of a local dispatching, if the VER plants should be forced to provide network services like the conventional production units, the resources for compulsory regulation could be provided by storage systems, in accordance with the specific user or a trader who sells this services or the grid operator.

In Italy, some companies are studying possible solutions where the company involved in this investment acts as an intermediary between utilities and consumers of electricity (especially the "prosumer") through the management of a storage system. They offer to the utilities the service of detachment / modulation load / generation according to the specific requirements; to the consumers they offer continuity in consumption and sale of the electrical energy. This figure that we can call "storage manager" would be very similar to the current ESCO - Energy Service Companies, which have had and currently have a "propulsive" role in the spread of energy efficiency measures.

# 6. The financial feasibility of ESS: Literature review – economic yardsticks

Understanding the financial/economical feasibility of ESS is not a simple task. This is due to the multitude of variables involved in this matter, which are critical in evaluating the benefits and costs of each scenario. The first step that has been taken when facing this topic was to review the academic literature related to this issue. The intent was to comprehend means, methods and models that have been used by former researchers to assess this issue.

The aim of the review was to:

1. Determine which Evaluation Method (EM) was used in each paper to analyze the economic feasibility. The diverse yardsticks have been divided into categories in order to give a better framework to this matter.
2. Define the nature of the investor and of the area of application of the ESS.
3. Take note of the specifics of the ESS.
4. Take note of the reasons behind the choice of a particular economic indicator.

Paper by paper was reported the criteria used to assess the financial feasibility together with the area of application where the ESS was analyzed.

The structure of the layout used to develop this review is illustrated in Table 2.

In the Appendix A there is the complete list of the papers that used every economic yardstick.

**Table 10: Structure of the Literature review**

| Heading of the paper | EM based on costs | EM based on revenues and costs | Economic returns relevant to the ESS investor | Category of investor | Technology of the ESS | Reason for choosing one yardstick |
|---|---|---|---|---|---|---|
| | | | | | | |

## 6.1 Evaluation methods based on costs

One of the complexity regarding the ESS is the number of different technologies that are related to these kind of system. These technologies refer to the wide range of different forms in which energy can be stored, as electrochemical, mechanical, electric and chemical. Every technology has to be implemented, managed and kept available in particular ways. This explains why estimating and calculating the cost of a ESS leads to a delicate path.

Assessing the economical viability of ESS in some contexts means to calculate its costs. In these cases, the earnings that could be generated from the installation of a ESS are not relevant. The reason behind this is that a storage system can be installed

in a situation where is needed a certain supply of power. The choice is not between installing a storage system or not; the problem is choosing the most efficient way to answer to a power/energy load.
These studies usually compare; either two or more different ESS technologies (e.g. Pumped Hydro Storage Vs Batteries) or a system comprehensive of RES and ESS with a traditional source engine (e.g. a PV solar and batteries Vs diesel engine). Every mean of evaluation has been gathered in three different cost categories.

*6.1.1 Lifecycle cost*
The *lifecycle cost* (Türkay & Telli, 2011) (Zakeri & Syri, 2015) (Ghofrani, Arabali, Etezadi-Amoli, & Fadali, 2013)(LCC) is defined as the Present Value of all the costs that are related to the subject in analysis (in this case the ESS), starting from the investment to the last cost of disposal.
Analytically:

$$\text{LCC} = \sum_{t=0}^{n} \frac{C_i}{(1+r)^t}$$

$C_t$ = cost of the ESS System in period t
t = the time of the expense: t=0 is the time when the investment started, t=n is the period where the ESS is no longer useful.
r = the discount rate: the interest rate that could be earned on an investment with a similar rate of risk: also known as the opportunity cost or hurdle rate.

When mapping the literature on the theme a few simplifications has been made since not all the paper used this precise definition of lifecycle cost, but the principle of the analysis could be assimilated to the LCC. We mapped papers that reported:

- a calculation of costs during all lifecycle period (e.g. not just investment cost or running cost)
- a discounting of the cost values

Between two different investments, both showing the same outcome in terms of answering a specific consumption load, the most profitable investment is the one having the minimum Lifecycle Cost. Its unit of measurement is € (or $).
LCC it has been the most used economic yeardstick; it's present in 43 different papers.

*6.1.2 Cost of energy produced*
When applied to a RE generation system, ESS can be considered a piece of the overall energy production structure. Thus when assessing its economical feasibility it's reasonable to compare the cost of energy produced of the (ESS + RES) system with a different mean of generation of energy (RES without ESS – traditional source etc). Between two systems the most financially sustainable is the one having the minimum cost of energy produced. A precise definition of cost of energy produced

was introduced by the International Energy Agency (IEA) in the "Guidelines for The Economic Analysis of Renewable Energy Technology Applications" in 1991. It's named *levelized cost of electricity* (Ouyang & Lin, 2014)(Zakeri & Syri, 2015)(Blechinger, Seguin, Cader, Bertheau, & Breyer, 2014) (LCOE) and it's defined as:

$$LCOE = P_{Electricity} = \Sigma_t((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t}) / (\Sigma_t(Electricity_t*(1+r)^{-t}))$$

| | |
|---|---|
| $Electricity_t$: | The amount of electricity produced in year "t"; |
| $P_{Electricity}$: | The constant price of electricity; |
| $(1+r)^{-t}$: | The discount factor for year "t"; |
| $Investment_t$: | Investment costs in year "t"; |
| $O\&M_t$: | Operations and maintenance costs in year "t"; |
| $Fuel_t$: | Fuel costs in year "t"; |
| $Carbon_t$: | Carbon costs in year "t"; |
| $Decommissioning_t$: | Decommissioning cost in year "t". |

(MIP, Politecnico di MIlano School of Management, Energy & Strategy Group s.d.)
LCOE is the price that electricity should be sold at, in order to repay all the costs of the RE system. Its unit of measurement is €/Kwh (or $/Kwh).
When mapping the literature on the theme a few simplifications has been made: not all the paper used this precise definition of cost of energy produced, but the principle of the analysis could be assimilated to LCOE. In particular papers showing:

- a calculation of the cost per Kwh produced
- the calculation of costs need to refer to the lifecycle of the system

There have been found 30 papers showing LCOE.

*6.1.3 Other cost tools*

Some of the paper that have been reviewed disclose different means of evaluation. This category pools those yardsticks that don't resemble the above mentioned criteria; nevertheless the analysis is based on some sort of cost measurement. In some cases the analysis calculate part of the costs that make the LCC, as the investment cost or running cost. In other papers it's developed a model or a simulation that defines a cost measure that is not LCC or LCOE. All these different cost measurement are disclosed in this category.
There are seven papers that show a cost tool that isn't ascribable at LCOE or LCC.

## *6.2 Evaluation methods based on revenues and costs*

Calculating the economical feasibility of ESS can be treated as a classic investment decision problem, thus can be solved using the standard financial and economic means of evaluation. In these studies it's given a particular cost structure, a context of application and an oversight of the market where the storage was assessed. The revenues associated with the investment in ESS are different from case to case, depending on the kind of investor and on techno-economical landscape. The distinction is left for the following paragraph.

All the data are organized in order to resume the financial analysis with the following means of evaluation. All the economic yardsticks in this section refer to the deterministic criteria of evaluation of an investment. The first three (NPV, PI, IRR) use the discounted cash flow logic while the last two don't. All the papers showing these yardsticks have been mapped in our analysis.

*6.2.1 Net present value*

The *net present value* (NPV) consists in the discounted algebraic sum of the n*et cash flow* (NCF) related to the investment (Azzone G. 2005) (Susan M Schoenung & Eyer, 2008) (Kapsali & Kaldellis, 2010).

The NCF is defined, excluding taxation and financial capital issues, as the cash flow coming from the operations management plus (minus) the cash flow coming from the investments.

The cash flow (CF) is calculated as: revenues minus operations monetary cost.

$$NPV = \sum_{t=1}^{T} \frac{CF(t)}{(1+r)^t} + \frac{V_T}{(1+r)^t} - I$$

CF(t) = cash flow in period t.

r = the discount rate: the interest rate that could be earned on an investment with a similar rate of risk: also known as the opportunity cost or hurdle rate.

$V_T$ = the value of the asset at the end of the lifecycle – the cost of disposal

I = the initial expense of money, the starting investment.

An investment is profitable if NPV > 0. Between two investments the most profitable is the one having the grater NPV.

There are 21 papers showing NPV.

*6.2.2 Profitability index*

The *profitability index* (PI) (Hoppmann, Volland, Schmidt, & Hoffmann, 2014) is very close to the NPV. It's the ratio between the discounted cash flow generated from the investment and the discounted value of the investments (excluding the final value of the investment).

$$PI = \frac{\sum_{t=0}^{T} \frac{CF(t)}{(1+r)^t}}{\sum_{t=0}^{T} \frac{I(t)}{(1+r)^t}} = \frac{NPV}{\sum_{t=0}^{T} \frac{I(t)}{(1+r)^t}} + 1$$

The condition for an investment to be profitable is PI > 1, that is equivalent to impose NPV > 0. Some difference between the two indexes could arise in presence of budget constraints that could limit the amount of the investments. In this case the PI is more appropriate.
This is by far the least used ME, it's been found just one thesis that shows PI.

- Hoppmann, Joern, Jonas Volland, Tobias S. Schmidt, and Volker H. Hoffmann. 2014. "The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems - A Review and a Simulation Model." *Renewable and Sustainable Energy Reviews* 39. Elsevier: 1101–18. doi:10.1016/j.rser.2014.07.068.

The specific reason that brought (Hoppmann et al., 2014) to choose this yardstick it's here reported: "We use the profitability index to measure storage profitability instead of the NPV since we optimize the storage size for different points in time of investment. The differences in optimal storage size over time would make the profitability of storage hard to compare if we used an absolute measure of profitability. Therefore, we report the storage profitability as the NPV per EUR invested. The optimal storage size over time is reported as a separate output variable.

*6.2.3 Internal rate of return*

The *internal rate of return* (Bradbury et al., 2014) (Rodrigues et al., 2014) (Parissis et al., 2011)(IRR) it's defined as the discounting rate that makes the NPV of an investment equal to 0.

$$\sum_{t=0}^{T} \frac{NCF(t)}{(1 + IRR)^t} = 0$$

It is important that this equation has just one positive solution, otherwise it can lose its meaning. Descartes' theorem gives a sufficient condition for the using of IRR: if the coefficients of the polynomial of the above mentioned equation present just one change of sign, it's guaranteed that the equation has just one positive solution. That is likely to happen for the NCF of average investments, where the only negative term is the one in period 0 when the starting investment is made. For a more complete analysis of the problem refer to Bernhard (1977), Bernhard and Norstrom (1980) and (M. Kapsali 2010).
An investment is to be considered profitable if IRR > r; r is the opportunity cost or hurdle rate. Economically speaking, the IRR is the yield of the money that are invested in that asset. Thus between to different investments, has to be chosen the one with the higher IRR.
Papers are 17 papers that assessed IRR.

*6.2.4 Payback time*

The *payback time* (PT) (Zhang & Wan, 2014)(Ozbilen, Dincer, Naterer, & Aydin, 2012)(Yan, Zhang, Chen, Xu, & Tan, 2014) is defined as the moment when the cash flow generated from the investment cover the initial expense.

$$\sum_{t=0}^{PT} NCF(t) = 0$$

An investment has to be made if its PT is inferior to the one set by the company or by the investor. The limit of this index is that it doesn't take under consideration the remuneration of the capital through time; moreover the PT doesn't report any measure of economical return beyond the repayment period. It's widely used by companies for its simplicity. There are 14 papers that have used the Payback time.

*6.2.5 Net income*

In this category have been depicted all the papers that presented a raw analysis of the earnings of these investments. The *net income* is defined as the balance between operational incomes – operational cost + (−) cash flow from investments. It's not a deeply precise evaluation method since it doesn't take into account the discounting issues and it's not a structured method. 28 papers have been found presenting an economic yardstick that was reconduced to this category.

# 7. Definition of the economic returns from ESS

## *7.1 Economic returns relevant to the ESS investor*

In this chapter it's been assessed what are the valuable returns of the ESS from an economical point of view. The aim was to assess what specific return has been taken into account in the academic literature, in order to give some indications (in CHAPTER 9) on the elements that have to be considered when assessing the economic viability of ESS.

Be noted:

One aspect that has to be considered when assessing the return from applications of energy storage systems, is the efficiency of the system. Since every energetic transformation produced in the real world is not reversible, there will be a loss for every conversion that is implied in the process of storing energy. When assessing the return for every unit of energy that is stored and discharged, it has to be considered this aspect. Here it's given the analytical process that lays beyond this principle.

The variables of the problem are:

$T_1$= Time when the energy is stored in the system

$T_2$= Time when the energy is discharged from the system

$P_1$= Price or "value" of charged energy in period $T_1$ [€/kWh]

$P_2$= Price or "value" of discharged energy in period $T_2$ [€/kWh]

$X_1$= Quantity of energy charged in period $T_1$ [kWh]

$X_{s1}$= Quantity of energy stored in period $T_1$ [kWh]

$X_{s2}$= Quantity of energy stored in period $T_2$ [kWh]

$X_2$= Quantity of energy discharged from the system in period $T_2$ [kWh]

$\eta_{ch}(t)$= Efficiency of charge of the system; it gives the percentage of the input energy that is actually stored in the system. It is a measure of the energetic losses from charging the system. It depends on the specific technology

$\eta_{st}(t,T)$= Efficiency of storage of the system; it defines the fraction of energy that is available in the storage system at period $T_2$. It's a measure of the losses of the storage system during the period that the energy has been stored in the system. It depends on the specific technology and on the time that has passed between $T_1$ and $T_2$

$\eta_{dh}(t)$= Efficiency of discharge of the system; it gives the percentage of the stored energy that is actually available for the final use (sale, consumption...). It measures the energetic losses from transforming the physical mean of storage into electric power. It depends on the specific technology

When we refer to the "value" of energy (or power), we consider the precise economic value of the single unit of energy [kWh] in period $T_1$ for the specific economic player. This "value" differs form one context to another: it could be the sale price of energy on the power market (e.g. for an investor that sells energy) or the price of purchase of energy (for a consumer load).

$\eta_{ch}(t)$, $\eta_{st}(t,T)$, $\eta_{dh}(t)$ are > 0 and < 1 by definition.

In period $T_1$ the storage system is charged, and the amount of energy stored depends on the efficiency of the technology involved (1):

$$X_{S1} = X_1 \times \eta_{c\hbar}(\mathrm{t})$$

After a period ($T_2 – T_1$) while the energy has been stored in the system, the energy available in the storage system hinges on the efficiency of storage technology and on the time lapse (2):

$$X_{s2} = X_{S1} \times \eta_{st}(t, T)$$

At the end of the storage process, in period $T_2$ , the quantity of energy that can be discharged from the system is (3):

$$X_2 = X_{s2} \times \eta_{dh}(t)$$

Because of equations (1), (2), (3) the following sentence is verified (4):

$$X_2 = X_1 \times \eta_{c\hbar} \times \eta_{st} \times \eta_{dh}$$

In order not to lose money from the operation of charging and discharging energy from the ESS, the condition that has to be granted is (5):

$$P_1 \times X_1 \leq P_2 \times X_2$$

The break-even price or “value” of energy that would enable the owner of the ESS plant not to lose money is the one coming from the equation (6):

$$P_1 \times X_1 = P_2 \times X_2$$

Reformulating (7):

$$\frac{P_1}{P_2} = \frac{X_2}{X_1}$$

Because of sentence (4) the following sentence is true:

$$\frac{P_1}{P_2} = \frac{X_1 \times \eta_{c\hbar} \times \eta_{st} \times \eta_{dh}}{X_1}$$

which leads to (8):

$$P_2 = \frac{P_1}{\eta_{c\hbar} \times \eta_{st} \times \eta_{dh}}$$

Sentence (8) is complete from an energetic point of view; from an economical perspective it has to be considered the variable cost ($C_v$) that has to be sustained for every operation involved in the process of purchasing, storing and selling (e.g. these could be the fees that have to be paid for using the power grid, etc.).
Another variable that has to be taken into consideration is the "Cycle cost" of the technology. It's been assessed that different technologies have a different number of cycles (as charging – discharging cycle) that can be executed from the beginning of the life cycle until the decommissioning. The cycle cost is defined as: $C_C = \frac{C_0}{Nc}$, with $C_0$ investment cost of the ESS and $N_c$ number of cycles that the specific technology is able to provide. Thus a solid valuation of the investment cost of the storage system allocated to the single operation cycle is represented by the cycle cost. $C_v$ and $C_c$ have to be evaluated with regards to the discharged energy, so that the unit of measure is the same. $C_v$ and $C_c$ have to be divided for the discharged energy $X_2$.Thus the final price or "value" of the discharged kWh that would enhance the manager of the ESS system not to lose money in the process is (9):

$$P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$$

For some examples of efficiencies related to the purchasing prices and a similar analysis of the matter please refer to (Pearre & Swan, 2014), (Krajačić et al., 2004), (Fares & Webber, 2014).

The categories of returns have been divided as follows:

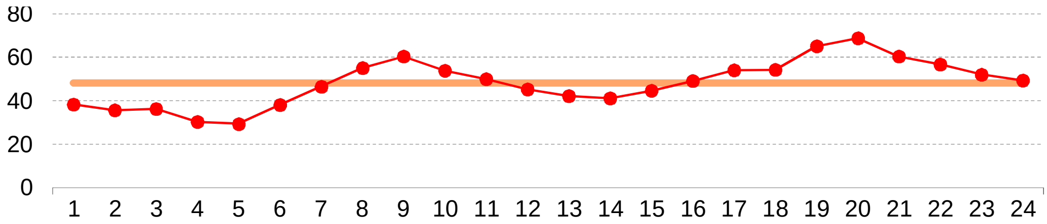
### *7.1.1 Time-shift returns*

The most clear and relevant category of returns of ESS is related to the possibility to gain from the difference of economic value of electric power in different time periods. This wide category of earnings gives a specific return in accordance with the particular area of application. In the next paragraphs it's given an explanation of the particular development of this principle depending on the different areas of application.

#### *Arbitrage*

Arbitrage involves the storing of low priced electricity available during periods when demand for electricity is low, so that the electric power can be sold later when the price for electricity is higher. Energy sold on the electric energy market reaches its peak price during periods of highest demand.

**Figure 30: Electric power hour price on the MGP in Italy, 13 March 2015, €/MWh.**




The potential of this return is highly dependent from the specific market of electric power. Here we take as an example the Italian power market. In Italy the market for the exchange of electric power is named the Italian Power Exchange market (IPEX). (De Bosio & Verda, 2015)

The IPEX Market is composed by the Spot Electricity Market, the Forward Electricity Market and the Platform for physical delivery of financial contracts concluded on IDEX – CDE. The Spot Electricity Market is the place where electricity trading occurs. This consists of three different sessions:

- Day-Ahead Market (abbreviated as MGP, in Italian), where the main stocks are assigned. As displayed in Figure 26, if we consider the price range within a day, the minimum hour price in this market for a 13 March 2015 is 29,41 €/MWh and the maximum daily price is 68,85 €/MWh.
- Intra-Day Market (abbreviated as MI, in Italian), where adjustments are operated on the basis of the grid capacity.
- Ancillary Service Market (abbreviated as MSD, in Italian), where some of the plants provide their availability to modify their operation in order to prevent from unexpected request variations (De Bosio & Verda, 2015).

Arbitrage affects the areas of application that have the sale of electricity to the grid as the fundamental income voice. Thus “RES on grid” and “T&D” areas of application gain from arbitrage as the return related to time-shift applications. Thirty-nine papers have taken into account arbitrage as one of the most interesting voice of revenues of ESS.

*In-house consumption*

This return refers to the Prosumer and the Micro-grid, where there is a consumption load coupled with a renewable energy production system. In this case the ESS is used to increase the In-house consumption rate of the overall system. The economic return is given by the gap of economic value between:

1. the power generated and sold to the market
2. the power purchased from the grid.

Let’s take as an example the case of one prosumer that has a photovoltaic generation system.

Without a storage system, the owner of the PV would use exactly the same amount of power produced by the PV system when the consumption load matches the production profile of the PV system. During periods when the production profile is higher than the consumption load the PV would sell the excess energy to the power grid; in periods when the production profile is lower than the consumption load, the prosumer would need to buy electricity on the power market. Since the price of sale of electric power is lower than the price of purchasing it from the power grid, the ESS would enable the owner of a RES-ESS system to benefit from the difference between these two values. There are 14 papers that have evaluated this specific return.

*Load shift*
This is the case of the area of application “Consumer”. The economic value originated from the time-shift potential of the ESS applied to these contexts is called Load shift. It refers to the difference between the purchasing price of electric power in two different periods. The owner of an ESS is able to buy electric power that exceeds the user consumption profile in periods when prices are low and consume it in periods when prices are high. The returns from this category of application are once again strongly dependent on the specific power market.

*7.1.2 Power quality*
Assessing the return of power quality applications in not a simple task. (Eyer et al., 2004) gives an interesting explanation of the financial returns related to this topic. This return is very end-user-specific and is hard to generalize. It affects specifically commercial and industrial consumers; it is relevant primarily for those for whom power outages cause moderate to significant economic losses. Poor power quality issues are well documented. Technical details are not covered deeply here, for a complete analysis please refer to (Fuchs & Masoum, 2008) (LaCommare & Eto, 2004).
In the most general terms, power quality related financial benefits accrue if energy storage reduces financial losses associated with power quality damages. Power quality anomalies relevant here are those that cause loads to go off-line and/or that damage electricity-using equipment and whose negative effects can be avoided if storage is used.
From a macroeconomic point of view, one recent study (Coll-Mayor, Pardo, & Perez-Donsion, 2012) indicate an interesting methodology for estimate this economic aspect.
The methodology proposed is based on the following mathematical model, defined as follows:

$$Value = EHnP \times VoLL \times ELP$$

where Value represents the value of the economical losses [€], EHnP means equivalent hours of non-Production [h], VoLL means value of Lost Load [€/kW h], ELP means equivalent lost power [kW]. The estimation of the EHnP is not an easy task; one consideration that can be made is that the EHnP is proportional to the length of interruptions and to the depth of the sag. VoLL is considered as the added value generated by an activity divided by the energy consumed by this activity. At country level if the VoLL shall be used for comparing the energy behaviour of the industry in different countries and can be estimated as: $VoLL_{Country} = \frac{GDP}{TEC}$ where GDP represents the Gross Domestic Product [€] and TEC represents the Total Energy Consumption [GWh], which is the electrical energy a country consumes in one year. The ELP (Equivalent Lost Power) is the loss of power experienced in an interruption. The lost of power depends on many variables, such as the time of day or the day in the week when the interruption took place. For further information on the methodology please refer to (Coll-Mayor et al., 2012).

In order to evaluate the actual financial costs of power quality issues (and return of an ESS for this) for the specific user, there are two different categories of losses that have to be taken into consideration (Reichl, Schmidthaler, & Schneider, 2013):

1. Direct costs. These are the costs that are immediately caused by a power cut. For example, the costs of repairing a device that has broken after a power quality issue. This category of costs is easily detectable and precisely calculable.
2. Indirect costs. These are the costs that influence the system where the power outage has taken place. They form part of the total losses, which are causally linked to the absence of electricity supply in the aftermath of a breakdown (Reichl et al., 2013). The calculation of these side-effects is not easy. It depends on the opportunity cost of the component of system where the outage has taken place. For example, if it takes place in a company and it causes an arrest of the production that causes the loss of a sale, the opportunity is the loss profit of the sale. This is more complicated to estimate and is very user-specific.

Luckily there is a relative easy way to calculate the return of en ESS in providing solution to power quality issues. In fact, as an upper limit, the power quality benefit cannot exceed the cost to add the “conventional” solution. For example: if the annual power quality benefit (avoided financial loss) associated with an energy storage system is €70/kW-year and another equipment that if installed would solve this problem costs €40/kW-year, then the maximum benefit that could be ascribed to the energy storage plant for improved power quality is €40/kW-year (Eyer et al., 2004). The only hypothesis that has to be granted in using this valuation is that the “conventional” solution’s cost must be lower than the cost linked to power quality issues.

No theses have taken into account this category of return.

### *7.1.3 Ancillary services*

There are some services that the owner of a ESS can provide and sell to the manager of the power grid. (Eyer et al., 2004) give an explanation of the various ancillary

**Figure 31: List of Ancillary Services and their common definitions** (Eyer et al., 2004).

| | |
|---|---|
| 1. System Control | Scheduling generation and transactions ahead of time, and controlling some generation in real time to maintain generation/load balance. |
| 2. Reactive Supply & Voltage Control | The generation or absorption of reactive power from generators to maintain transmission system voltages within required ranges. |
| 3. Regulation | Minute-by-minute generation/load balance within a control area to meet NERC standards. |
| 4. Spinning Reserve | Generation capacity that is on-line but unloaded and that can respond within 10 minutes to compensate for generation or transmission outages. "Frequency-responsive" spinning reserve responds within 10 seconds to maintain system frequency. |
| 5. Supplemental Reserve | Generation capacity that may be off-line or curtailable load that can respond within 10 minutes to compensate for generation or transmission outages. |
| 6. Energy Imbalance | Correcting for mismatches between actual and scheduled transactions on an hourly basis. |
| 7. Load Following | Meeting hour-to-hour and daily load variations. |
| 8. Backup Supply | Generation available within an hour, for backing up reserves or for commercial transactions. |
| 9. Real Power Loss Replacement | Generation that compensates for losses in the T&D system. |
| 10. Dynamic Scheduling | Real-time control to electronically transfer either a generator's output or a customer's load from one control area to another. |
| 11. Black Start | Ability to energize part of a grid without outside assistance after a blackout occurs. |
| 12. Network Stability | Real-time response to system disturbances to maintain system stability or security. |

services, as defined by the Federal Energy Regulatory Commission (FERC) as those services necessary to support the delivery of electricity from seller to purchaser while maintaining the integrity and reliability of the interconnected transmission system ("the power grid") (see Fig. 27).

(Anderson & Leach, 2004) analyses the ancillary services market in the UK, (Madlener & Latz, 2013) the minute reserve market on the German power grid, (Fertig & Apt, 2011) the value of ancillary services on the Electric Reliability Council of Texas U.S. . (De Bosio & Verda, 2015) simulate the returns on the Ancillary Service Market in Italy for a CAES installation.
Something very importan that has to be taken into consideration is whether there is a market where is possible to sell the provision of these services, or another way that enables the owner of the ESS system to benefit from the provision of these services. Most studies that take into account ancillary services are assessing large scale plants that sell these services on apposite markets.
Up to now owners of small ESS are not able to provide this category of services for technical reasons and because the are no economic ways to profit from them.
In the academic literuature reviewed the sale of grid services has been considered only in "RES on grid" and "T&D" areas of application. There have been found thirteen papers that take into consideration the provision of ancillary services and the related economic return. For example let's consider the a 1 MW solar plant in Italy. The possible future obligation for this kind of plant to make available the 1,5% of the nominal power (15 kW) for the regulation services for all the hours that the system produces (4700 hours/year) would cost 10000 €/year of missed production. An ESS would help to save this amount of money (Energy&strategy Group & Politecnico di Milano, 2013).

7.1.4 Capacity payment
A capacity market can be defined as a market scheme, in which the regulator defines the total required capacity of the system. The regulator then leaves the pricing per unit of capacity to the market — e.g. through a public auction process (HM Government, 2012)(Söder, 2010). Therefore, the regulator can steer the total installed capacity through the definition of the required capacity, but not the price for the provided capacity as it is determined by the market. In some capacity markets, such as the ones of PJM Interconnection LLC (PJM) that is a Regional Transmission Organization in the United States, regulators define demand curves for capacity rather than fixed capacity requirements to prevent strategic behaviour and the exercise of market power. In a system with capacity payments, either all, or only selected plants receive a fixed or variable compensation for available capacity (Baldick, Helman, Hobbs, & O'Neill, 2005). In such a system, the regulator sets a price paid to the targeted generators. Hence, the regulator can only steer the installed capacity indirectly, by setting the price and leaving it to private operators whether or not to invest.
There have been found only three papers that displayed this category of return in the economic analysis.

*7.1.5 Imbalance duties*
In some countries (e.g. in Italy) the government has developed a strategy to internalize the externalities that are provoked by integrating VRES in the power grid.

Thus is obliging the owners of plants thar produce electicity from VRES to keep the power production between certain limits imposed by the owner's own forecast; if the production strongly differs from the forecast the owner of the plant is obliged to pay a fee. The installation of a ESS could clearly help the owner of the ESS to save this expense. This return only affects the owners of VRES. Since imbalance duties are not so spread, there are not papers that take into consideration this return in the economic assessment.

## 7.2 Economic returns that affect a third-party

The spread of ESS could represent a strong improvement for other actors different from the investor of the storage system. Other parties that would have an economical benefit from the diffusion of ESS are the power grid operators and society in general. In this paper we won't discuss over the returns for "world at large" or society in general, for this topic it's suggested the review of papers (Dansoh, 2014)(Yan et al., 2014) (Gilmore, Apt, Walawalkar, Adams, & Lave, 2010). Here we take into consideration the economical return that effects the management of the power grid, distribution and transmission side. The economical reason that lays behind the grid related returns is that every issue mentioned in paragraph 2.2 and 2.3 has to be solved in rather expensive ways.

Here there are a few examples of the specific features of ESS that are proved to have a return on the grid, but that are hardly sealable on a market:

- Integration of not controllable power sources: nuclear and renewable
- Deferring investments for maintenance and upgrade of T&D lines

Every return is defined in [€/Kw], so it has to be considered as a return per power capacity of storage installed.

There are two different kinds of grid related return: in the first category there are the one that the investor of the ESS can benefit from, in the second one the returns that the investor cannot take advantage from. There is a strong difference between these two categories. When different investors are in the position to assess the financial feasibility of an ESS, they obviously take into consideration only the returns that can be accounted in the business plan. For example, if there is the chance for them to sell the provision of grid services in a market, this return is going to be taken into account in the business plan and is going to effect directly the return on this kind of investment. Otherwise if installing an ESS determinates also a lowering of the costs of, let's say, the transmission operator, this won't be having an effect on the single investor and thus won't be relevant in assessing the return on the investment. The main difference is whether these returns can be sold to the specific manager of the power grid or if there isn't any way to benefit from these returns. In this category there have been the papers that assess some kind of returns for other actors ("parties") that cannot be internalized in the financial assessment of the investor's business plan. These papers are (Drury, Denholm, & Sioshansi, 2011), (Eyer et al., 2004), (Susan M Schoenung & Eyer, 2008), (Yan et al., 2014).

# 8. The financial feasibility of ESS: Literature review – Contexts, players, economic yardsticks and technology

Every different investment in an energy storage system has to be evaluated considering the specific context of application and the category of investor. The reason behind this is that the return of every category is different from the other ones. When reviewing the literature on the economical analysis of ESS there have been found different classes of application of storage systems. These are resumed in six categories of contexts of application of ESS, depicted in the following paragraphs. The definition of these categories of application has been made both through an empirical evaluation and an deductive analysis. The variables that define a specific category are:

- Application to a VRES
- Connection to the power grid
- Presence of a consumption profile, defined as a "Load"

This categorization give 8 different areas of application, defined in Table 11:

**Table 11: Areas of application of ESS**

| | VRES: **YES** | VRES: **NO** | |
|---|---|---|---|
| Connection to power grid: **YES** | Prosumer / Micro-grid (1) | Consumer (2) | Load: **YES** |
| | VRES on-grid (3) | Transmission & Distribution (4) | Load: **NO** |
| Connection to power grid: **NO** | VRES off-grid (5) | NULL (6) | Load: **YES** |
| | NULL (7) | NULL (8) | Load: **NO** |

This categorization has defined eight different contexts on application of ESS. Three of these don't have sense since:

- Presence of a ESS without being coupled with a VRES or a power grid (categories 6 and 8) doesn't make sense because there would be no source of power to fill the ESS, making it useless;
- Presence of a RES without a consumption load or a power grid wouldn't be reasonable because the power produced from the VRES wouldn't have a target.

In the following paragraphs are defined the specific areas of application. In one case the classification has produced a category which was further divided into two categories. This is the case of application coupled with VRES, connected with the power grid and applied to a consumption load. In this category we find “Prosumer” and “Micro-grid”. The distinction is made to highlight the “micro-grid” system, as a new way to manage different sources of energy (renewable and conventional) and loads, using an IT system as a manager of the different components.
In the segment “Transmission & Distribution” have been mapped all the investment relevant to the classification, thus: No presence of VRES, No load associated but the presence of a link with the power grid. In this category we can find different actors and business models different one to the other. There are assessments on the return for private companies that are not involved in other business in the industry. In this category we could also find the companies that manage the power grids. In this paper we don’t analyse the return or evaluation method for the companies that manage the grid, transmission or distribution side. The reason behind this is that assessing the return for the manager of the grid would necessarily involve having a number of information that are highly business specific and industry-related, which are not available. Moreover there haven’t been found any paper that analyse the return for the specific category of the DSO & TSO. Thus we leave the assessment of the economic feasibility of ESS for this specific category of investor (DSO & TSO) to future investigation.
The classification here reported properly defines the different areas of application of ESS; a posteriori in the literature review there have been found paper that assessed only these areas of application. As said before, in this review there have been analysed 103 studies. In our review we have taken under consideration only the studies that show a detailed economic analysis of the matter. Many analysis have been left outside of the review because the economic assessment was not complete. The number of studies that have reviewed every single case of application is presented in table 12. The area of application more investigated by the researchers is “Variable renewable energy sources on grid” (42). The Microgrid is the area of application less explored from the economic side (4), probably due to its relative recent development. Another area of application the has stimulated the attention of the researchers has been the use of ESS applied to the power grid without being coupled with a VRES or with a consumption profile (22). There have been found a discrete number of studies that assessed VRES off grid (20) and Prosumer (15). One context of application that has not particularly stimulated the attention of the academic world is the one regarding Consumer, with only 5 papers assessing it. There have been four studies that assessed two or more different areas in the same investigation, that’s why the overall sum is 108.

Table 12: Number of studies that assessed each area of application

| Area of application | VRES on grid | VRES off Grid | Prosumer | Consumer | T&D | Microgrid |
|---|---|---|---|---|---|---|
| Number of studies | 42 | 20 | 15 | 5 | 22 | 4 |

In the next paragraphs it will be explained the nature of every single area of application. The nature of this side of the analysis has been to give an explanation of every single area of application; furthermore to assess which economic means of evaluation were used by each researcher to assess the economic sustainability of this kind of systems.

## *8.1 Variable renewable energy source on grid*

Most of the papers reviewed have assessed ESS applied to a VRES connected to the power grid. These are power plants with a medium-large power capacity: they produce electric power and sell it on the power market (to consumers, to companies, to other companies that sell energy etc.). The kind of VRES power plant could be solar photovoltaic, wind or in some peculiar cases wave power.

This category of investor is particularly interested in the possibilities offered by ESS. Storage technologies could enable the owner of a RE generation plant to have partial or full control on the energy generation of these kind of power plants, and to manage in the most efficient way the generation of electric power.

In table 15 it's showed the number of time that every evaluation method has been used in all the papers to conclude the economic analysis of the academic papers reviewed. Cost yardsticks have been used 50 times in 28 different papers. 17 papers report only analysis based on costs, while 11 dissertations disclose an analysis both on revenues and costs. Revenues-cost yardsticks have been used 36 times in 25 papers. 14 paper disclosed an accurate analysis only on revenues-costs measures.

Table 13: Yardsticks found for VRES on grid

| LCC (Life-cycle cost) [€] | Cost of energy produced [€/Kwh produced] - LCOE | Other cost tools | NPV [€] | Profitability Index NPV per euro invested | PT = Payback time [Years] | IRR | Net income (Operational Incomes - operational costs) |
|---|---|---|---|---|---|---|---|
| 20 | 11 | 4 | 9 | 0 | 8 | 7 | 12 |

The EM most used is the Life-cycle cost. There is a good balance between paper that have used measures based on cost and on revenues-costs. Generally papers that have made analysis only using cost measures are those that investigate different storage technologies. Between the studies that analyse only costs, is common to point out the cheapest technological alternative as the most promising one. Nevertheless in our opinion the most accurate evaluation methods are the ones that consider both revenues and cost. Installing an ESS has to be considered as a pure economic investment and evaluated as one. The only methods that can assess the actual economical return are the ones considering both revenues and costs, and particularly we address the NPV and IRR as the most financially solid. In table 14 we can see what are the most used voices of income found in the theses. The most important voice of income for this category of investor is obviously arbitrage (22). Power quality and In-house consumption are not relevant (n.r.) thus there are no theses that assess them. A few theses consider Ancillary services (5) and capacity payment (1). There is no study assessing "Imbalance duties" voices of income: this is probably due to the fact that there are just a few governments that implement this regulation policy.

**Table 14: Voices of income found for VRES on grid**

| Arbitrage | Imbalance duties | Power quality | In-house consumption | Ancillary Services | Capacity payment |
|---|---|---|---|---|---|
| 22 | 0 | n.r | n.r | 5 | 1 |

## *8.2 Variable renewable energy source off grid*

This category of investors include companies or private owners that need to provide a certain amount of power to a single or a multitude of users that are not connected with the power grid. Due to geographical reasons these users cannot be attached to the power grid. Thus they have to find a different source of power that supplies the sufficient electric energy for the particular kind of user. VRES can be applied and used in many different situations, and these class of consumers are often situated in areas where VRES are available (most of all solar and wind sources). Problems regarding the intermittency of VRES have been explained in paragraph 2.2. The nature of this class of power source makes it necessary for a consumer to use a storage system applied to the power source. This enables the VRES + ES system to

provide usable energy. This category involves a wide range of contexts, from small mountain shelters to small islands communities (with very small grids).
From the economical side this investment decision is driven by the overall cost of the different alternatives. Since the system is off-grid there is no way for the ESS to provide grid services or selling energy on the market. Thus the investor is bonded to invest in one system that generates energy for one or multiple users. There is no choice between investing or not investing in one generation device; one investment has to be made, thus the economic problem is choosing the most cost competitive one. Thus the economic evaluation concerns the analysis on the cheapest way to supply the requested power capacity.
Our analysis perfectly matches this principle: out of 20 studies, 18 run a detailed analysis based on costs and just four papers use an evaluation method based on revenues and costs (see table 15).

**Table 15: Yardsticks found for VRES off grid**

| LCC (Life-cycle cost) [€] | Cost of energy produced [€/Kwh produced] - LCOE | Other cost tools | NPV [€] | Profitability Index NPV per euro invested | PT = Payback time [Years] | IRR | Net income (Operational Incomes - operational costs) |
|---|---|---|---|---|---|---|---|
| 15 | 14 | 0 | 2 | 0 | 2 | 3 | 1 |

LCC is the most used yardstick, followed closely by the Cost of energy produced. There are no voice of income for this area of application, as explained in chapter 9.

## *8.3 Prosumer*

In the last years a new category of players has risen. It's broadly referred to as Prosumer. This category represents companies or private owners that have invested in a power generator. So there is the presence of all three variables that define an area of application (see table 11). There is a connection to the power grid, there is the presence of a VRES and a consumption profile. The energy produced by the system is both consumed in-house and sold on the energy market. The amount of energy sold or consumed depends on the power source and on the consumption profile of the user. The profile of these actors varies depending on the size and nature of the power system and on the consumer load. For this category of investors both evaluation methods categories are rather reasonable. Since the energy is consumed in-house, using the Cost per kWh produced of the VRES + ES system is very reasonable if compared to the cost of purchasing energy on the market (this concept refers to the definition of "grid parity"). On the other side there is no obligation to invest in this system, thus it can be treated as a pure investment decision and evaluated with the classic financial yardsticks.

Table 16: Yardsticks found for Prosumer

| LCC (Life-cycle cost) [€] | Cost of energy produced [€/Kwh produced] - LCOE | Other cost tools | NPV [€] | Profitability Index NPV per euro invested | PT = Payback time [Years] | IRR | Net income (Operational Incomes - operational costs) |
|---|---|---|---|---|---|---|---|
| 4 | 5 | 1 | 4 | 1 | 5 | 3 | 4 |

Out of 15 studies, 8 use an EM based on revenues-cost, 10 based on costs and 3 papers use both methods. We can find a discrete balance between papers that used EM based on costs and on revenues and costs. The single EM most used are LCOE and Payback time (5 papers) followed by LCC, NPV and Net Income (4).
The voice of income most assessed is In-house consumption (14) and arbitrage (8). No paper assessed Power quality returns or ancillary services (see table 17).

Table 17: Voices of income found for Prosumer

| Arbitrage | Imbalance duties | Power quality | In-house consumption | Ancillary Services | Capacity payment |
|---|---|---|---|---|---|
| 8 | 0 | 0 | 14 | 0 | n.r. |

## *8.4 Consumer*

An energy storage system can be installed by a "user", that is a domestic or an industrial consumer, without being coupled to a RES. The average size of instalment investigated is small to medium, depending on the size of the "consumption profile". The technologies are energy-oriented, since the main purpose of an ESS in this context is to profit from arbitrage. In some particular cases, as for consumers that are served by a poor-quality power grid, the aim of an installation could be to provide power-quality features. The characteristics of this area of application in relation with installing an ESS are:

1. A consumption load
2. A connection to a power grid
3. No RES involved

There are 5 papers related to this area of application. The reason that explains the relative lack of interest in this area of application is related to the small economic

returns that can be achieved by a ESS installed to a user load without being coupled with a RES.
Two papers use an EM based on costs, four use an evaluation based on revenues and costs and just one dissertation employs both methods. One interesting fact is that all the papers that assessed this context with revenues-costs measures have employed the Net Income yardstick. As voices of income, 4 out of five papers used Load-shift as a voice of income. There were no other voices of income assessed.

### *8.5 Transmission and distribution*

In this section of the classification, we have mapped every study that assessed an energy storage system that was applied to the power grid (transmission and distribution side) without being coupled to a RES or a consumption profile. This player could be a private investor or the firm that manages the transmission/distribution power grid. From a technical point of view these two "investors" would be able to benefit from the same category of returns. The main difference between the two players regards the evaluation the economic return that depends on the nature of the investors; the firms that manage the power grid has to face risks and opportunities that are very industry specific, thus very difficult to understand from the outside. This is easily understandable from the fact that no paper out of 103 evaluates the return for the manager of the grid.
There have been found 22 dissertations related to this category of application (table 18). Ten studies show a detailed analysis of the costs, 19 an evaluation based on revenues and costs and 7 disclose both categories of analysis. As for the "VRES on grid" category, the opinion expressed in this study is that the means of evaluation that are comprehensive of revenues and costs are the most reliable methods to be implemented here. It should be assessed if it profitable to install an ESS, not how much would it cost. This logic is followed by the researchers on the matter since only three papers present a complete analysis only based on costs.

**Table 18: Yardsticks found for Transmission and distribution applications**

| LCC (Life-cycle cost) [€] | Cost of energy produced [€/Kwh produced] - LCOE | Other cost tools | NPV [€] | Profitability Index NPV per euro invested | PT = Payback time [Years] | IRR | Net income (Operational Incomes - operational costs) |
|---|---|---|---|---|---|---|---|
| 8 | 2 | 2 | 7 | 0 | 3 | 6 | 10 |

With regards to the voices of income, in table 19 there are shown the results of the analysis. For this area of application the framework for evaluating the different voices of income is more simple, since there are just three economic returns that can be taken into account. Arbitrage is the most assessed (18), followed by ancillary services (8) and last capacity payment.

**Table 19: Voices of income found for T&D**

| Arbitrage | Imbalance duties | Power quality | In-house consumption | Ancillary Services | Capacity payment |
|---|---|---|---|---|---|
| 18 | n.r. | n.r. | n.r. | 8 | 2 |

## *8.6 Micro-grid*

A micro-grid is a group of interconnected loads and distributed energy resources (DER) with defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro-grid and can connect and disconnect from the grid to enable it to operate in both grid connected or island mode (*U.S. Department of Energy*). These system can benefit from installing a ESS in the subsequent ways. There have been found a very few economic assessments on ESS applied to a micro-grid. The total number of dissertations that have assessed a Microgrid is 4. This is probably due to the fact that this area of application is not developed as the other ones. Another complexity regarding this area of application is related to the large number of different features that are included in a micro-grid. This entails that is not easy to isolate the specific economic return due to the instalment of a ESS on a micro-grid.

All of these papers showed an analysis based on costs; only one has been based on both cost and revenues-cost measures. Since the analysis are based basically on costs, there are no voices of income evaluated.

## *8.7 Technology*

An energy storage system can be implemented using a wide range of different technologies. The technology used is a key component of the ESS evaluation. It effects the functionalities and therefore the areas of application of ESS; moreover the specific technology is the main driver that influences the costs of the storage system. In this review we have analysed the technologies that have been assessed by the academic society. The aim of this section is to discover which technologies have risen mostly the attention of the academic society. In this review we have taken note of the category of technology that was assessed in the economic evaluation of all the papers have been revised in our dissertation.

In general terms, out of 103 papers revised, 60 studies considered just one technology in the analysis. There have been found four dissertations that have decided to model their analysis without dealing with a specific technology: (Susan M

Schoenung & Eyer, 2008), (Ghofrani et al., 2013), (Eyer et al., 2004), (Santos, Moura, & Almeida, 2014).
Thirty nine papers have assessed more than one technology. Some of these papers build their study on the specific analysis and characterization of the technologies that are involved in the storage applications like (Luo et al., 2015), which is giving a great improvement to our assessment. Other studies take into consideration five or more different technologies in their assessment: (Bradbury et al., 2014), (Zakeri & Syri, 2015), (Rodrigues et al., 2014), (Sundararagavan & Baker, 2012), (S.M. Schoenung & Hassenzahl, 2003), (Kaldellis, Zafirakis, & Kavadias, 2009), (Pearre & Swan, 2014).

**Table 20: Categories of technology assessed in our analysis, and papers that have investigated it.**

| BATT - Lead acid | BATT - Li-ion | BATT - NaS | BATT - Other | CAES | PHS | Fuel Cell | Flywheel | ESS technology - Other |
|---|---|---|---|---|---|---|---|---|
| 30 | 24 | 15 | 23 | 33 | 31 | 24 | 10 | 15 |

In table 19 there are shown the number of time that a certain technology has been taken into consideration. As more than 40 papers consider more than one technology it's easy to understand why the overall sum of the numbers is far from 103. If we consider the physical category of storage, electrochemical is by far the most investigated with 92 papers. Regarding the single technology, there are three categories of technology that have been investigated the most: Compressed air energy storage (33), Pumped hydro storage (31) and Lead-acid batteries (30). At a second level we can find Li-ion batteries (24), Fuel cells (24) and all the categories of batteries excluding Lead-acid, Li-ion and NaS (23) (see chapter 3.2.1). The categories of technology that have been assessed the least from an economical point of view are NaS batteries (15), the category that resumes all the categories of technology that haven't been mapped in this study (15) (see chapter 3.2.1) and finally Flywheel. For a complete list of the papers that investigate every technology please refer to the Appendix B at the end of the study.

## *8.8 Comments and findings*

Some interesting conclusions can be deduced from this review.

- First of all, ESS's most interesting areas of application are the ones that connect to the grid. Just a few studies (20 out of 103) do not relate to the grid. It is clear that the future economic potential of ESS lies on grid related applications.

- Most of the studies (77/103) refer to ESS directly applied to RES. The most interesting profits arise when storage systems are employed with RE generation. These two findings lead us to understand that the areas of application of ESS that have been studied the most are grid connected and applied to a RES.
- The two categories of evaluation methods have been used almost the same number of times (87 revenues-cost, 82 only cost). The most used EM is the LCC (present in forty-three papers) followed by “Cost of energy produced” and “Net Income” (both thirty-one papers). Between the classic financial evaluation methods, NPV is the most adopted (twenty-two dissertations) followed by IRR (17 studies) and Payback Time was used 16 times. A key finding has been that the economic evaluation of ESS is often left to the conclusive part of the analysis and doesn’t represent the core part of the study. As we explain in the previous chapters, defining the economic return is not a simple task due to the complexity of actors and scenarios. It’s reasonable that if a study runs the analysis on some technical aspect of the ESS, when it comes to the economic assessment the most reliable alternative is to base the analysis on objective and plain measures as the costs
- Social and grid related measures haven’t been largely taken into consideration in the studies reviewed. Only four papers on one hundred and three papers have considered grid related returns that it’s not possible to benefit from. The logic reason behind this is that when evaluating an investment, it has to be considered only the returns that are directly influencing the investment. But this particular category of systems (ESS) have their true reason of being if implemented in a context where it’s possible to improve the management of a RES or of the power grid. The company that manages the grid (transmission or distribution) or the social community financially benefits from these investments, but the only actor that bears the costs is the consumer/investor. These returns have to be taken into consideration even if it’s not possible to benefit directly from them, since there is some other party (the TSO or the DSO in particular) that is economically gaining from the instalments. One barrier that is limiting the possibility to profit from this category of returns is that there are some technical and regulatory issues that need to be solved before RES and ESS are able to provide grid services. Another complication is that these kind of returns are undeniable but it’s very difficult to calculate the exact return for every kW of ESS installed. For these main reasons the economic returns related to the grid are not considered by the academic literature.

# 9. Framework for a correct evaluation of the economical sustainability of ESS

As can be drawn from the literature review, there is a substantial disparity between the evaluations of the economical feasibility of energy storage systems. These differences generally refer to:

1. Targets of the analysis
2. Voices of income
3. Evaluation procedures

Thus in this paper it's proposed an evaluation framework that has the aim to give a few simple guidelines that would help academics in structuring the economic evaluation of ESS. The evaluation paths are divided by area of application of ESS. There are a few principles that are shared between the the different areas of application and need to be always followed:

- The analysis needs to be differential. It has to show a benchmark situation and the comparison with the potential implementation of a ESS. It's necessary that it's evaluated the precise return from installing a ESS, compared with the case of non-installing ESS. E.g. for the area of application VRES on grid, the evaluation cannot be done solely of the whole VRES + ESS system: it has to show the economic analysis of the VRES by itself and then the analysis of the VRES + ESS system. The comparison between the two returns will show if the employment of an ESS is profitable.
- The investigation needs to point out if the potential investor would have an interest in investing in an ESS. So, a part from two areas of application that will be later discussed, it cannot solely rely on yardsticks based on costs for example. The yardstick that has to be used in the conclusive part of the analysis has to be an indicator of the actual economic return of an investment, since the aim of an economic operator is to maximize his own profit. Generally speaking, the analysis has to produce an output that would give to a potential investor the size of the return on an investment in ESS. Thus the most proper yardsticks that can be used are the classic deterministic criteria of evaluation of an investment; in particular the NPV and IRR (see paragraph 6.2.1 and 6.2.3) use the discounted cash flow logic and are widely known economic methods, features that make them the most useful economic yardsticks.
- All the voices of income of ESS have to be considered. Even if not easy to assess, all the potential benefits of an ESS for the investment have to be investigated in order to produce a complete economic analysis. In chapter 7 are explained all the returns in specific terms. In the upcoming part of this chapter there is the list of the specific returns according to the area of application.
- A complete economic evaluation should take into consideration the economic returns for all the actors involved. This entangles the estimate of the returns

also for the social community and for the managers of the grid (see paragraph 7.2). Even if these returns don't refer to the investor, they should be assessed because they would rise the attention of the society on the effect of ESS on the wellness of society at large. These category of investigation could bring the legislator to ponder the implementation of subsidies that would make ESS more profitable.

Given these hints that are relevant to all areas of application, in the next paragraphs it is developed a series of guidelines that are higly specific to the area of application.

## 9.1 VRES on grid

For this area of application, the objective of the analysis is to assess whether the implementation of an ESS to a VRES is to be considered viable for an industrial player that has the aim to maximaze the profit. NPV and IRR are the most suitable yardsticks for the analysis. Here is the list of the voices of income that should be considered when assessing this matter.

### *9.1.1 Arbitrage*

An ESS could be used by the owner of a VRES generation plant to store energy in periods when prices are low and sell it on the market when prices are high. Making reference to the equation (9) of chapter 7.1 : $P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$, the value of $P_1$ is equal to the off-peak price of power and $P_2$ to the price of power in periods of high demand. In order to gain from the arbitrage operation, it must be fulfilled the sequent espression:

$$P_2 \geq \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$$

The terms of equation (9) are explained in chapter 7.1.

### *9.1.2 Imbalance duties*

In many countries in order to contrast the variability coming from VRES, the regulator of the energy system (in Italy GSE - www.gse.it s.d.) has introduced a duty to be paid from the owner of the VRES generation plant. Installing a ESS would enable the owner of the power plant to save this amount of money. This return is relevant only in those contexts where it's present a regulation constraint as the above-mentioned one.

### *9.1.3 Ancillary services*

This return would be possible if this kind of services are marketable. So it must be present a market where would be possible to gain for saling these services. In Italy there is the Market of ancillary service (MSD)(see chapter 7.1.1 and 7.1.3). In this area of application ESS would be able to provide primary, secondary and tertiary reserve.

*9.1.4 Capacity payment*

It should be possible for the owner of VRES plants to provide capacity available for the manager of the power grid. Without ESS it wouldn't be possible for the VRES to have available power for a certain period of time, which is necessary for providing this kind of service.

## 9.2 Prosumer

For this area of application the evaluation has to assess if a potential player would have an economic return in investing in an ESS. Thus the most suitable economic yardsticks are NPV and IRR. The voices of income that need to be considered are here reported.

*9.2.1 Maximizing in-house consumption*

It's more profitable for the Prosumer to use the energy he produces rather than selling it on the market. Applied to equation 9 of paragraph 7.1 : $P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$, the value of power $P_2$ for a Prosumer is the cost of purchasing energy in another period of time. $P_1$ is the price of sale of energy in period 1. In order to profit from the "time shift" application, the following constraint has to be granted again:

$$P_2 \geq \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$$

The price $P_1$ could be given by a subsidy, thus it must be paid attention to the country context of application. The terms of the above-mentioned equation are explained in chapter 7.1.

For example, in Italy a storage system of 3 kWh (2kW) applied to a solar panel of 3 kW allows an increase of the share of the energy consumed by the family household between 30-45%, granting an earning per year of 175 € (supposing a cost of purchasing energy of 0,2 €/kWh and a price of selling of 0,105 €/kWh).

*9.2.2 Imbalance duties*

As said before, in many countries in order to contrast the variability coming from VRES the regulator of the energy system (in Italy GSE - www.gse.it s.d.) has introduced a duty to be paid from the owner of the VRES. Installing a ESS would enable the owner of the power plant to save this amount of money. This return is relevant only in those contexts where it's present a regulation constraint as the above-mentioned one.

*9.2.3 Power quality*

Storage systems would also soften the disturbs that can occur on the transmission and distribution lines. This regards the continuity of service from the power grid. For the assessment of this return please refer to paragraph 7.1.2.

*9.2.4 Ancillary services*
This return would be possible if this kind of services are marketable. So it must be present a market where would be possible to gain for the sale of these services. In Italy there is the Market of ancillary service (MSD)(see chapter 7.1.1 and 7.1.3). For small scale ESS plants, this return would be possible in a future where small distributed ESS are able to provide grid services. In this case ESS could provide primary voltage regulation.

## 9.3 Consumer

This area of application, as said before, is probably the least interesting from an economic point of view. Anyway the most proper way to evaluate the implementation of an ESS in this area is to use the NPV or the IRR. The voices of income are here reported.

*9.3.1 Load shift*
The time shift application in this case grants the owner of the ESS to store energy when prices are low and use it when prices are high. In $P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$, $P_2$ is the price of energy in times when the tariff is higher and $P_1$ the maximum tariff for electric power. It's true that in order profit it should be granted:

$$P_2 \geq \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$$

The terms of the above-mentioned equation are explained in chapter 7.1. This return for the area of application Consumer is very narrow. For example, in Italy there is a slight difference between the cost of energy during peak hours and off peak hours for domestic users. From Enel website (www.enel.it s.d.) (market leader in Italy) it's showed that the final difference between the two prices is less than 0,01 €/kWh. Thus we can expect that the economic return from arbitrage of installing an ESS for a private household without RES is not so interesting, compared to other contexts of application.

*9.3.2 Ancillary services*
This return would be possible if this kind of services are marketable. So it must be present a market where would be possible to gain for the sale of these services. In Italy there is the Market of ancillary service (MSD)(see chapter 7.1.1 and 7.1.3). For small scale ESS plants, this return would be possible in a future where small distributed ESS are able to provide grid services. In this case ESS could provide primary, secondary and tertiary voltage regulation.

*9.3.3 Power quality*
Storage systems would also soften the disturbs that can occur on the transmission and distribution lines. This regards the continuity of service from the power grid. For the assessment of this return please refer to paragraph 7.1.2.

## 9.4 T&D

This area of application refers to the employment of large-scale ESS connected with the power grid. The evaluation should point out if a potential investor would gain from the implementation of an ESS, thus once again the most suitable yardsticks are NPV and IRR. Here are reported the voices of income to evaluate.

### 9.4.1 Arbitrage

In this context of application, energy is not produced in concomitance with the ESS. Arbitrage activity would require to buy energy from the power grid in time of low demand and to sell it in periods of high demand to a higher price. In $P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$, $P_2$ is the price of sale of energy in high demand periods and $P_1$ the price of purchased energy in low demand period. It's true that in order profit it should be granted:

$$P_2 \geq \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$$

The terms of the above-mentioned equation are explained in chapter 7.1.

### 9.4.2 Ancillary services

This return would be possible if this kind of services are marketable. So it must be present a market where would be possible to gain for the sale of these services. In Italy there is the Market of ancillary service (MSD)(see chapter 7.1.1 and 7.1.3).
An ESS installed at this stage of the supply chain would enable the owner to provide any grid service described in paragraph 7.1.3.

## 9.5 Micro-grid

When applied to a Micro-grid it could be really difficult to assess the differential return from installing the ESS. This is due to the fact that a micro-grid is a complex combination of different devices (IT network, loads, VRES, storage systems etc.) so the ESS could be defined an essential component of the overall system. Thus there are two paths to evaluate the ESS for a micro-grid:

1. Considering the ESS a component that is necessary for the operation of the micro-grid. In this case the economic evaluation has to be done of the micro-grid as a whole. The economic return should be evaluated considering every element of the system. The voices of income and the evaluation methods are not considered in this paper.
2. Considering the ESS an un-necessary element, thus evaluating it as a normal investment. The most proper yardsticks are NPV and IRR. In this case, the voices of income are reported in the next paragraphs.

### 9.5.1 Maximizing in-house consumption

It's more profitable for the micro-grid to use the energy that is produced by the VRES plant rather than selling it on the market. The return is the same of the Prosumer, so in $P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$, the value of power $P_2$ for a micro-grid is the cost of purchasing energy in a low demand time period. $P_1$ is the price of sale of energy in period 1. In order to profit from the "time shift" application, the following constraint has to be granted again:

$$P_2 \geq \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$$

Let's take as an example one micro-grid with a total load of 2700 Kwh and one solar plant of 1 Mw in Italy. If it was installed an ESS of 500 kWh (500 kW), it would enable to increase the share of in-house consumption of 15% generating earnings for 15000 €/year (supposing a cost of purchasing of 0,19 €/kWh and a price of selling of 0,105 €/kWh).

*9.5.2 Power quality*

Storage systems would also soften the disturbs that can occur on the transmission and distribution lines. This regards the continuity of service from the power grid. For the assessment of this return please refer to paragraph 7.1.2.

*9.5.3 Ancillary services*

This return would be possible if this kind of services are marketable. So it must be present a market where would be possible to gain for the sale of these services. In Italy there is the Market of ancillary service (MSD)(see chapter 7.1.1 and 7.1.3). For small scale ESS plants, this return would be possible in a future where small distributed ESS are able to provide grid services. In this case ESS could provide primary voltage regulation.

*9.5.4 Imbalance duties*

As said before, in many countries in order to contrast the variability coming from VRES the regulator of the energy system (in Italy GSE  - www.gse.it s.d.) has introduced a duty to be paid from the owner of the VRES plant. Installing a ESS would enable the owner of the power plant to save this amount of money. This return is relevant only in those contexts where it's present a regulation constraint as the above-mentioned one.

## 9.6 VRES off- grid

The implementation of an ESS to a VRES that is not connected to the grid, but is connected to a consumption load has to be considered as a peculiar investment. There is the need to answer to a consumption load; if the investor wants to implement a VRE plant to produce electric power, there is the need to employ an ESS in order to make the system work. Thus the investment has to be evaluated as a whole, VRES + ESS. The result has to be compared with a technical alternative, e.g. a traditional engine. The economical yardsticks can be also based on costs, since the aim of the analysis is point out the less expensive alternative. LCOE could be a valuable yardstick to compare the cost the enrgy produced by the ESS + VRES

system compared with the levelized cost of producing energy with another alternative.
In table 21 there is the final framework for evaluating the economic feasibility if ESS. It gives the information about what voices of income must be taken into consideration; about the nature of the economic yardsticks that should be used (as a proxy for the aim of the evaluation); and about the value of $P_1$ and $P_2$ in the equation $P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$ of paragraph 7.1.
Be noted:
When we refer to the "value" of energy (or power) $P_1$, we consider the precise economic value of the single unit of energy [kWh] in period $T_1$ for the specific economic player. This "value" differs form one context to another: it could be the sale price of energy on the power market (e.g. for an investor that sells energy) or the price of purchase of energy (for a consumer load).
$P_2$ is the same principle applied to period $T_2$. For the complete analysis of the matter please refer to paragraph 7.1.

**Table 21: Framework for a correct evaluation of economic sustainability of ESS**

| Area of application | Arbitrage | In house consumption | Load shift | Power quality | Ancillary services | Imbalance duties | Capacity payment | Yardstick based on costs | Yardstick based on revenues and costs | Value of $P_1$ | Value of $P_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VRES on grid | X | | | | X | X | X | | X | Off peak sale price | Peak sale price |
| Prosumer | | X | | X | X | X | | | X | Sale price | Purchasing price |
| Consumer | | | X | X | X | | | | X | Off peak purchasing price | Peak purchasing price |
| T&D | X | | | | X | | | | X | Off peak purchasing price | Peak sale price |
| Micro-grid | | X | | X | X | X | | X | X | Sale Price | Purchasing price |
| VRES off grid | | | | | | | | X | X | n.r. | n.r. |

## *9.7 Matching between services and economic returns*

One interesting aspect is to assess what features of ESS can be used to have an economical return. The aim is to investigate what technologies and technical features lays beyond the categories of economic returns defined in chapter 7. In table 18 it's defined what features are included in the category of returns. The majority of economical retunrs can be ascribed to the technical service Time-shift. So the most interesting technologies and applications will be the ones able to provide this service. Vice-versa, under the category of economic return labelled as Ancillary services can be found a wide different number of technical services. Thus evaluating what are the services that can produce economic value, is important to see wheter there is a market to sell this kind of services, and if it is worth it. Power quality is both an economical return and a service, making it easy to identify. With regards to the Up-grade deferral and  Congestion relief returns, they are not shown in the table since there is no way to benefit directly from them for the private investors because it would be difficult to create a market to benefit from them.

**Table 22: Matching between features and economic returns**

| Services | Arbitrage | In-house consumption | Load shift | Power quality | Ancillary services | Imbalance duties | Capacity payment |
|---|---|---|---|---|---|---|---|
| Power quality | | | | X | | | |
| Transient stability | | | | | X | | |
| Regulation | | | | | X | | |
| Spinning reserve | | | | | X | | |
| Voltage control | | | | | X | | |
| Time-shift | X | X | X | | | X | |
| Load following | | | | | X | | |
| Firm capacity | | | | | X | | X |

# 10. Conclusion

Through the last years the spread of the Variable renewable electricity sources (VRES) has defined some important changes in the way the power grid is managed. The reason behind this is that VRES are intermittent and unpredictable. In chapter 1 it has been shown how policies can influence this industry and how VRES have been developing in the world, with Asian countries leading as amount of MW installed per year in the last years, and Europe (once "market leader") slowing down. In chapter 2 it has been presented the characteristics that make VRES so difficult to manage and its influence on the power grid. Later on ESS have been presented as a solution of this problem, since their specific features can solve different VRES related problems. In chapter 4 battery energy storage systems projects all around the world were assessed in order to understand the stage of development of the "market"; there have been point out the core economic variables that are relevant to define the appeal of the different markets, and a summary of the most interesting projects in Italy, US, UK, China, Germany and Japan. It has been defined that the price of energy, the percentage of penetration of VRES in the national grid and the presence of constraints in transmission/distribution infrastructure are important variables that can give an idea on what is the appeal of a market. Later on was discussed (based on a analysis from the Energy&Strategy group) the stage of development of the industry of ESS with a definition of the main actors and players involved.

Then we analysed the problem of assessing the economic feasibility of energy storage systems. This is a complex problem because this evaluation involves different aspects as different political, environmental and social backgrounds; different kind of actors who could get involved in this investment whose return has to be identified and analysed case by case; different technologies that can be used as a ESS; different economic yardsticks and evaluation methods that can be taken into account when defining this analysis. To understand this matter it was developed a deepen review of the literature on this topic: 103 different thesis were analysed in order to understand which evaluation methods have been used. Particular attention was given to the specific yardstick employed to define the economic return. Every work has been classified according to many variables as the economic yardstick exploited in the analysis, the area of application of the ESS, the voices of income taken into consideration in the dissertation and the technology assessed. Chapter 6 gives the recap of the various economic yardsticks that were found in the lit review. They were splitted into categories according to the aim of the analysis: theses which economic analysis was directed into defining a problem of minimizing costs used Yardsticks based on costs; dissertations that built a problem focused on maximizing profit used a Yardstick that was based on revenues and costs. The problem of maximizing the utility of the economic investor can have two different economic paths: in one case to minimize costs, in the other case to maximize profit. Yardsticks based on costs and yardsticks based on revenues and costs has been used to define this two different properties of the economic analysis. In chapter 7 we define every voice of income, giving some guidelines to be taken into consideration while defining every economic return. Particularly, it was defined an equation that gives a few hints to have a quick idea of the break-even value of the energy that is discharged from the system, in order not to lose money on the time-shift application of ESS: $P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$. The value of energy differs from one area of application to the other, as explained in chapter 9. In chapter 8 it was given the result of the analysis that was run on the literature, depending on the different areas of application. It was defined a scheme to define the nature of the area of application based on three variables: the connection to the power grid, the presence of a VRES and the presence of a consumer load. So it was assessed, divided by context of application, the number of theses that used a particular economic yardstick and the voices of income taken into consideration in the analysis. It was found a disparity among  the evaluation methods and voices of income employed. Many theses don't take into consideration all the voices of income that can be estimate; other studies produce an analysis that has the wrong target. E.g. some papers evaluate the economic return of ESS applied to a VRES (VRES on grid – area of application) using as the output of the economic analysis a yardstick based on costs, which is not the target of an economic player that operates in this area of application. This difference concerned economic yardsticks, voices of income and the target of the economic analysis: for these diversities is difficult to compare the different studies from this point of view. Another interesting fact in that it was not indicated the reason for choosing a specific economic yardstick. All these reasons brought us to define some simple guidelines that should be followed by academics that face the problem of the evaluating the economic feasibility of ESS. Divided by area of application it was defined the voices of income that need to be considered, the aim of the analysis and the following economic yardstick that need to be used. Considering the above-mentioned equation, it was indicated what is the value of energy that need to be taken into consideration when making that analysis. The purpose of the last part of this dissertation was to define a common economic evaluation method; this would lead to more precise and complete analysis. If we consider the economic revenue that comes from improving Power Quality, out of 24 papers that should take into consideration this return (belonging to Consumer, Prosumer and Micro-grid areas of application), none of these theses consider this return. We can suppose that this is due to the fact that it is a difficult revenue to estimate. In this paper we introduce an interesting hint to define this kind of return; the financial return coming from Power quality improvement has an upper limit given by the cheapest technological alternative that could solve this problem. For example: if the annual power quality economic return (prevented financial loss) associated with an energy storage system is €70/kW-year and another equipment that if installed would solve this problem costs €40/kW-year, then the maximum benefit that could be ascribed to the energy storage plant for improved power quality is €40/kW-year.

Another fact that should be highlighted in the evaluation is related to the economic returns of the ESS that affect a third-party. These returns are improving mostly the operations of the companies that manage the power grid and partly society at large. These returns should be estimated in order to move the attention of the legislator and of other parties (e.g. the operators of the power grid) to consider possible subsidies or other ways to internalize these catgory of returns. Even if these returns shouldn't be considered in the evaluation of the return from the investment, nevertheless they should be estimated since the very reason of being of ESS lays in improving the management of the power grid.
The most relevant economic return for ESS is related to time shift applications. This is remarked by the fact that out of 91 theses that could consider this return, 66 have taken it into consideration. But assessing this revenue could be lead to some difficulties. The equation $P_2 = \frac{P_1}{\eta_{ch} \times \eta_{st} \times \eta_{dh}} + \frac{C_v + C_c}{X_2}$ could help academics in analysing the economic return of ESS given by time-shift applications. The effective economic returns that can be achieved with ESS should be tested using this equation. It gives the break-even value of the energy that is discharged from the system, in order not to lose money on the time-shift application. Table 21 explains the value of $P_2$ and $P_1$ [€/kWh] given the particular area of application. If the value of energy in the second period of time doesn't cover the losses for the energetic transformation ($\eta_{ch} \times \eta_{st} \times \eta_{dh}$), the variable cost of the operation and the cycle cost of the technology divided by the energy discharged, thus the charge-discharge cycle of the ESS is certainly not producing economic value. This equation is not to be applied to cover deeply the economic evaluation of the matter but gives a quick and easy way to have an idea about the range of economic values of energy that could make time-shift application profitable.
It is left for further investigation the economic return of installing an ESS for the manager of the distribution and transmission power grids; there were no dissertation that analysed this matter, thus it was difficult to make such a complex analysis that has his roots deep down in industry-specific matters.

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*Energy storage technology – Other*
**Thermal storage**: (Hessami & Bowly, 2011), (Rodrigues et al., 2014), (Comodi et al., 2014), (Luo et al., 2015)
**Capacitors**: (Bradbury et al., 2014), (Luo et al., 2015)
**Supercapacitors**: (Luo et al., 2015), (Ren et al., 2012), (Hittinger et al., 2012)
**SMES**: (Bradbury et al., 2014), (Zakeri & Syri, 2015), (S.M. Schoenung & Hassenzahl, 2003), (Luo et al., 2015), (Ren et al., 2012)
**PTG**: (de Boer et al., 2014)
**Organic chemical hydride**: (Obara et al., 2013)

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