INTERNATIONAL JOURNAL OF INTELLIGENT CONTROL AND SYSTEMS
VOL. 18, NO. 1, MARCH 2013, 17-27

Energy Storage Technologies and Requirements for Wind Power Plants

Maitane BERECIBAR and MengChu ZHOU

Abstract- **Wind power generation in electric power systems increased in the past years because of the huge technology advances and is still going up, but it cannot be forgotten that the wind is an intermittent power source. This is why the need of storing the energy came up. Moreover, the price of the storage is quite high. This work has two purposes. The first one is to review the existing energy storage technologies that are mature or under active development for wind power. The second one it to investigate the optimal amount of energy storage necessary to keep the energy output constant to feed the grid. The research into different kinds of technology storages allows one to select the best one by considering such criteria as cost, lifetime, efficiency, energy density and some special requirements. Four places all over Spain are selected and their wind profile is evaluated. In this evaluation the number of days in which there is not enough wind or there is too much wind are counted. Also, the average wind speed during this time is calculated. After that, a specific wind power model is selected and some calculations are done. Then the average power output and the needed capacity storage are estimated. Finally, after selecting an appropriate storage model, the results are obtained and presented.**

Index Terms—**Wind power generation, energy storage, energy density, and wind power model**

1. INTRODUCTION

Wind power generation in electric power systems enjoyed significant increase in the past years because of the huge technology advances and will continue to grow in the near future. Unfortunately, the wind can blow and stop frequently in a short period of time and can be totally absent when it is most needed. Moreover, large-scale integration of wind power in an electric grid can produce large power fluctuations, and result in a high risk in providing a continuous power supply. Clearly, such risk may be effectively reduced if one employs sizable energy storage devices and releases the stored energy during low wind or no wind periods.

The appropriate operating method for storing energy is to maintain the energy storage facility in its fully charged condition, and use the stored energy to avoid load curtailment situations. Practically, a commitment is made to the system to provide a quite constant amount of power. Then, if the actual power output is greater than the commitment, the excess energy should be stored, but in the other way, if the actual power is less than the commitment, then the stored energy will be used.

The problem of storing the energy is the cost of the batteries. This cost is so high that the excess energy is not stored at most wind power plants.

This work aims to investigate two issues, i.e., existing energy storage technologies suitable for storing much energy from wind, and the optimal amount of energy storage necessary to keep the energy output to feed the grid according to the profile of the wind energy during a specific period of time.

Section 2 discusses ten energy storage technologies that can be potentially used to store renewable energy. Section 3 presents the wind power and its related technologies. Section 4 gives the mind power model to be used in the estimation of storage requirements. Section 5 estimates the need for energy storage capacity given a wind power plant at various sites. Section 6 concludes the paper.

2. ENERGY STORAGE TECHNOLOGIES

The need for energy storage is evident by the intermittent ability to produce electricity from both wind turbine or wind farms and the problems of supplying and maintaining connectivity to the electrical grid. Energy storage technologies have been and are continuously being developed. A good number of methods have been considered, tested, and even implemented into small scale, commercial applications. Among them are:

1) Pumped hydro storage,
2) Compressed air storage,
3) Flow batteries,
4) Metal-air batteries,
5) Sodium sulfur batteries,
6) Li-Ion batteries,
7) NiCd batteries,
8) NiCd batteries,
9) Flywheels,
10) Lead-acid batteries, and
11) Electrochemical capacitor storages.

They will be briefly discussed as follows.

2.1. Pumped Storage

The most practical application for wind energy storage is wind powered hydro storage at present. A typical pumped storage plant is given Fig. 1 [2]. Wind turbines provide renewable energy to run the pumps that relocate the water to the upper reservoir. The wind energy is being

---

This work is in part supported by the National Science Foundation under Grant Number CMMI-1162482. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Maitane Berecibar is in the Department of Alternative Generation Systems, IK4-Ikerlan, Technology Park of Alava, Juan de la Cierva,1, Miñano Mayor, Alava, Spain (e-mail: mberecibar@ikerlan.es).

MengChu Zhou is with The KeyLaboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai 200092, China and also ECE Dept., New Jersey Institute of Technology, Newark, NJ 07102, USA (e-mail: mengchu@ieee.org).

converted to potential energy for later use. Obviously, this application would be restricted to wind regions where their geographic elevation difference is about 400 feet or more. The storage capacity is limited by the volume of upper and lower reservoirs [2]. Another possibility is underground pumped storage using flooded mine shafts or other cavities existing in nature.

Such idea began in the 1890s, when pumped hydro was first used in Italy and Switzerland. By 1933 reversible pump-turbines with motor-generators were available. Now, adjustable speed machines are being used to improve efficiency. Pumped-hydro storage is available at almost any scale with discharge times ranging from several hours to a few days. Its efficiency is quite high and falls between 70% and 85%. Note that pumped storage is the most widespread energy storage system in use on power networks. Its main applications are for providing energy management, frequency control, and reserve capacity. Over 90 GW of pumped-hydro storage, approximately 3% of global generation capacity, are currently installed worldwide [3].

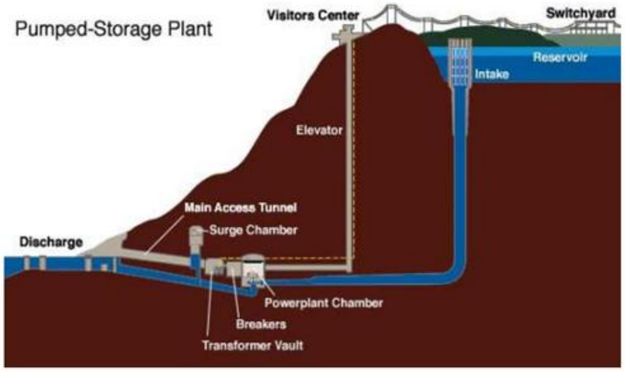


Fig. 2. Pumped-Storage Plant [2].

2.2. Compressed Air Energy Storage

This method uses wind energy to compress air and store it in underground caverns or abandoned mines. When energy demands increase, the compressed air is released into a gas turbine and mixed with natural gas to burn as fuel and generate electricity. In this technology, the wind regions must be close to existing geological features such as caves and abandoned mines. The storage capacity is limited by the volume of the cavern and the pressure at which it is stored [2].

Compressed Air Energy Storage (CAES) systems produce the same amount of electric power as a conventional gas turbine power plant but with less than 40% of the fuel. They are also "regulatable" because the plants can be operated during the whole generation cycle. The pollutants emissions are reduced, during generation a CAES plant burns only about 4000 Btu's of oil or gas per kWh of output and thus produces only about 1/3 as much pollutants per kWh as gas turbines. CAES plants also offer a rapid response time, a black-start capability, they provide efficient load following and have attractive ramp rates, making the system more flexible. They are more reliable plants than other due to their less number of fluctuations. They can also adapt to the load shape [4].

Recent advancements in the technology include above-ground storage in empty natural gas tanks and 'mini-CAES', a transportable technology that can be installed at or near individual loads [3].

The first commercial CAES was a 290-MW unit built in Hundorf, Germany in 1978. The second one was a 110-MW unit built in McIntosh, Alabama in 1991. In some areas of west Texas can find their significant deployment. Research is also being performed concerning such storage systems, e.g., how to store and reuse the heat of compression to heat the compressed air before expansión, thereby eliminating the use of natural gas in the system [3]. A typical CAES plant is illustrated in Fig. 2 [2].

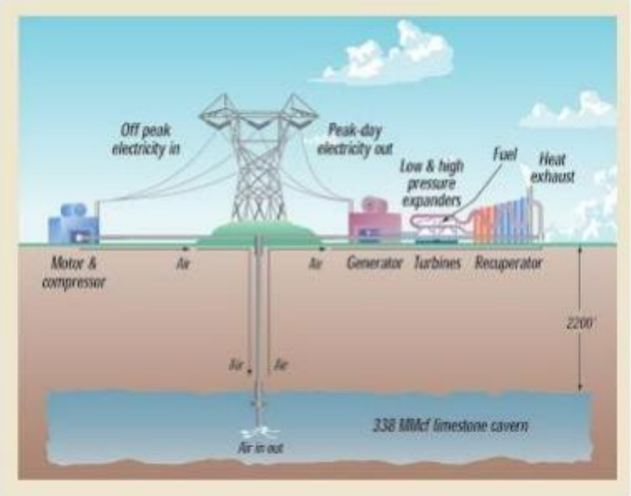


Fig. 1. A CAES plant [2].

2.3 Flow Batteries

The flow batteries store energy in charged electrolytes and utilize proton exchange membranes similar to fuel cells. Its architecture is given in Fig. 3 [2]. This storage

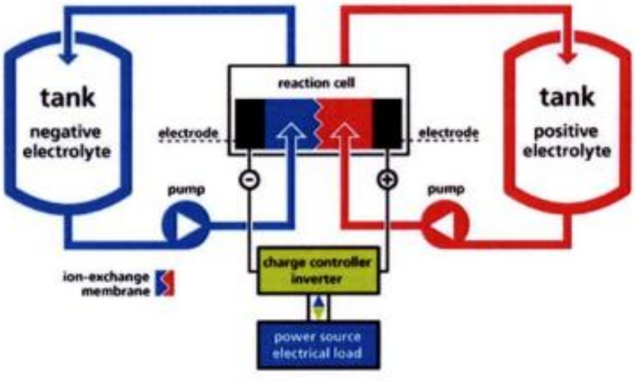


Fig. 3. Schematic representation of Flow Batteries [2].

technology is still under development. It is not mature enough for practical wind energy application. Battery size, tank capacities, containment, and cell life are among the most critical issues to be addressed [2].

Flow batteries have fast speed of response, and the capability of high power and long discharge times making them suitable for a range of energy storage applications. Energy density tends to be lower than other systems but this is not usually critical for utility use. The critical issues for successful commercial exploitation of flow batteries are the manufacturing, installation, system integration, reliability and operation and maintenance. For large scale applications, flow batteries have the potential to offer a low life cost [5].

2.4 Metal–Air Batteries

Metal-air batteries, as shown in Fig. 4 [3], are the most compact and least expensive one available. They are also environmentally benign. Their main disadvantage is that their electrical recharging is very difficult and inefficient. Rechargeable metal air batteries that are under development have a life of only a few hundred cycles and their efficiency is about 50% only. The anodes in these batteries are commonly available metals with high energy density like aluminum or zinc, which release electrons when oxidized. The cathodes or air electrodes are often made of a porous carbon structure or metal mesh covered with proper catalysts. The electrolytes are often a good OH- ion conductor such as KOH. The electrolyte may be in liquid form or a solid polymer membrane saturated with KOH [3]. More efforts are required into order to move this technology to the practical use stage.

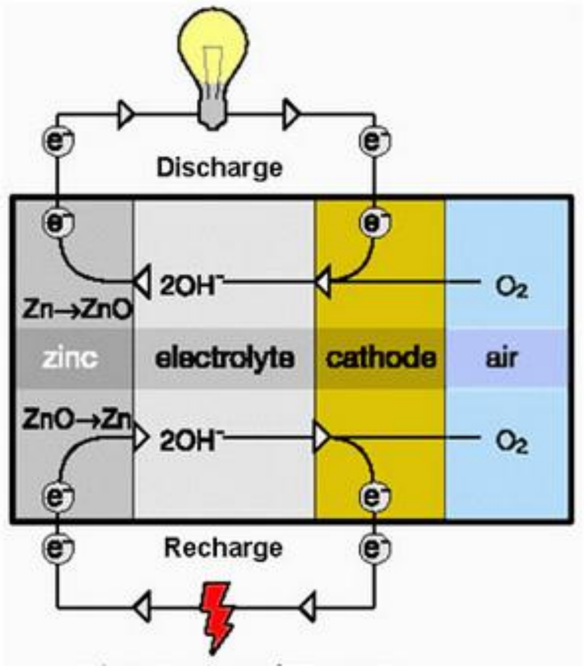


Fig. 4. Metal-Air batteries [3].

2.5 Sodium Sulfur Batteries

Sodium Sulfur (NaS) batteries are high capacity battery systems developed for electric power applications. Feasibility studies of various demonstration projects have shown that this technology is attractive for use in relatively large-scale battery energy-storage system applications due to its outstanding energy density, efficiency, zero maintenance and long life cycle (up to 15 years) [6].

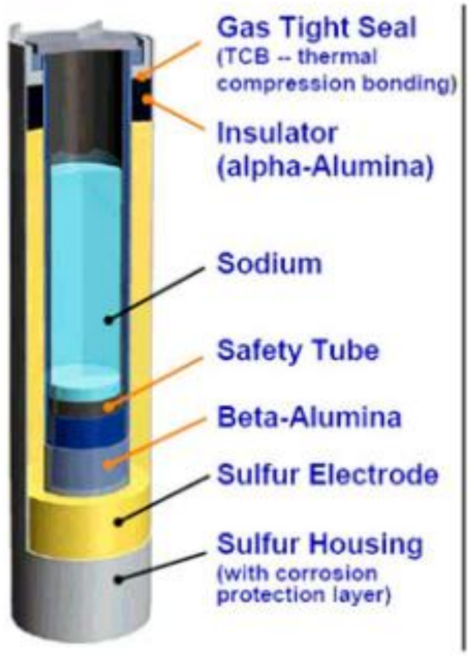


Fig. 5. Central sodium tubular cell [6].

The active materials in a NaS battery are molten sulfur as the positive electrode and molten sodium as the negative. The electrodes are separated by a solid ceramic, sodium”-alumina, which also serves as the electrolyte. This ceramic allows only positively charged sodium-ions to pass through. During discharge, electrons are stripped off the sodium metal (one negatively charged electron for every sodium atom) leading to the formation of the sodium-ions that then move through the electrolyte to the positive electrode compartment. The electrons that are stripped off the sodium metal move through the circuit and then back into the battery at the positive electrode, where they are taken up by the molten sulfur to form polysulfide. The positively charged sodium-ions moving into the positive electrode compartment balance the electron charge flow. During charge, this process is reversed [3]. This hermetically sealed battery is kept at approximately 300℃ and is operated under conditions such that the active materials at both electrodes are liquid and the electrolyte is solid. At this temperature, since both active materials react rapidly and because the internal resistance is low, the NaS battery performs well. Because of reversible charging and discharging, the NaS battery can be used continuously [7].

In general NaS cells are highly efficient (typically 89%). Higher efficiency cells can be designed and built but the battery's cost increases.

NaS battery technology has been demonstrated at over 190 sites in Japan. More than 270 MW of stored energy suitable for 6 hours of daily peak shaving have been installed. The largest NaS installation is a 34-MW, 245-MWh unit for wind stabilization in Northern Japan. The demand for NaS batteries as an effective means of stabilizing renewable energy output and providing ancillary services is expanding. The U.S. utilities have deployed 9 MW for peak shaving, backup power, firming wind capacity, and other applications. Projections indicate that development of an additional 9 MW is in-progress. At present, several projects are also under way in Europe and Japan [3]. Figure 5 illustrates the tubular design of sodium sulfur battery with a central sodium electrode [6].

2.6 Li-Ion Batteries

In a Li-ion battery as shown in Fig. 6, the cathode is a metal oxide which has been treated with lithium and the anode is made of layers of graphitic carbon. The electrolyte is made up of lithium salts dissolved in organic carbonates. When the battery is being charged lithium ions move out of the cathode and into the electrolyte solution where they are free to move to the negative electrode. At the carbon anode they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge. The scheme of this battery is in the next picture.

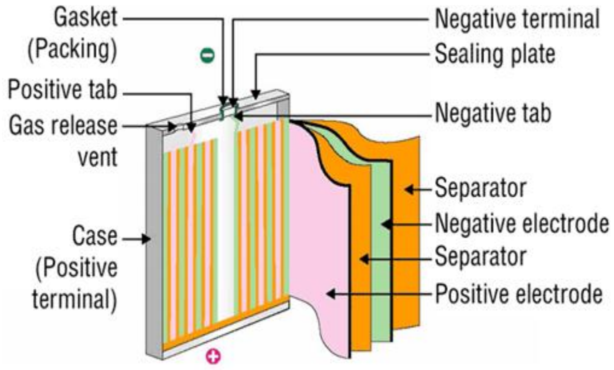


Fig. 6. Li-Ion battery provided by www.baj.or.jp

The main advantages of Li-ion batteries, compared to other advanced batteries, are:

i. High energy density (300-400 kWh/m3, 130 kWh/ton)
ii. High efficiency (near 100%)
iii. Long cycle life (3,000 cycles @ 80% depth of discharge)

Sony introduced Li-ion batteries in the early 1990s. In just a few years they took over 50% of the small portable market and today dominate the consumer electronic market. Nevertheless, a number of challenges remain for large-scale Li-ion batteries. The main hurdle is the relatively high cost due to special packaging, internal overcharge protection circuits, and thermal management considerations. Several companies are working to reduce their manufacturing cost in order to capture large energy markets [3]. However, Lithium ion technology has been hugely successful in the portable battery market. Efforts to scale these products up to larger capacities are not straightforward, since the portable technologies mostly use cobalt oxides in the cathode material and this material would be too expensive for the larger cells. Development is under way on a wide range of cathode materials and one of the early successes is with doped nickel oxides [8].

2.7 NiMH Batteries

NiMH batteries as shown in Fig. 7 are composed of nickel hydroxide on the positive electrode and an alloy consisting of vanadium, titanium, nickel and other metals on the negative electrode [9].

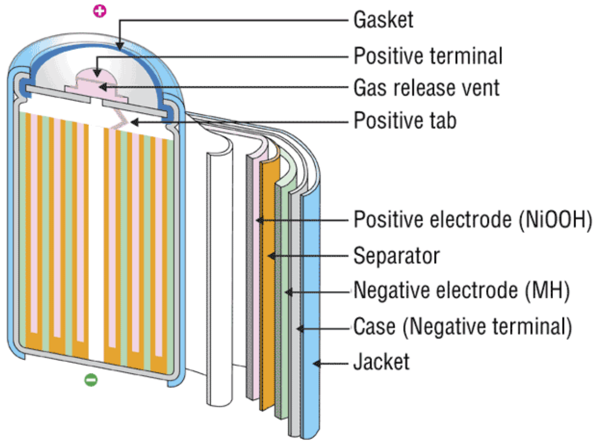


Fig. 7. NiMH battery provided by www.baj.or.jp

A NiMH battery can have two to three times the capacity of an equivalent size NiCd, and their energy density approaches that of a lithium-ion cell. NiMH batteries have replaced NiCd for many roles, notably small rechargeable batteries. NiMH batteries are very common for AA batteries. NiMH batteries normally operate at 1.2V per cell, somewhat lower than conventional 1.5V cells, but will operate most devices designed for that voltage.

About 22% of portable rechargeable batteries sold in Japan in 2010 were NiMH. In Switzerland in 2009, the equivalent statistic was approximately 60%.This percentage has fallen over time due to the increase in manufacture of li-ion batteries: in 2000, almost half of all portable rechargeable batteries sold in Japan were NiMH.

NiMH battery is reported favorable one by several reasons, such as high energy density, low prices, non-toxic and safety, and can be applied for the microgrid system. NiMH battery has unique characteristics comparing with the other types. It has been reported that its open circuit voltage has very strong hysteresis characteristics, and several methods have been used to develop the model for the state of charge estimation from its open circuit voltage [10].

One significant disadvantage of NiMH batteries is a high rate of self-discharge; a NiHM battery will lose as much as 3% of its charge per week of storage. In 2005 a low self-discharge NiMH battery was developed.

In recent years, NiMH batteries are being considered a good option due to its higher energy density and, specially, because it is an environment friendly technology. With regard to the cost, the initial higher prices of NiMH batteries are being adapted to new market situation. The main disadvantage is that NiMH technology is not so robust as other batteries as for example NiCd batteries [11].

2.8 NiCd Batteries

Similar to NiMH batteries, Nickel-cadmium (NiCd) batteries as shown in Fig. 8 have a legendary reputation for robustness, reliability and service life. This is the benchmark technology for difficult and demanding applications: operating temperatures from -40 ℃ to +60 ℃ (because the electrolyte has a very low freezing point), excellent cycling capability (up to 3,000 cycles), long storage life, and low or zero maintenance. Because of the structural materials they use, nickel-cadmium batteries are exceptionally robust, and exempt from risk of sudden failure [12].

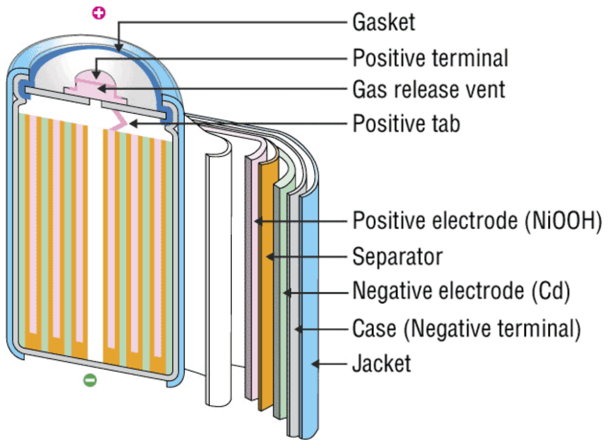


Fig. 8. Ni-Cd battery provided by www.baj.or.jp.

NiCd batteries have proved for a long time that they are a reliable source of power. They can also accept high charge rates for quick recharging. The main advantages of these batteries are their high specific power, long cycle life, low maintenance, acceptable range of operating temperature and robustness [11].

2.9 Lead-Acid Batteries

Lead-acid batteries as shown in Fig. 9 have been the most widely used energy devices for more than 100 years. With the introduction of new chemistry batteries and other energy storage devices currently in progress, the lead-acid battery is now facing competition in utility scale energy storage applications [8]. However, lead-acid batteries are an inexpensive and popular storage choice for power quality, and some spinning reserve applications. Their use for energy management, however, has been limited by their short cycle life.

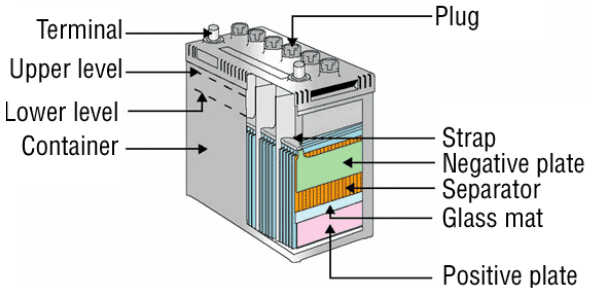


Fig. 9. Lead-Acid battery provided by www.baj.or.jp.

2.10 Flywheels

These devices store energy in a rotating mass. Energy can be absorbed from a wind generated electric motor that spins a flywheel. This stored energy can then be released through the use of an electrical generator powered by the flywheel's momentum. The capacity of the energy stored can be increased through increased speed at which the flywheel rotates or by increasing the number of flywheels in the system [2]. Flywheels are just beginning to be commercialized. Although the flywheel is primarily thought of as a power device, there are some that can deliver multiple KWh [8].Initial performance reviews show an increase in overall energy efficiency for small power plants [2]. Figure 10 shows an individual flywheel unit and a conceptual flywheel storage plant.

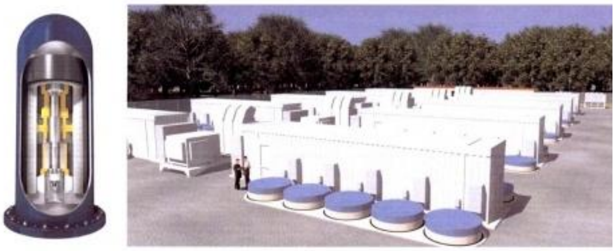


Fig. 10. An individual flywheel unit (left) and conceptual flywheel storage plant (right)

2.11 Electro-mechanical Capacitors

Electro-mechanical capacitors (ECs) store electrical energy in the two series capacitors that exist in the electric double layer (EDL) at the interface of each electrode and the electrolyte solution. The distance over which the charge separation occurs is just a few angstroms. The capacitance and energy density of these devices are thousands of times larger than those of electrolytic capacitors.

Compared to lead-acid batteries, ECs have lower energy density but they can be cycled tens of thousands of times and are much more powerful than batteries (fast charge and discharge capability) [3].

2.12 Comparisons

There are many aspects that have to be considered, e.g., the capacity, cost, life-cycle, efficiency and size and weight of the storage. In general, the cost of each kWh is one of the most important factors for stationary applications. It depends on many different factors, such as: application, efficiency, life cycle, initial capital cost, operations and maintenance and storage-device replacements. Low efficiency increases the effective energy cost as only a fraction of the stored energy could be utilized. Low cycle life also increases the total cost as the storage device needs to be replaced more often.

Metal-air batteries have the highest energy density. However, the electrically rechargeable types, such as zinc-air batteries, have a relatively small cycle life and are still in the developmental stage. Note that the actual cost of any storage system, as it has been said, depends on many factors and the assumptions and the means of calculating some of the values used are subjective and continue to be debated, even among experts in the field. The data as shown in Table 1 for the technologies is based on certain standard assumptions for the applications and expert opinions.

To find the most appropriate batteries for storing energy in a wind farm, several factors must be taken into account. In Table 2, we summarize the cost (per cycle, per energy unit, per power unit), efficiency, lifetime and energy density (weight and volume) for various energy storage technologies. We also annotate some interesting and important special requirements about them.

By considering the cost of each storage technology, we find that Li-Ion, NiMH, NiCd, Lead-Acid batteries, Flywheels and Electromechanical Capacitors have quite high cost, per cycle and per energy unit. Hence, we need to reject these types of energy storages for our purpose.

Secondly, according to the efficiency of storages, Metal-Air batteries are found to very inefficient since they can achieve only 50% of the highest rate that other technologies can achieve. Moreover, their lifetime range is quite low. As a result, they should not be used.

Then, according to their energy density data, pumped storages and flow batteries should be out of consideration

Table 1: Efficiency, lifetime and densities of the different storage technologies

Storage Technology	Efficiency (%)	Lifetime (80% DoD Cylces)	Weight Energy Density (Kwh/ton)	Volume Energy Density (Kwh/m3)
Pumped Storage	70-85 Medium	10K-100K High	0.5-1.5 Low	0.3 Low
Compressed Air	70-80 Medium	10K-100K High	30-60 Medium	2 Low
Flow Batteries	70-85 Medium	1K-10K Medium	20-27 Low	25-30 Low
Metal-Air	40-50 Low	100-1K Low	150-400 High	300-900 High
Sodium Sulfur	85-90 High	1K-10K Medium	100-175 High	150-300 High
Li-Ion	95-99 Very High	1-10K Medium	90-175 High	200-350 High
NiMH	60-67 Medium	1-10K Medium	25-60 Medium	25-90 Medium
NiCd	60-67 Medium	1K-10K Medium	25-60 Medium	25-90 Medium
Lead-Acid	72-76 Medium	100-1K Low	20-30 Medium	20-85 Medium
Flywheels	90-95 High	10K-100K High	10-15 Low	10-20 Low
Electromechanical Capacitors	95-99 Very High	10K-100K High	15-20 Low	10-30 Low

due to their low rates on both areas.

At this point, the only two left are Compressed Air energy storages and Sodium Sulfur batteries that apparently are the most suitable to achieve our goal. Comparing both, Compressed Air energy storages have worse rates on efficiency and energy densities. Sodium Sulfur batteries instead are more expensive, their lifetime rate is lower and they need special safety requirements.

To conclude with, giving more importance to the costs and of course the security and safety, Compressed Air storages will be chosen for continuing with the research of the project.

3 WIND ENERGY

3.1 Wind Terminology

It is important to have clear terminology defined.

- Start-up Speed: This is the speed at which the rotor and blade jointly begin to rotate.
- Cut-in Speed: It is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 11.27 and 16.09 Km/h for most turbines.
- Rated Speed: It is the minimum wind speed at which the wind turbine will generate its designated rated power.
- Cut-out Speed: At very high wind speeds, typically between 72.42 and 128.75 Km/h, most wind turbines cease power generation and are shut down for both technical and safety reasons. Having a cut-out speed is a safety feature that protects the wind turbine from damage [13].

3.2 Power in the wind

Wind is merely the movement of air from one place to another. Wind speed generally increases with height above ground. This is because the roughness of ground features such as vegetation and houses cause the wind to be slowed down [14].

Table 2: Costs and special requirements of different storage technologies

Storage Technology	Capital Cost per cycle (□ /KWh)	Capital Cost per unit Energy ($/KWh)	Capital Cost per unit Power ($/KW)	Special requirements
Pumped Storage	0.1-2 Low	70-200 Low	700-1800 Medium	-Location -Economical
Compressed Air	3-7 Medium	50-100 Low	600-1K Medium	-Location -Need Gas Fuel
Flow Batteries	7-90 High	150-2K Medium	800-3K Medium	-Need doubling energy density -Need long duration membrane materials
Metal-Air	0.1-2 Low	40-70 Low	1K-2K Medium	-Difficulty for energy charging -Very high energy density at a low cost
Sodium Sulfur	9-40 High	400-950 Medium	1K-2500 Medium	-Safety requirements
Li-Ion	20-100 High	800-4K High	1500-4K Medium	-Special charging circuit
NiMH	30-100 High	850-3500 High	700-1400 Medium	-Nontoxic -Safe
NiCd	30-100 High	850-3500 High	700-1400 Medium	-Very robust
Lead-Acid	30-100 High	400-1K Medium	400-900 Low	-Oldest batteries, most developed -Sensitive to operating temperature
Flywheels	8-30 Medium	-High Power 5K-7K High -Long Duration 1K-5KHigh	-High Power 270-600Low -Long Duration 3K-10KHigh	-Ideal for frequent charge/ discharge of power
Electromechanical Capacitors	3-30 Medium	-High Power 7K-10KVery High -Long Duration 100-300 Medium	-High Power 100-500Low -Long Duration 250-700 Low	-Ideal for frequent charge/ discharge of power

A wind turbine converts the kinetic energy in wind into the mechanical energy of a rotating shaft. Usually that rotating mechanical energy is converted immediately by a generator into electrical energy. Power electronic controls convert the electricity into the correct frequency and voltage to feed into the power grid [15].

The power in the wind is proportional to: The area of windmill being swept by the wind, the cube of the wind speed and the air density (that varies with altitude). But these parameters are not enough to calculate the actual and real power that can be extracted from the wind. It depends on more several factors, such as the type of machines and rotors that are used, the sophistication of blade design, friction losses, and the losses in the pump or other equipment connected to the wind machine. The formula leads to [14]:

$$P_M = ½\, C_p\, \rho\, A\, V^3 \tag{1}$$

Where P_M is power (in watts) available from the machine and C_p is the coefficient of performance of the wind machine in the range from 0 to 1, ρ is the air density in kilograms per cubic meter (kg/m^3), A is the swept rotor area in square meters (m^2) and V is the wind speed in meters per second (m/s).

3.3 Wind speed data

Wind speed data are needed. Furthermore, to make a comparison among different places, four different sites have been chosen, all of them located in Spain. The first weather station is located in Bilbao, Txurdinaga. The second one is placed in the Canary Islands, in Las Palmas de Gran Canaria at Telde. Next one is positioned in Madrid and the last one in Barcelona, specifically in Vic. The data to be evaluated are the maximum wind speed of these four places. Daily data from November 2011 to April 2012 will be used.

3.4 Power Estimation

Three different cases for these four places are evaluated. First one is how many batteries are needed in the worst case, when the smallest range of speed wind is valid. According to what has been said before, the cut-in speed is 16.09Km/h and the cut-out speed 72.42Km/h. Secondly, for the best case the wind speed range generates power with wind speeds between 11.27Km/h and 128.75Km/h. Lastly, the average case takes in to account wind speeds from 13.68 to 100.5Km/h.

A general formula can be derived, i.e., given the number of days, n, during which average power x can be generated over a year and the maximum number of consecutive days during which no power is generated, m, a storage capacity can be designed as follows:

$$E_C = mnx/365 \tag{2}$$

This will ensure the ideal daily output, on the average, $nx/365$.

As the information that has been evaluated goes from November 1 until the last day of April, the above formula will be changed into:

$$E_C = mnx/182 \tag{3}$$

The next formula calculates the daily average wind speed. If the wind speed of any day during this period is not inside the established wind speed limits, this particular wind speed is not summed. This is made because the wind speed is so high or so low that no power is generated.

The battery storage capacity must be designed based on this worst case. The next formula is applied to all the next cases:

$$A_i = \Sigma_j D_{ij}/182 \tag{4}$$

where A_i means average wind speed for location i, and D_{ij} is the jth day's average wind speed excluding the wind below cut-in speed and above cut-out one for location i.

After making the wind profile evaluation, the number of days without enough wind and the average wind speed of that place from November 2011 to April 2012 is calculated, having used the just mentioned formula. All these data are shown in Table 3.

Table 3: Results of the evaluation: Number of consecutive days with not enough wind and the average wind speed.

Place	Best wind conditions: Cut-in speed: 11.27 km/h Cut-out speed:128.75 km/h	Average case: Cut-in speed: 13.68 km/h Cut-out speed:100.5 km/h	Worst case: Cut-in speed: 16.07 km/h Cut-out speed: 72.42 km/h
Bilbao	1 day 31.75km/h	2 days 31.39km/h	6 days 28.39km/h
Canary Islands	No days without enough wind 32.89 km/h		
Madrid	6 days 15.85km/h	9 days 14.27km/h	13 days 11.59km/h
Barcelona	4 days 24.52km/h	5 days 24.32km/h	8 days 22.22km/h

4. WIND POWER MODEL AND ESTIMATION OF ENERGY STORAGE

4.1 Model

To calculate the power output of a windmill, the information that is required is the coefficient of performance of the windmill and the area of the swept rotor is required.

From the curve of the coefficient of performance of a wind machine, which depends on the wind speed, the next data is obtained. For the case of Bilbao where average wind speed in the worst situation is 28.39Km/h the coefficient of performance will be approximately 0.35. In the case of Madrid, with a wind speed of 11.59Km/h, C_p is 0.1. For the last case in Barcelona, in where the speed is 22.22Km/h, the coefficient is approximately 0.32.

From the datasheet of the Wind Turbine WES30 250kW, provided by Wind Energy Solutions (WES), it is specified that the rotor diameter is 30m large. From this it is obtained that the area of the swept rotor is 706.85m^2. This is considered as a medium scale wind machine.

$$A=\pi r^2=\pi(15m)^2 = 706.85m^2$$

4.2 Estimation

For all cases by using (1) with A=706.85m^2 and ρ=1.225kg/m^3, we obtain the next P_M values: Bilbao 74.14kW, Madrid 1.43kW and Barcelona 32.54kW.

As studied before, the maximum number of consecutive days without enough energy is 6 days for Bilbao, 13 for Madrid and 8 for Barcelona. If each number of days is multiplied by the average power output that has been just estimated, the needed capacity for each will be known. Table 4 shows the results of the calculation.

Table 4: Results of the capacity storage

Place	Average power output (kW)	Number of days	Needed capacity (kW)
Bilbao	74.14	6	444.84
Madrid	1.43	13	18.59
Barcelona	32.54	8	260.32

4.3 Storage Requirement

The storage technology which is going to be used is the compressed air energy storage (CAES). The selected storage systems are from the company PNU, and their capacities are 3kW, 5kW, 10kW, 100kW and 200kW.

They have different benefits like their low cost, low maintenance, their consistent high performance and power availability. Even in hostile environments they are highly reliable and furthermore their installation is fast and easy.

The units are environmentally very tolerant due to the fact that they have a very low environmental impact and minimal disposal issues [16].

For the selected places, different compressed air storages will be needed for each place. In the first place, Bilbao, for 6 days in a row 444.84kW will need to be covered. Two stores of 200kW and a single one of 100kW are going to be used.

For the second place in Canary Islands, as mentioned before no storage will needed because the wind speed in the evaluated time is never too strong or not enough for not producing energy.

In the third place, Madrid just 18.59kW will be needed to cover 13 days without enough wind. For this case, two compressed air storages of 10kW will be used.

To finish with this section, in the last place in Barcelona 260.32 kW will be needed due to the lack of wind during 8 days. To cover this, a single storage of 100kW and another one of 200kW will be needed.

5 CONCLUSIONS

Wind power was increasingly used in electric power systems during the past years. It is well-known that such power is indeed an intermittent power source. This paper summarizes various storage technologies that can be potentially used to store energy. The selection of such technologies in of critical importance in guaranteeing the steady power delivery from a wind power plant. Depending upon the historical weather information, the most appropriated technology should be selected. This paper then estimates the storage requirements based on the wind profile at four different locations.

As more renewable energy sources are integrated into the electricity grid, more challenges arise due to their intermittence issues. High-capacity, low-cost, highly-reusable, and environmentally-benign energy storage technologies must be developed to deal with them. Their applications to various renewable energy generation plants need to be made by considering various factors as a future research direction.

ACKNOWLEDGEMENT

The authors would like to thank the comments provided by the anonymous reviewers.

REFERENCES

[1] P. Hu, R. Karki, and R. Billinton, "Reliability evaluation of generating systems containing wind power and energy storage," *IET Generation, Transmission & Distribution*, March 2009. www.ietdl.org.

[2] T. Ernest, *Wind Energy Storage.* Project Manager – Financial Consulting , Harris Group Inc. http://www.epoverviews.com, 2012.

[3] Electricity Storega Association (ESA). *Pumped Hydro.* February 2012. http://www.electricitystorage.org.

[4] R. B. Schainker and M. Nakhamkin. "Compressed -Air Energy Storage (CAES): Overview, Performance and Cost Data for 25MW to 220MW Plants," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No. 4, pp. 790-795, April 1985.

[5] A. Price, "Technologies for energy storage - present and future: Flow batteries*,"* in *2000 IEEE Power Engineering Society Summer Meeting*, pp. 1541 – 1545, Seattle, WA, 2000.

[6] L L. W. Chung , M. F. M. Siam , A. B. Ismail and Z. F. Hussien "Modeling and simulation of sodium sulfur battery for battery-energy storage system and custom power devices," in *Proc. Nat. Power Energy Conf.*, pp. 205 -210, 2004

[7] J. Fraser, *The Energy Blog.* January 18, 2006, http://thefraserdomain.typepad.com.

[8] G. P. Corey, "Batteries for stationary standby and for stationary cycling applications part 6: alternative electricity storage technologies," In *Proc. of* 2003 *IEEE Power Engineering Society General Meeting*, pp. 164-169, July 2003.

[9] P. Claudia, A. Guerrero, F. Ju, J. Li, G. Xiao and S. Biller, "Hybrid/Electric Vehicle Battery Manufacturing: The-state-of-the-art," to appear in *Contemporary Issues in Systems Science and Engineering*, M C. Zhou *et al*. (Eds), IEEE/Wiley, 2014.

[10] N. A. Windarko, J. Choi, and G.-B. Chung "Improvement of electrical modeling of NiMH battery for application of Microgrid System," in *2010 IEEE Energy Conversion Congress and Exposition*, 4243-4248 , Atlanta, GA, Sept. 2010.

[11] J. C. Viera, M. Gonzalez, J. C. Anton, J. C. Campo, F. J. Ferrero, and M. Valledor, "NiMH vs NiCd Batteries under High Charging Rates," in *Proc. of 2006 IEEE Telecommunications Energy Conference*, pp. 1-6, Providence, RI, Sept. 2006.

[12] Group, *The* Saft.*Nickel-Cadmium (Ni-Cd).* 2007, http://www.saftbatteries.com.

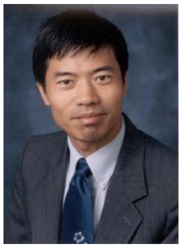
[13] J. F. Manwell, J. G. McGowan and A. L. Rogers, *Wind Energy Explained: Theory, Design and Application*, Wiley, West Sussex, UK, 2009.

[14] British Wind Energy Association, http://www.uk-energy-saving.com/wind_power.html, 2013

[15] D. Watson, *Wind Turbines and the Energy in Wind*, http://www.ftexploring.com, 2013

[16] Pnu Power, www.pnu-power.com, 2013

Maitane Berecibar received her B.S. degree in Electrical and Electronics Engineering from the University of Mondragon, Spain in 2009. She developed her final degree project in the University of Brno, Czech Republic, named "Quality of Service of Free Space Optical Links". Her M.S. degree in Automatics and Electronics Engineering was obtained in 2012 from University of the Basque Country in Bilbao, Spain. In order to obtain this degree, she developed a project named "Estimating Storage Requirements for Wind Power Plants" at New Jersey Institute of Technology. She is now pursuing her Ph. D. degree in the Technology Research Centre IK4-Ikerlan, and performing the research on "Degradation and Estimation Algorithms of SOC and SOH in Lithium Ion Batteries". She has also attended several lectures such as "Power Electronic Systems" given by Ingeteam, which is a market leader specialized in electrical engineering and the development of electrical equipment, motors, generators and frequency converters and "Industrial Robot Programming" taught by Dr. Meter Hess, Professor of the University Georg Simon-Ohm of Nürnberg. During her study at New Jersey Institute of Technology, USA, she took the courses of "Transients in power systems" and "Renewable Energy Systems".



MengChu Zhou received his B.S. degree in Control Engineering from Nanjing University of Science and Technology, Nanjing, China in 1983, M.S. degree in Automatic Control from Beijing Institute of Technology, Beijing, China in 1986, and Ph. D. degree in Computer and Systems Engineering from Rensselaer Polytechnic Institute, Troy, NY in 1990. He joined New Jersey Institute of Technology (NJIT), Newark, NJ in 1990, and is a Professor of Electrical and Computer Engineering and the Director of Discrete-Event Systems Laboratory. He is presently also a Professor at the MoE Key Laboratory of Embedded System and Service Computing, Tongji University, Shanghai, China. His research interests are in intelligent automation, Petri nets, sensor networks, semiconductor manufacturing, Web service, workflow, lifecycle engineering and sustainability evaluation, and energy systems. He has over 490 publications including 11 books, 230+ journal papers (majority in IEEE transactions), and 18 book-chapters. His recently co-authored books include *Deadlock Resolution in Automated Manufacturing Systems: A Novel Petri Net Approach*, Springer, New York, 2009 (with Z. Li), *System Modeling and Control with Resource-Oriented Petri Nets*, CRC Press, New York, 2010 (with N. Wu) and *Business and Scientific Workflows: A Web Service-Oriented Approach*, IEEE/Wiley, New Jersey, 2013 (with W. Tan).

He was invited to lecture in Australia, Canada, China, France, Germany, Hong Kong, Italy, Japan, Korea, Mexico, Singapore, Taiwan, and US and served as a plenary speaker for several conferences. He is the founding Editor of IEEE Press Book Series on Systems Science and Engineering. He served as Associate Editor of IEEE Transactions on Robotics and Automation from 1997 to 2000, and IEEE Transactions on Automation Science and Engineering from 2004-2007, and is currently Editor of IEEE Transactions on Automation Science and Engineering, and Associate Editor of IEEE Transactions on Systems, Man and Cybernetics: Systems, IEEE Transactions on Industrial Informatics and IEEE Transactions on Intelligent Transportation Systems. He served as Guest-Editor for many journals including IEEE Transactions on Industrial Electronics and IEEE Transactions on Semiconductor Manufacturing. He was General Chair of IEEE Conf. on Automation Science and Engineering, Washington D.C., August 23-26, 2008, General Co-Chair of 2003 IEEE International Conference on System, Man and Cybernetics (SMC), Washington DC, October 5-8, 2003, Founding General Co-Chair of 2004 IEEE Int. Conf. on Networking, Sensing and Control, Taipei, March 21-23, 2004, and General Chair of 2006 IEEE Int. Conf. on Networking, Sensing and Control, Ft. Lauderdale, Florida, U.S.A. April 23-25, 2006. He was Program Chair of 2010 IEEE International Conference on Mechatronics and Automation, August 4-7, 2010, Xi'an, China, 1998 and 2001 IEEE International Conference on SMC and 1997 IEEE International Conference on Emerging Technologies and Factory Automation. He organized and chaired over 100 technical sessions and served on program committees for many conferences. Dr. Zhou has led or participated in 50 research and education projects with total budget over $12M, funded by National Science Foundation, Department of Defense, NIST, New Jersey Science and Technology Commission, and industry. He was the recipient of NSF's Research Initiation Award, CIM University-LEAD Award by Society of Manufacturing Engineers, Perlis Research Award and Fenster Innovation in Engineering Education Award by NJIT, Humboldt Research Award for US Senior Scientists, Leadership Award and Academic Achievement Award by Chinese Association for Science and Technology-USA, Asian American Achievement Award by Asian American Heritage Council of New Jersey, and Outstanding Contributions Award, Distinguished Lecturership and Franklin V. Taylor Memorial Award of IEEE SMC Society. He is founding Co-chair of Enterprise Information Systems Technical Committee and Environmental Sensing, Networking, and Decision-making Technical Committee of IEEE SMC Society. He is a life member of Chinese Association for Science and Technology-USA and served as its President in 1999. He is Fellow of IEEE and American Association for the Advancement of Science (AAAS).