Distributed vs. Centralized Energy Storage for Power System Applications

Electrical Engineering Project

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1 Introduction

In modern power systems, the role of an energy storage system (ESS) is more and more discussed. Recently, California passed an energy storage mandate calling for 1325 MW of energy storage by 2020 [1]. The goal of California is to reach 33 percent of its power supply to come from renewables by 2020, and because of the intermittency of their production, solutions must be found to integrate those sources to the grid. Storage is one of them.

The goal of this project is to investigate the roles of ESSs in a power grid, and more specifically the differences between centralized and distributed energy storage. Their location on the grid and how this affects the type of ESS will also be examined. The question of the intermittency of the energy production and how this affects the storage systems will also be analysed, thanks to the addition of wind farms to the system.

To achieve this goal, an Australian power market modelling and simulation software, Plexos, was used. With this software, a modified version of the IEEE reliability Test System was modelled. The changes were made to introduce distributed ESSs and wind farms.

Once the system was modelled, different scenarios were studied. Three cases were analysed: the first one was simply the system with no storage; the second one was a centralized ESS (a pumped-hydro plant); and the last one was three distributed ESSs (batteries).

Wind farms were introduced to see how the uncertainty and the variability of wind were modifying the previous cases. Wind was first model as perfectly predictable, and then with a difference in the wind forecast and the actual generation. The purpose of this double model was to see if errors in the forecast would change the use of storage.

The cost paid by the load will be the main criterion in the comparison of those scenarios (i.e. if ESSs allow to do savings), but the generators revenues and some other non-economical criterions (differences in unit commitment, emission of CO2) will also be taken into consideration.

In this report, the literature reviewed will be summed up. Different applications and types of energy storage systems (ESS) will be reviewed, the difference between centralized ESSs and distributed ones will be revised, and some real examples of existing ESSs will be given.

2 Literature Review

2.1 Distributed and Centralized Energy Storage Systems

Distributed ESSs can be described as numerous small on-site storage systems, connected to the edge of the network, whereas centralized storage systems tend to be larger units, in a smaller number, and connected to the transmission network. Another big difference between distributed ESSs and centralized ESSs is that the distributed ones are not subject to location restrictions. The major
(centralized) ESS is pumped-hydro storage (PHS). However, it is only available in mountainous areas (underground pumped-hydro has not been realized yet, even if projects exist). This is a strong drawback in countries without big mountain chains. And even in countries with appropriate geological formations, the sites where PHS is possible and economically feasible will soon or later all be used. (In Europe, the potential for pumped hydropower storage is about 10 times the actual one [2]; however some countries [3] are already using almost all their potential, like Switzerland where over 85% [3] of the potential is used).

Distributed ESS can be located everywhere on the grid. Either near the generation or near the consumers, connected to the transmission network or to the distribution one. They have no location restrictions. This is a great advantage, because the applications they provide change their optimum location on the grid. For example, a study showed that a superconductive magnetic energy storage (SMES) combined with a StatCom would have a better performance if it was connected near a load area instead of near generation (with however an increased cost) [4].

A scheme of a power system with a centralized ESS is shown in Figure 2.1.1.

![Figure 2.1 Small network with a centralized ESS (a dam)](image)

The power system in Figure 2.1 is basic. It is composed of generators (that can be wind farms, fuel plants, nuclear plants, etc.) that are connected to the transmission network. A centralized ESS (a dam) is also connected to this transmission network. As discussed above, dams are usually far from
the consumptions nodes and therefore are connected to the transmission network. A distribution network is also attached to the transmission network, and different loads are connected to it. In Figure 2.2, the same system is shown but this time with distributed ESSs (here just a battery) at every node to emphasis the fact that they don’t have any location restrictions.

![Diagram of Energy Storage Systems](image)

**Figure 1.2 Small network with distributed ESS**

### 2.2 Applications of Energy Storage Systems

There are a lot of different applications in the grid for ESS. The most important ones will be listed and explained. Given that the topic of my project is related to the grid, transport applications won’t be considered.

Those applications differ a lot in term of power and energy required, and they have different time scales.
2.2.1 Grid Stabilization

Grid stability is the capacity the grid has to regain a state of equilibrium after a disturbance (transients, interruptions, sags or swells) in order that the system remains intact [5]. Three examples that can cause grid instability are:

1) Rotor Angle instability happens when a short circuit occurs on a transmission component that causes the generators to accelerate and lose synchronization with the grid. The effect is oscillation of the voltage on the line (transients). If those oscillations are not damped, the generator will trip offline. This may lead to an overload of transmission equipment, and then lead to the instability of the total system.

2) Frequency excursion occurs when there is a strong difference between generation and load (e.g. when a generator trips or when generation is not sufficient).

3) Voltage instability occurs when a load require a large amount of reactive power, exceeding the capacity of the reactive power sources. This increase in load is accompanied by a drastic voltage drop.

Those cases will now be discussed and we’ll see how storage can help.

2.2.1.1 Rotor Angle Stability

The angular position of the rotors of synchronous generators remains constant to provide voltage in phase with the grid voltage. However, if synchronism is lost, angular oscillations can occur. An energy storage system can be used to regulate the oscillations, by switching between charge and discharge modes at the frequency of the oscillations (e.g. 0.5 to 1 Hz [5]) to cancel their effect. Those storage systems need a really fast response and the ability to switch between charge and discharge modes really quickly. Therefore suitable technologies are SMES, super capacitor, flywheels and batteries.

2.2.1.2 Frequency Excursion Suppression

Frequency excursion suppression allows the grid to maintain a stable frequency (in a small interval, i.e. around 50 Hz in Europe), even in case of severe system disturbance. The stability requires that the system can quickly recover the balance between load and generation in case of the loss of a part of the generation or a part of the load [5]. During the time when a generator trips and the time when the replacement reserves are brought online (between 15 and 30 minutes, depending on the system and the available units), there are spinning reserves that must be used. Usually, it’s generators that are increasing their output. But instead of those, or in addition, energy storage systems could be used. They need to be really fast, have a quite big power and energy output, and therefore the suitable technologies are batteries.

2.2.1.3 Voltage Stability

To improve the voltage stability, injections of reactive and real power for small durations (order of seconds [5]) must be produced. SMES, batteries and super capacitors could be used, because of their ability to provide short bursts of power.

2.2.2 Load Levelling/Peak Shaving

Load levelling is the rescheduling of loads (usually industrial loads) to cut electrical demand; or the production of energy during off peak period for storage, as shown in Figure 2.3. Peak shaving is the reduction of the demand during peak demand or the rescheduling of certain loads from peak
demand to off peak demand [6]. This may avoid large investments on new transmission or generation.[7] The suitable ESSs need to have a big capacity (if we want the load levelling or the peak shaving to be really effective, a large amount of energy must be stored with a high efficiency), and therefore PHS and CAES seem to be adequate. Batteries are also used. For example, in the USA, a 1.2 MW NaS battery is used in the Charleston Substation to provide 7.2 MWh of on-demand power, and by peak shaving the load each days, the ESS enables a deferment of transmission upgrade for six or seven years. Then the battery will be located in another substation where deferment is needed.

2.2.3 Energy Arbitrage
The ability of storing energy at one time of the day and then discharging it at another time, effectively shifting the energy consumption, is what is called energy arbitrage. The purpose is to earn money by doing this, storing low cost energy during time of off-peak demand and selling it at high cost during time of peak demand. The difference in price between peak and off peak demand must be big enough to compensate the losses encountered in the storage process.

The ESSs suitable for this are high capacity and long discharge time ESSs, i.e. PHS and CAES or batteries.

2.2.4 End User Peak Shaving
Undesired grid voltage effects at end/user level can be black out, voltage sags (short period interruption), voltage peaks and variable fluctuation (flicker) [7]. Almost all consumers need a stable power supply, especially industrial loads. ESSs can be used to diminish the fluctuations of those end user negative effects. Suitable technologies are batteries, SMES, super capacitor or flywheels. Centralized ESSs are not usable because they are usually far from the load.

2.2.5 Reserves
There are different types of reserves that must come on line at different times when there’s suddenly not enough generation to meet the demand (a generator that trips offline, or the loss of a transmission line). The first reserve is called the frequency response reserve (because it must be
available immediately after the loss of the generator or the transmission line in order to mitigate the drop in frequency). Then there’s the spinning reserve (composed by online generator increasing their output, it’s called “spinning” because it refers to the fact that generators are already online and spinning) and finally the replacement reserve (it is composed by new units that are brought online in order to compensate the loss in generation). The replacement reserve must be available within the 30 minutes that follow the fault.

Spinning reserve is defined as “the amount of generation capacity that can be used to produce active power over a given period of time which has not yet been committed to the production of energy during this period." [6] It is either generators that can increase their output, or energy storage systems that can act as generators over a period of time (until the replacement reserve comes in line, i.e. new generators have been started to meet the demand).

Suitable technologies are really fast devices with high burst of power, like SMES flywheels or super capacitor in the first seconds (frequency response reserve), then batteries in the first minutes and finally CAES or PHS as “spinning” reserve.

2.2.6 Black Start
It is the ability of a power source to go from a shutdown condition to an operation condition without assistance from the electrical grid. Then the power source can re-energize the grid and help other generators to go online. Power sources can be reenergized via ESSs, combined with diesel generators. ESSs need to have significant power capabilities (typically 10 MVA [5]), and sufficient energy to deploy generator from a cold state, which takes 15 minutes to one hour for a gas turbine. Suitable technologies are batteries, PHS and CAES.

2.2.7 Integration of Renewable Energy
Wind and solar are two resources that are, by nature, variable and uncertain. Therefore, they won’t necessarily be available when they are needed. For example, the energy produced by a solar panel is maximal at noon as shown in Figure 2.5, but the peak consumption is around 6 pm.
Figure 2.5 Irradiance in January on a 35 degrees south facing tilted array located at the engineering building of UCD

This Figure doesn’t even account of the variations due to clouds or atmosphere changes. Wind is even more volatile, and is also difficult to predict. Figures 2.6 and 2.7 show respectively wind production and electricity consumption in Ireland on a random day, the 16th of September 2013. We can see that the wind falls when the consumption is reaching its peak value.

Figure 2.6. Wind generation

Figure 2.7. System demand

Source: EirGrid
Storage systems could help integrating the renewables by storing energy when there’s too much production and not enough consumption and releasing it when the opposite situation occurs.

Suitable technologies are PHS, CAES and batteries. Thermal energy storage (molten salts) is also used in combination with solar power plants. An example of this combination is the solar thermal power plant of Andasol in Spain that uses 28 500 tons of salt to provide 50 MW of storage for 7.5 hours, at an efficiency of 93%.

Another example is a study that has been made in the UK where it was proven that vanadium redox batteries could be added next to a wind farm to allow it to provide frequency regulation, and therefore improve its integration to the grid.

2.2.8 Uninterruptible Power Supply (UPS)
Some loads are so critical, that even in the case of the complete loss of the production, they still need to be supplied. One can think about hospitals, data servers, government vital services, prisons, etc. This concept is illustrated in Figure 2.8.

![Figure 2.8 Concept of Uninterruptible Power Supply](image)

In Fairbanks, Alaska, a battery of 40 MW that has 7 minutes of storage can provide emergency power supply to 12000 people until the diesel generators are started up.
2.3 Types of Energy Storage Systems

Different applications in which ESSs can be used have been reviewed. However, they all require different characteristics. Fortunately, there are lots of different energy storage systems and they differ in many characteristics: efficiency, cycle life, energy and power density and self-discharge. Those ESSs can be categorized in four groups: electrochemical energy storage, mechanical energy storage, electrical energy storage, thermal energy storage. The criterion of classification is the form in which energy is stored.

The ESSs reviewed in this report are shown in Figure 2.9.

![Figure 2.9 Different Types of Energy Storage Systems](image)

Those ESSs are also associated with their key parameters in Table 1. For each parameter, the red cells indicate the best EESs in the category and the blue cells indicate the worst.
<table>
<thead>
<tr>
<th>Name</th>
<th>Efficiency [%]</th>
<th>Cycle Life</th>
<th>Energy Density [Wh/kg]</th>
<th>Power Density [W/kg]</th>
<th>Self-Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Acid</td>
<td>70-80</td>
<td>200-2000 cycles</td>
<td>20-35</td>
<td>25</td>
<td>Low</td>
</tr>
<tr>
<td>Li-Ion [7]</td>
<td>70-85</td>
<td>500-2000 cycles</td>
<td>100-200</td>
<td>360</td>
<td>Low</td>
</tr>
<tr>
<td>NiMh [7]</td>
<td>50-80</td>
<td>&lt; 3000 cycles</td>
<td>60-80</td>
<td>220</td>
<td>High</td>
</tr>
<tr>
<td>NaS [7]</td>
<td>70</td>
<td>2000 cycles</td>
<td>120</td>
<td>120</td>
<td>Medium</td>
</tr>
<tr>
<td>Vanadium Redox [7]</td>
<td>80</td>
<td>1600 cycles</td>
<td>25</td>
<td>80-150</td>
<td>Negligible</td>
</tr>
<tr>
<td>Pumped Hydro Storage</td>
<td>65-85</td>
<td>&gt;20 years</td>
<td>0.3</td>
<td>Depends on the height</td>
<td>Negligible</td>
</tr>
<tr>
<td>Flywheels (steel) [7]</td>
<td>95</td>
<td>20000 cycles</td>
<td>5-30</td>
<td>1000</td>
<td>High</td>
</tr>
<tr>
<td>Flywheels (composite)</td>
<td>95</td>
<td>20000 cycles</td>
<td>50</td>
<td>5000</td>
<td>High</td>
</tr>
<tr>
<td>CAES [7]</td>
<td>60-80</td>
<td>&gt;20 years</td>
<td>10-30</td>
<td>Depends on the plant</td>
<td>Low</td>
</tr>
<tr>
<td>SMES [8] [9] [10]</td>
<td>&gt;95</td>
<td>20 years</td>
<td>1-11</td>
<td>&gt;10000</td>
<td>High</td>
</tr>
<tr>
<td>SuperCapacitor[11]</td>
<td>95</td>
<td>$10^6$ cycles</td>
<td>Low</td>
<td>4000-10000</td>
<td>High</td>
</tr>
<tr>
<td>PCM Molten Salts</td>
<td>70-95</td>
<td>5-12 years</td>
<td>80-200</td>
<td>80-300</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Table 1 Different features of ESSs

We can learn a lot of things from this table. First, the ESSs with a high power density have a rather small energy density (e.g. SMES, Super Capacitors and flywheels). This indicates that the applications that provide the ESSs to the grid (either short burst of power or longer period of smaller generation) will strongly determine the type of ESSs.

We also see that PHS doesn’t have huge advantages on its competitors, except in cycle life. An interesting fact is that it has a low energy density even though it’s used in energy applications. This low energy density is counterbalanced (and in fact caused) by the size of the PHS systems which are enormous. A long cycle life allows big infrastructure to be built, and therefore a long time to recover the capital costs and therefore a low cost. This low cost is why pumped hydro systems are so widely used.

The cost has two aspects, a cost per kW and a cost per kWh, reflecting the fact that ESSs cannot be used in every application. The cost is shown in per kW in Figure 2.01 and in per kWh in Figure 2.11.
The source of the data is a paper presented at the 2012 IEEE Electrical Power and Energy Conference [9]

Super capacitor and SMES are not shown in this graph because their value of 20000 and 25000$ per kWh are out of scale.

On those graphs we see that PHS, CAES and TES have a really low per kWh cost, whereas SMES and batteries have a rather low cost per kW. Lead acid batteries have a low cost in both, but as shown in Table 1, they have a low cycle life and power density, and a medium energy density and efficiency.

The different types of energy storage systems will now be reviewed.
2.3.1 Electrochemical Energy Storage

2.3.1.1 Lead Acid Battery
It is composed by a “spongy” lead as negative active material and a lead dioxide as positive active material. The whole system is immersed in a diluted sulfuric acid electrolyte. Its main strength is the low cost of its materials and production. Unfortunately it has a low power and energy density. It is mainly used in cost sensitive application where the downsides (low power and energy density) are not an issue.

2.3.1.2 Li-Ion Battery
It works on the principle of lithium ions moving between the anode and cathode to produce current. Its strengths are the high energy density and the fact that it has no memory effect (which improves the life cycle) and a low self-discharge. Unfortunately it is quite expensive to build and lithium is a limited resource. The main applications are cell phones, laptop and other portable equipment.

2.3.1.3 NiMH Battery
This battery uses nickel oxyhydroxide for the positive electrode and metallic cadmium for the negative electrode. It has a high power density, a proven safety (it has been used for many years), it is also resistant and has a long life. However, the self-discharge is high. It was used in the first electric/hybrid vehicle in the 90’s and 2000’s.

2.3.1.4 NaS Battery
It consists of molten sulphur at the positive electrode and molten sodium at the negative one, separated by a solid beta alumina ceramic electrolyte. Positive sodium ions go through the electrolyte and combine with sulphur to form sodium polysulfide. It has a high power and energy density, a long life cycle, a rather low cost (because it is built in low cost and abundant materials). However, it has a strong downside: the operating temperature is 300-360 degrees Celsius. Therefore it needs to be heated externally. It is used in grid application (load levelling, UPS) and the worldwide installed capacity is about 200 MW [11].

2.3.1.5 Flow batteries (vanadium redox)
This battery has two electrolytes that are stored in tanks, and they are pumped in the reactor where a reversible chemical reaction happens (production or consumption of current), as shown in Figure 2.12. Therefore the total stored energy is decoupled from the rated power. The rated power depends on the reactor size and the stored capacity depends on the auxiliary tanks size. This implies that the capacity is limited only by the size of the tanks. Unfortunately, the energy density is rather low, and therefore if a big capacity is needed huge tanks must be built. However, if size is not a problem, then the decoupling is a really strong benefit. The applications provided are power quality control applications (UPS, frequency and voltage control), emergency power, back-up power, and integration of renewable energy. The worldwide installed capacity is 38 MW.
2.3.1.6 Vehicle to Grid, V2G
Due to different factors (necessity of reducing carbon dioxide to reach the goals set by the Kyoto Protocol [12], increase in oil prices, environmental awareness) electric or hybrid vehicles are a growing part of the vehicle sales. Therefore, more and more electric vehicles will be connected to the grid when they are charging. The batteries of those vehicle (lead-acid, NiMh, lithium-ion) can work as distributed resources to smooth the load curve [13].

2.3.2 Mechanical Energy Storage

2.3.2.1 Pumped Hydro Storage (PHS)
Water is pumped from a low reservoir to a high reservoir (an artificial lake, retained by a dam) and therefore energy is stored as potential energy. The water is then released through turbines to generate power. It has a high capacity, a good efficiency and therefore a low cost. However, it has geographical constraints (mountainous areas are needed). The applications are: peaking capability, reserve supply and balancing capability to support renewables sources, load levelling and peak shaving. It can also work as load during low demand periods, if generation is too high. The size range depends on the dam. In Ireland, it is 292 MW for the Turlough Hill one[14], but in country with mountains, it can be way higher, in Switzerland, La Grande Dixence has an installed capacity of 2000 MW[15] and in China the Three Gorges Dam has an installed capacity of 22500 MW [16].

2.3.2.2 Flywheels
It is an ESS that stores energy in a rotating mass. The energy stored is kinetic energy and is given by:

\[ E = \frac{1}{2} I \omega^2 \]

Where \( I \) is the inertia of the rotating mass and \( \omega \) is the angular velocity.

Therefore, the higher the speed, the higher the energy stored. As the inertia is given by:
in the case of a cylindrical flywheel of mass m and radius r, it is more efficient to increase the speed of rotation than the mass in order to store more energy.

Therefore, high speed devices are working around 10000 RPM (and even up to 60000 RPM for the most modern flywheels [17]). Energy is stored and released via an electric motor. The strength of the flywheel is that it can provide a very high peak power. Therefore it is used in power quality applications. It is also used in a few companies to avoid that voltage sags or voltage losses interrupt the industrial production. Nonetheless, it seems not economically viable, as the main constructor, Beacon Power bankrupted in 2011 [19]. The size range of the devices is the kW scale [11].

2.3.2.3 Compressed Air Energy Storage (CAES)

In a CAES plant, electricity is used to compress air during off-peak periods. This compressed air is stored in a natural cavern (salt mines) or in a reservoir. Then when the demand has grown again, the air is heated in a gas turbine, it’s expending and gas fuels are added and the turbine is rotating. There are only 2 existing plants, one in Huntorf, Germany, and the other one in McIntosh, Alabama, United States. The strengths of this storage system are its high capacity and its low cost. The downside is the special site requirement. Huntorf plant is mainly used as spinning reserve and peak shaving and McIntosh plant is used for arbitrage, load management and peak shaving [5]. Lots of other projects were studied but none were built. A recent project, the Norton plant in Norton, Ohio, US (a huge 2700 MW plant) was planned first for 2005-2006, but was not realised so far. This is apparently due to lack of investments due to the economic situation [20].

2.3.3 Electrical Energy Storage

2.3.3.1 Superconductive Magnetic Energy Storage (SMES)

The energy is stored in the magnetic field created by a current flowing through a superconducting coil. The material, to be superconducting, must be cooled to a temperature of 4-6 K. Therefore the operating temperature is really low and a cooling circuit, which will consume a lot of energy and money, must be used. However, SMES have a high power density and have a really fast dynamic response (range of 1 millisecond). Therefore they are suitable for grid voltage and angular stability and short duration power quality [5 & 11].

2.3.3.2 Super capacitor

Super capacitors (or ultra-capacitors) work in the same way than usual capacitor: energy is stored in the capacitor by charge separation. The capacitance is given by:

\[ C = \frac{A\varepsilon_r\varepsilon_0}{d} \]

Then the energy stored is given by

\[ E = \frac{1}{2}CV^2 \]
Where $\varepsilon_0$ is the vacuum permittivity, $\varepsilon_r$ is the relative permittivity, $A$ the area of the plates, $d$ the distance between the two plates and $V$ the voltage applied.

To achieve a great amount of energy stored, the area of the plates (if plate capacitor) and the relative permittivity of the dielectric must be high, while the distance between the two plates must be as small as possible. The applications in the grid are short term high power applications (frequency control, voltage control). It is also used in transport applications, as short duration energy storage for hybrid-electric vehicle [5]. Another interesting application is the Bridge Power Systems: the super capacitors can carry a critical load away from a failing source to a stable alternate one, via a rapid isolation from the failing source. 80-90% of the short circuits are just a momentary missing voltage replacement, which implies that no alternate source needs to be added (250 ms of average duration [5]), and therefore super capacitors are perfectly fitting. In case of a severe fault, and during the transition between bulk mode and island mode (the micro grid is disconnected from the bulk grid), the super capacitors are helpful to smooth the transition between the two modes. They are also really efficient to deal with peak load, because of its high power and energy density. They are also useful if the load needs a high instantaneous current (motors).

2.3.4 Thermal Energy Storage

In thermal energy storage, energy is stored in form of heat, and is released either in this form (heating systems) or transformed in electricity via a heat turbine.

2.3.4.1 Hot Water Thermal Energy Storage

Energy can be stored by heating water. This is often used when a solar thermal collector is used in a heating system, but it can also be done at bigger scales in hot water tanks. For example, “Am Ackermannbogen” in Munich, Germany is a district where the heating is powered by 2761 m$^2$ of solar collector. This energy, if not used directly, is stored in a tank of 5700m$^3$, which is shown in construction in Figure 2.13 [21].

![Figure 2.2 Thermal Tank Energy Storage](image-url)
2.3.4.2 Phase Change Materials Thermal Energy Storage (PCM)

PCM are materials that are changing their state in a narrow interval of temperature (solid-solid or solid-liquid). It’s increasing the achievable storage capacity at a given temperature, as shown in Figure 2.14.

![Figure 2.3](image)

An example of PCM materials is molten salts, heated at 390 degrees in turns into a liquid which is transferred via a heat exchanger and pumped in a second tank where the heat generated is used to produce steam that is then used in a steam turbine. The process is shown in Figure 2.15 [23].

![Figure 2.4](image)

2.4 Different Energy Storage Systems for Different Applications

We’ve seen that ESSs could be used in a lot of different applications in the grid. Moreover, those applications require different characteristics in term of power, energy, time of response and duration and therefore different ESSs are used. Figure 2.16 shows different applications in function of the power and the duration required, and Figure 2.17 shows different ESSs that could be used.
The cost of those ESSs varies a lot, but it seems that big infrastructure and big investment costs is the most profitable way of providing kWh (see PHS TES and CAES in Figure 2.10) whereas kW cost tends to be low in smaller systems like batteries (see Figure 2.11).

We’ve seen that the energy, power, time were key parameters for ESSs. The question upon which my project is based is to determine how another parameter, location, affects those ESSs.
3 Description of the system modelled

3.1 Description of the Software Used
PLEXOS® Integrated Energy Model is a power market modelling and simulation software. It can optimize power systems over different time scales (long-term: 1-40 years, medium-term: 1-5 years, short-term: < 1 year). For this project, only short term schedule was used. The optimization is realized using mixed-integer programing (MIP). It deals with pricing, unit commitment, constraints modelling, Monte Carlo simulation and stochastic optimization.

The simulations were run for one year, with a resolution of one hour, and a day-ahead forecast of 24 hours.

3.2 Description of the system modelled

3.2.1 Generation
The generation system is composed of 32 units that are dispatched among different nodes. There are 2 nuclear steam units (400 MW), 9 coal steam units (1x350 MW, 4x155 MW and 4x76 MW), 11 oil steam units (3x197 MW, 3x100 MW and 5x12 MW), 4 combustion units (4x20MW) and a hydro plant (6x50MW). All those plants have different incremental cost curves but they are all piecewise linear. Their characteristics are shown in appendix B, in Table 3 (capacity, minimum stable factor, heat rates and start-up costs) and Table 4 (type of fuel used, location, min up and down times, max ramp up and ramp down times, operation and maintenance charges).

The data is coming from the IEEE reliability system, except for the min up and down times and the ramp up and down rates that were not provided. They were taken from a European Commission JRC Institute for Energy paper [26].

The fuel costs are not up to date and were taken as given in the IEEE reliability test system. However even if this might introduce a small bias (oil is taken as three times more expensive than coal, not between 7 and 10 as it is today [27]), the system was built with those prices and it didn’t evolve since (oil plants did not shut down and were not replaced by coal plants).

Wind was also added to the system. The data was the 2013 forecast and actual generation of Ireland taken from the EirGrid website. It was scaled to the size of the IEEE reliability system.

3.2.2 Load
Using the data from the IEEE reliability test system, a load of one year was modelled, with hourly, daily, weekly and seasonal variations, as illustrated in Figures 3.1 and 3.2. We see in the weekly differences that the peak load is smaller in the week-end, and that the overall consumption is also smaller. This depicts the fact that some people are going out, some industries are closed, etc. We can also see that late in the evening the consumption is higher than during a week day, and it could show that people are staying awake later during the weekend.
The seasonal differences are also pretty interesting. We can see that in all cases the peak load is around meal time (when the oven, microwave, etc. are on). But in summer, it is around noon, which is probably a consequence of air-conditioning systems that are on during the warmest time of the day, and in winter, the peak load is at 6pm, and this is because there’s no need for air conditioning during winter but heating is necessary.

The peak load is 2850 MW, and the load is dispatched among different buses as shown in Table 5 in appendix C. The total consumption over the year is 15.3 TWh. Ireland had an electricity consumption of about 26 TWh in 2011 [28].

3.2.3 Transmission Network
The transmission network is composed of two voltage levels: 138kV and 230 kV. There are 5 transformers between the two parts of the system. Their characteristics and the characteristics of the lines are shown in Table 6 in appendix D.
3.2.4 Diagram of the Test System
The diagram of the test system is shown in Figure 3.3. The addition of the nodes in red was done in order to have dead-end nodes where it would be easier to add constraints that would allow the use of storage. If storage was added anywhere in the network, it would not necessarily be used. Difficulties had to be created to guarantee the use of storage.
3.3 Description of the ESSs modelled

Two types of ESSs were modelled. Both had the same model, shown in Figure 3.4. The idea is that there are two reservoirs and that energy is pumped from the lower reservoir to the upper one, consuming energy from the grid, and released the other way around to produce energy. The system with the two reservoirs is a closed-loop system and the efficiency appears only in the generator, i.e. more energy is inputted to the generator to pump energy than energy is outputted from the generator when energy stored in the upper reservoir is released. A distributed model, which was representing a set of flow batteries and a centralized one which was representing a pumped-hydro system were modelled. The differences between those two systems resided in the characteristics of the model: efficiency, energy stored, power output, (and of course location in the grid).

The distributed ESSs were modelled with the following characteristics: an efficiency of 80%, a power output of 20 MW and a capacity of 0.02 GWh (1 hour of storage). A difference between the pump mode and the release mode was also introduce to illustrate the fact that it takes more time to store energy than to release it. Therefore the max release of the tail reservoir was set to 10 MW whereas the max release of the head reservoir was set at 20 MW.

The centralized ESS was modelled with the following characteristics: an efficiency of 75%, a power output of 60 MW and a capacity of 0.3 GWh (5 hours of storage).

The comparison between the case with centralized storage and with distributed storage was a bit ambiguous. Indeed, how can we compare two different scenarios with different characteristics? And it was not possible to give the same power output and the same capacity to the distributed ESSs and to the centralized one. A compromise was found by modelling three distributed ESSs that together would gave the same power output (60 MW) as the centralized one, but they still had a smaller capacity.
3.4 Verification Process

In order to verify if the model of the IEEE Reliability system was working properly (i.e. not doing switch on/off of units every hours, dispatching the cheapest units first), simulations of the first month were done and the results analysed.

3.4.1 Is the load looking as expected?
The load for the first month is shown in Figure 3.5

As expected, there are variations during day and night time, and also during week days and weekend days. There are always 5 days with a peak load at about 2300 and then two weekend days with a peak load at about 2000. We also see that generation is changing slightly every week. It was also confirmed with excel that the load was exactly the same than the data inputted.

3.4.2 Which generators are scheduled?
Hydro is always online, because its fuel cost is 0. Therefore its output should be 6x50x24 kWh = 7.2GWh and that’s what we can see, as shown in Figure 3.6
However, at first, it was not always the cheapest units that were dispatched. For example, as shown in Figure 3.7, the nuclear units, which are the same, didn’t have the same generation output. This appeared to be due to transmission constraints, as when they were all removed (ideal transmission lines, i.e. no resistance or reactance and no max flow), the same units had the same production (e.g. the two nuclear generators were both set at their maximum output).

Without transmission constraints, the units were scheduled in this order:

- Hydro (max output)
- Nuclear (max output)
- Big coal plant
- Other coal plants
-Big oil plants

-Small oil plants (that were almost never scheduled)

This scheme is what we expect. If expensive units (oil plants) need to be started, bigger units will be started first because even if they have bigger start-up costs they are meant to be able to generate energy at a lower cost than small units.

3.5 Different scenarios studied

Different scenarios were studied in this project. They are shown in Figure 3.8, and commented in sections 3.5.1 and 3.5.2

3.5.1 Wind

The first big difference between those scenarios was the addition or not of wind, which could be perfectly predictable or have a certain degree of uncertainty. Then simulations were run in each of those sub-models without storage, with distributed storage near load (at a dead-end node and at the node just next to it) and near generation and with centralized storage. The uncertainty of the wind was modelled as shown in Figure 3.9, i.e. with two simulations. The first simulation was done with the wind forecast, and the unit commitment of slow units (nuclear plants and big coal units) was then inputted to a new simulation with a realized wind. Therefore fast units had to adapt to the big unit that were already committed and to the changes in the wind.
The differences between wind forecast and realized wind are shown in Figure 3.10. The wind farms generate 1270 GWh in a year for the forecast case and 1240 GWh for the realized one.

The wind penetration was about 20 %, which is quite big since the system has two nuclear plants (about 20% of the total energy produced) and is a rather small system (that doesn’t have interconnections to any other grid).
3.5.2 Different Locations for ESSs

3.5.2.1 Dead End Node
Distributed ESSs were added at the dead-end nodes in red on Figure 3.3 (page 21). The choice of dead-end nodes was motivated by the fact that difficulties had to be created in order to force the software to use storage.

3.5.2.2 Node Next to Dead-End Node
The same distributed ESSs have also been placed at buses 1, 2 and 7. Those buses are just next to the dead-end nodes of the previous case. The purpose of those two cases was to determine whether it was better to have storage at the extreme edge of the grid or close to the load but still interconnected with more than one line to the rest of the grid.

3.5.2.3 Distributed Storage near Generation
The same distributed ESSs than in the two previous cases are used. But they are located at different buses close to generation: bus 13 (3x197 MW Oil plant), bus 15 (155 MW Coal plant and 5 x12 MW Oil plant) and bus 24 (2x155 MW Coal plant and 350 MW Coal plant).

3.5.2.4 Centralized Storage
The centralized storage was located at bus 17. This bus was chosen because it has connections to the low voltage grid, to the nuclear plants and to a coal plant. It also doesn’t have any generation or load on it, which is quite coherent with the fact that a pumped-hydro system is in the mountains, far from the load and from the generation units.

4 Results

4.1 How is storage used?

Storage is used to provide energy arbitrage (see 2.2.3), i.e. storing energy during low price periods and restoring it during high price periods. As shown in Figure 4.1, the highest load period, which is also the highest price period, depends on the season. It is in the morning for both summer and spring, and in the evening in winter. We also expect energy to be stored at around 4 hours in the morning in all seasons.
The flows of the upper reservoir of an ESS for one year are shown in Figure 4.2. We see that energy is mostly stored between 23 pm and 3 am and released between 8 am and 12 am. This is not exactly what we expected but the reason is simple, when there is no wind the price is really stable, low during night and high during the day, as shown in Figure 4.3. Therefore it doesn’t reduce dramatically the cost if energy is stored at 3 am or 4 am.
We can see an illustration of those flows in Figure 4.4. It’s the lower reservoir of a distributed ESS in the scenario without wind.

There are two interesting thing to note. Energy is stored during time of off peak demand (in orange, the release of the down reservoir) and released during time of peak price period (in blue, inflow of the down reservoir). The other interesting thing is that the release occurs with a doubled output and over a shorter time period, reflecting the doubled power output given to the upper reservoir.

However, in the case with the wind, the price is evolving completely differently. We show on Figure 4.5 the inflow and release of the upper reservoir of a distributed ESS and the cost in the case of the uncertain wind scenario.
We can see that the release of the generator doesn’t always occur at the highest price. However, storage is now not only used for energy arbitrage, but also to integrate the big amount of relatively uncertain wind generation. We can see this in Figure 4.6 where the wind generation was plotted with the inflow and release of the upper reservoir of an ESS.

We clearly see that the release of the reservoir corresponds sometimes to drops in the wind generation.

Another interesting point is the net revenues of the ESSs. They also reflect this process of storing and releasing energy. As shown in Figure 4.7, there is negative revenue for the generator when it’s storing energy (from the grid point of view, it’s like the generator is consuming energy, acting like a
load), and a positive revenue when it’s releasing energy, acting like a “normal” generator. We also see that the positive revenues are bigger than the negative, and the ESS is therefore earning money. We plotted it here with the inflow and release of the upper reservoir to show how this was linked.

Figure 9 Generator net revenues, inflow and release of its upper reservoir. Non-ideal wind scenario with distributed ESS at dead-end node

4.2 Savings Realized by the Load

The savings realized by the load in the three scenarios are shown in part 4.2.1 (no wind), 4.2.2 (ideal forecast) and 4.2.3 (non-ideal forecast). Those savings were calculated as follows:

\[ \text{Savings} = \text{Cost to the load without storage} - \text{Cost to the load with storage} \]

4.2.1 No Wind

Figure 4.8 Savings Realized by the Load in the Scenario with no Wind
The first thing that strikes us when looking at Figure 4.8 is that even though all the distributed storage are allowing savings to the load, the centralized one leads to an increase in the cost of about 500,000$. This seems to be due to the fact that the load has to pay for an additional unit on the system that is not able to survive by itself (the generator has a negative net revenue).

We also see that the distributed case near generation doesn’t allow great savings (apparently because it’s far from the load, therefore it can’t really act on it).

The best case is the distributed storage next to load. Not at the dead-end node (extreme edge of the grid) but at the bus just next to it. This may have two reasons: the first one is that the ESSs maybe need more than just one connection to the rest of the grid in order to be fully operational, and the second reason could be that because there are also small loads at the buses next to the dead-end nodes, the ESSs are able to “work” for both loads (the one at the dead-end and the one on the bus next to it), allowing a better optimization.

### 4.2.2 Wind with Ideal Forecast

![Savings Realized with Ideal Forecast](image)

The introduction of wind has allowed the centralized case to also perform savings for the load. However, they are still below the one realized in the three distributed cases, which are all allowing greater savings than in the scenario without wind. We also note that the distributed ESSs near generation are now almost as performant as the two other ones. This is mainly due to the fact that they are placed close to wind farms, and therefore have a big optimization potential due to the variability and the uncertainty of the wind.
4.2.3 Uncertain Wind

In this case, the centralized ESS is generating much more than the three other storage systems, because of its bigger capacity. Therefore, to reduce the bias discussed in section 3.3, we can divide all results by the generation of each unit in order to obtain Figure 4.11. The results show that the distributed ESSs near the load are still the most profitable, and therefore an addition of a lot of those distributed ESS would me more profitable than the centralized case.

However, the fact that the big capacity is now allowing the biggest savings informs us of the importance of a big volume to integrate renewables to the grid. This is especially the case in our system with a big nuclear generation (slow units) and no connection to other systems (no
opportunity to import or export energy). The storage units have a big role to play, as a load when the
wind generation is big and as a generator when it’s low. Figure 4.12 show how the centralized PHS
helps in the integration of wind. We can see that when the wind farms are generating a lot, the PHS
stores energy, and when the wind drops the PHS releases this energy.

![Figure 4.12 Inflow and Release of the centralized ESS and wind generation of one of the 4 wind farms](image)

4.2.4 Conclusion Cost to Load

In the scenario without wind, the savings were the biggest in the case of the distributed ESSs next to
the dead-end nodes, and were representing 1.7% of the total cost without storage (about 7 M$). The
centralized ESS by contrast increased the cost paid by the load by 1.3% (about 5.5M$). The
introduction of a perfectly predictable wind allowed the ESSs to increase their performance, and the
most profitable ones were again the distributed ESSs near the dead-end nodes with savings of 2.2 % of
the total cost (8M$). Finally, the introduction of an uncertain wind has showed the importance of a
big storage capacity in order to reduce the cost paid by the load. The biggest savings were realized by
the ESS with the biggest capacity, i.e. the centralized one with savings of 2.5 % of the total cost
(about 9.25 M$). However, the savings per GWh generated were higher in the case of the distributed
ESSs near the dead-end nodes.
4.3 Generators Net Revenues

4.3.1 No Wind

We see in Figure 4.13 that the generator net revenues are all smaller with storage than without. One possible explanation is that storage reduces the price (the MW provided by the storage units are “free” MW and therefore the overall price is reduced), and so all generators see their pool revenue decrease. The peak unit has also its generation reduced.

4.3.2 Wind with Ideal Forecast

Figure 4.13 Generator net revenues in the scenario without wind Mind the scale

Figure 4.14 Generator net revenues in the scenario with predictable wind Mind the scale
The generators have increased a lot their revenue. This is due to the fact that the wind generation has a zero cost. Therefore its net revenue is just its income and it’s lifting the generators total revenues up. The conventional generators have however seen their net revenues reduced.

We also see that, as in the case without wind, the introduction of storage is reducing the generator net revenues, probably for the same reasons.

4.3.3 Uncertain Wind

![Figure 4.15 Generator net revenues in the scenario with uncertain wind](Mind the scale)

With the uncertainty of the wind, the distributed ESSs near the load are not reducing the revenues of the generators. However, even if the reduction is smaller, the distributed ESSs near generation and the centralized one are still reducing the generators net revenues.

4.3.4 Conclusion Generator Net Revenues

We’ve seen that storage tends to reduce the generator revenues. When there is no wind, the loss is included between 2.2% (distributed near load) and 12.6% (distributed near generation) of the total revenues when there’s no storage. When wind with an ideal forecast is added, the generators revenues are also dropping with storage, but this time the interval is much narrower: between 2.5% (centralized storage) and 6.5% (distributed near generation) of the total revenues. However, when the wind forecast is not perfect, the loss is reduced to zero in the distributed cases near the load and is greatly reduced in the case of the ESS near the generation. The reduction of revenues is still big in the case of the centralized ESS, with a loss of about 10% of the generator revenues.
4.4 Storage Net Revenues

4.4.1 No Wind

The revenues of the ESSs are all positive, except in the case of the centralized ESS. The fact that all the distributed ESSs have positive revenues can be explained by the fact that they earn money by arbitrage. So how does it come that the centralized doesn’t earn anything? As shown in Figure 4.17, Plexos doesn’t use the centralized ESS only for arbitrage. Because of its big size, Plexos uses it as generator when the demand is low and as a load when it is high. It may seem strange, but maybe it allows avoiding turning on an expensive unit, and therefore saves money. In the end this is what we expect from a centralized unit: performing system improvements rather than local ones. The fact that the centralized storage is not used as the distributed ones shows this difference. This is coherent with what we’ve seen in part 4.2.3, where the centralized ESS was helping to the integration of the wind, which is a system improvement.

Figure 4.16 ESSs revenues in the scenario without Wind

Figure 4.17 Inflow and release of the upper reservoir of the centralized ESS in the case without wind
4.4.2 Wind with Ideal Forecast

When ideal wind is added, the revenues of the distributed ESSs increase a little bit. This is due to the fact that the price differential is bigger (when there’s a lot of wind during low demand period the price is really low and when there’s no wind during high demand period the price is really high), and therefore energy arbitrage allows more earnings. The centralized ESS has now a positive income, which is however still low compared to the other one. It is also helping to the integration of wind.

4.4.3 Uncertain Wind

Revenues of the ESSs have increased again, and once more it’s because of an increase in the price differential. The centralized ESS has however decreased its income. This inconstancy in the results also shows us that it is performing larger-scale operation (i.e. Plexos is not trying to maximise its profits but is using the centralized ESS to improve the total system).
4.4.4 Conclusion ESSs Revenues
We’ve seen that all the distributed ESSs were earning money through arbitrage. Those revenues were increasing with the price differential, which was increasing when ideal and non-ideal predictable wind was added to the system. The centralized ESS however didn’t have any big revenues. This might be due to the fact that it is not performing energy arbitrage but it is used to help the whole grid.

4.5 Variation of the Characteristics of ESSs
The distributed ESSs at the dead end nodes were modified in order to examine the effect of their parameters. The different modifications were the following: doubled power output, doubled capacity and increased efficiency (from 80% to 90%).

![Savings Realized by the Load](image)

**Figure 4.20 Savings realized by the load in the distributed ESS at dead-end node case**

We see in Figure 4.20 that the savings realized by the load are greatly increased by the amelioration of the efficiency and by a bigger power output. The doubled capacity also improves the savings but in a lesser significant way. However, this must be the easiest thing to improve in flow batteries, as the storage tanks simply need to be extended (see 2.3.1.5). This also doubles the revenues of the ESS. Indeed, the energy stored is doubled and therefore twice as much money as in the normal case can be earned from arbitrage.
4.6 How to be sure that storage is responsible for the cost reduction

Apart from the fact that storage is the only thing which is changing between the different cases, we can also see that those reductions in price are made at hours when the storage generator is working, strongly relating those two variables. The correlation was calculated as follow:

\[ Corr = \frac{\sum(x_i - \overline{x}) \cdot (y_i - \overline{y})}{\sqrt{\sum(x_i - \overline{x})^2} \cdot \sqrt{\sum(y_i - \overline{y})^2}} \]

Where x and y are the two variables, i.e. the flows in the reservoir (shown in Figure 4.22) and the savings realized (shown in Figure 4.23)

The correlation coefficient found was 0.83, which implies a strong correlation between the two variables.

Of course correlation doesn’t imply causality, but as the only difference between the scenarios is the addition of storage, we can assume that storage is the source of the savings.
The negative flows correspond to inflows and the positive flows correspond to release. We can see that energy is stored at night and released during the day. Note that the sum of the inflow and release is zero, which is reflecting the nature of the closed loop system formed by the two reservoirs (see Figure 3.4).

4.7 Downsides of storage
4.7.1 Peak Units
Some peak units are not used anymore due to the introduction of storage, but they still could be needed in case of failure of another plant in the system.

We can see in Figure 4.24 that in the case without storage, this unit is generating only at the peak load, once in a year. But the addition of storage has the result that the unit is not used anymore, as shown in Figure 4.25.

![Figure 4.24 Peak plant generation in the case without storage](image1)

![Figure 4.25 Peak plant generation in the case with storage](image2)

The fact that a plant is not used anymore would lead to its shut down. We could argue that this is the law of the market and that if a unit is too expensive than it has to be replaced by a cheaper competitor. Nonetheless, storage cannot produce energy, and in case of a failure somewhere in the system, this peaking unit might be needed. Therefore, to keep it in the market, capacity payments should be provided. The question arising now is, is it really profitable to add storage if it leads to an increase in capacity payments. And the answer is: it depends if those capacity payments are lower than the savings realized by storage.
4.7.2 CO2 Emissions

Another effect of storage is the increase in CO2 emissions. In the test system with no wind, as hydro is always constant and at max output, the only remaining sources are coal, oil and nuclear plants. So a decrease in nuclear generation implies an increase in coal and oil generation and therefore an increase in CO2 emissions.

Figure 4.26 shows the decrease in nuclear generation in the scenario without wind.

![Figure 4.26 Generation of the nuclear plants over one year. Mind the scale](image)

We can see that the decrease in nuclear (i.e. the increase in coal and oil generation) is about 6.05 GWh. This is only a little fraction of the total generation (15.3TWh), but this is still the equivalent to the annual greenhouse gas emissions from almost 900 passenger vehicles [29]. Although it might seems very small, it’s not negligible, especially for country that are struggling to reach the Kyoto Protocol requirements.
5 Conclusion

This project has shown that the addition of storage to the test system was profitable for the load which was able to save money. Distributed energy storage systems near dead-end nodes but still interconnected to the rest of the network were able to provide the best savings (1.7% of the total cost paid by the load). However when a big amount of uncertain wind generation was added, the centralized ESS was providing the best savings because of its high capacity and because it was not only doing energy arbitrage. The parameters of the distributed ESSs were also studied and it appeared that the best way to improve the load savings was to improve the efficiency of the storage devices. However, it is in practice nearly impossible to do and an increased capacity, even if it didn’t greatly improved the savings in the cost paid by the load was significantly increasing the revenues of the ESSs.

However, some downsides have also arisen. The generation revenues were reduced (up to 10%) by the addition of storage. ESSs also introduced an increase in the use of coal and oil plants over nuclear, which led to an increase in CO2 emissions. Storage also forced some peaking units to shut down.

We’ve seen that the location of the storage systems strongly influence the application they are providing. In the case of the distributed units, energy arbitrage and a bit of peak shaving were providing but the centralized ESS was also helping to the integration of renewable energy.

6 Future work

The modelling of a real system with real characteristics (reserves constraints, electricity market, a smaller resolution of the simulation, a longer day-ahead forecast, and generator outage) should be undertaken to see if the same phenomenon would be observed in a tangible case. The precision of the storage model should also be increased (addition of constraints like ramp up and down rates, self-discharge) to allow different applications (frequency control, etc.). Different ESS should also be modelled.

A further analysis including the capital costs of the storage systems will also have to be undertaken to determine if the ESSs are economically viable for the people who invest in it.

When it comes to the integration of renewables, storage should also be rigorously compared to some alternatives like curtailment or interconnections with bigger networks.

Another point that will have to be taken into account is the energetic cost of production and operation of the ESSs. A recent study of Stanford University has shown that the overall energetic cost of batteries was not compensated by the energy saved from curtailment in the case of wind farms [30 & 31].
7 References


[2] European Commission website


http://unfccc.int/essential_background/kyoto_protocol/items/1678.php


[14] ESB Website
http://www.esb.ie/main/about-esb/ardnacrusha.jsp

[15] Grande-Dixence Dam Website
http://www.grande-dixence.ch/

[16] China Three Gorges Corporation Website
http://www.ctgpc.com/


[24] Copyright Solar Millenium AG


[28] Central Intelligence Agency, the World Factbook about Ireland,


[29] U.S. Environmental Protection Agency, Greenhouse Gas Equivalencies Calculator

http://www.epa.gov/cleanenergy/energy-resources/calculator.html#results


http://www.altenergystocks.com/archives/2013/09/clarifying_the_confusion_storage_and_cost_effectiveness.html
## A. Important Results

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B. Generator Properties

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## C. Load Distribution

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<td>Bus21</td>
<td>Bus22</td>
<td>500</td>
<td>0.0087</td>
<td>0.678</td>
</tr>
</tbody>
</table>

**Wind1to20**  
WindNode    Bus20    500    0.0087    0.678