

# Benefit Analysis of Wind Energy Storage by Time Shift Simulation

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**Abstract.** Currently there exist several energy storage technologies that are suitable for wind energy integration services. Energy prices in several countries (such as in Spain) are set for the day ahead market, which means the hourly prices are known the day before. This represents an opportunity for wind power plant owners. Wind energy generated in hours when demand and prices are the lowest could be stored and sold in hours when demand and prices are higher. This paper analyses the benefit of wind energy storage by time shift depending on climatological (wind), technological (storage facilities), and market (power prices) factors for the Spanish case, as exemplification of a methodology to be used in any other country. Wind energy time shift has been simulated for periods of time of 1 hour up to 9 hours considering two scenarios, a day with low wind energy generation and a day with high wind generation, in order to determine in which moments a beneficial exists with the different energy storage technologies. According to the results, on a day with high wind energy levels the gain obtained by time shifting wind energy from low to high demand hours could reach 68,1%, and on a day with low wind energy levels, the gain obtained by time shifting wind energy could reach 19,3%.

## Introduction

Currently there exist several energy storage technologies that are suitable for wind energy integration services. Energy storage can make wind energy more reliable and economically more attractive in an environmentally responsible way. Through the strategic utilization of storage, the use of renewable energy, and more specifically the use of wind energy, can in fact be improved.

The energy storage applications depend on the operational requirements and the duration and frequency of discharge. Possible value streams of energy storage include flexible capacity, energy arbitrage, system balancing and ancillary services, congestion management, renewable time shifting, forecast hedging, emissions and power quality. Energy storage allows for the improved management of energy supply and demand and can provide multiple valuable energy and power sources.

The relation between wind energy and demand curve is also very important. Wind is more similar to load than to conventional generation: wind and most loads are non-dispatchable resources, they have cycling behaviour, and they depend on weather conditions and sometimes deviate from the forecast. Energy storage can also be used to mitigate wind power curtailment.

In several counties the price of electricity (€/MWh) is lower when demand is lower which gives an opportunity for economic benefits by storing wind energy when demand is low and selling it during peak demand when prices are higher. This is the case in Spain, whose power system (wind power and electricity demand) is used to exemplify this methodological proposal.

The study is based on the technical characteristics and performance parameters, system costs, benefits and drawbacks, environmental impact, and commercial status of pumped hydro storage, compressed air energy storage, hydrogen fuel cell storage systems, flywheel energy storage systems and batteries and ultracapacitors. Also several battery energy storage technologies including lead acid, nickel cadmium, nickel metal hydride, lithium-ion, sodium sulphur, vanadium redox flow, zinc bromide, zinc chlorine, iron redox, sodium nickel chloride and nickel iron are considered.

This paper is also based on a previous work of the authors [1] that analysed in detail the power rating, discharge time, energy and power density, efficiency, life time and cycle life, environmental impact and capital cost of the energy storage technologies, as well as the technical and economic suitability of the different energy storage technologies for certain services and applications based on their specific technical requirements.

With this base, the time shift of 1 MWh of energy storage for a duration of 1 to 9 hours has been simulated using energy storage technologies. According to the results, on a day with high wind energy levels the gain obtained by time shifting wind energy from low to high demand hours could reach 68,1%. On a day with low wind energy levels, the gain obtained by time shifting wind energy could reach 19,3%.

Thus, as a summary, the paper analyses the benefit of wind energy storage by time shift depending on climatological (wind), technological (storage facilities), and market (power prices) factors for the Spanish case, as a methodology to be used in any other case. The particularities of wind generation and wind energy grid integration are analysed in section 1. Section 2 is devoted to Energy Storage, presenting a brief Energy Storage Technology Overview and analysing the Characteristics of the energy storage systems. In section 3 wind energy time shift has been simulated considering two scenarios, a day with low wind energy generation and a day with high wind generation, in order to determine in which moments a benefit can be achieved with the different energy storage technologies. Finally section 4 summarizes the conclusions of the simulation-based analysis.

## 1 Wind Energy

Wind energy is expected to be the cornerstone and driving force for the immediate application of a world energy system driven by renewable energy to completely substitute fossil and nuclear sources [2]. This work, through summarization of a research on optimally harnessing wind energy by means of energy storage, demonstrates that indeed wind energy is a front-runner in the process of clean energy transformation.

### 1.1 Wind energy generation

Wind energy is considered as a clean and competitive renewable energy resource. In developing countries, wind energy has already a significant share in the energy mix. In developing and emerging countries, wind energy is one of the main focus in the efforts made to respond to climate change and diversify the energy mix.

Wind power is one of the most popular and fast expanding sources of renewable energy; the worldwide installed wind capacity is expected to reach 631 GW (602 GW onshore) by 2020 according to [3]. Spain is one of the five traditional wind countries together with China, USA, Germany and India representing a 72% share of the global wind capacity. In fact, the total capacity installed in Spain by 2016 was 23 057 MW [4].

### 1.2 Wind energy integration

Wind energy is intermittent and weather and location dependent. These characteristics of wind energy create challenges for wind integration in power systems.

Wind speed is not constant, making electricity output uncontrollable. Electricity output variations are not perceptible in the range of seconds to minutes. In one day, however, the cumulative wind energy production at country level can ramp from near maximum to near zero and vice versa. This translates in additional energy required to match supply and demand immediately.

Wind resource is partially unpredictable. For the grid, this means maintaining reserves for additional power when wind energy generation produces less than expected. Dispatchable loads must also be available at times when wind generation produces in excess.

Another characteristic of wind energy is that generation must be located where the best wind resources are. These locations are often far from the places where the power will be consumed. Connecting wind power to the grid requires most times new transmission capacity.

Wind power variability and the impacts that it has on power systems have been studied in [5], which states that wind power integration impacts on power systems depend on the level of flexibility the systems have and on the wind penetration level. The general impacts identified in this study are generation efficiency (it affects other conventional generation units), necessity for back-up reserves, curtailed wind energy, reliability, transmission and distribution losses and voltage and reactive power.

In [6], the authors studied the potential challenges of integrating wind energy in power systems focusing on social impacts, economic impacts, environmental impacts and technical impacts.

Power systems that take in large amounts of wind power need to be flexible to deal with the variability and uncertainty. The needed flexibility could be achieved with grid friendly wind energy generation, improved flexibility in conventional generation, transmission expansion, operational enhancement and demand response. Energy storage can be an important player in adding flexibility as it can act both as generation and load [7-9].

## 2 Energy Storage

### 2.1 Energy storage technology overview

One of the characteristics of electricity is that it cannot be stored directly, requiring continuously balancing with the demand, this resulting in costly implications. Sufficient generating capacity is required to match the highest demand level, even though the capacity increment is only needed for short periods of time and infrequently [10, 11].

Also, due to the inability to store electricity, reserve generating capacity must be maintained available as spinning or non-spinning reserves for potential changes in the load or the unplanned loss of a generation plant [10].

Although it is not possible to store electricity directly, it can be converted to other forms of energy that can be stored. The stored energy is converted to electricity when needed. Energy storage is a fundamental intermediary between variable energy generation sources and variable loads. Without it, energy generation is forced to equal consumption. The greatest advantage of energy storage is that it is capable of moving energy through time.

From the electrical system standpoint, the energy storage systems act as loads during storage and as sources of electricity when returning energy to the system [10]. Electrical energy can be stored in energy forms such as mechanical, chemical and electro-chemical, electromagnetic, and thermal (this one not interesting for this study) [12,10]:

i. Mechanical energy storage. Mechanical energy storage technologies are pumped hydroelectric storage (PHS) [13], compressed air energy storage (CAES) and flywheel energy storage. In PHS the energy is stored as potential gravitational energy while in CAES, the energy is stored as potential pressure energy. Flywheel energy storage consists of storing energy in the form of rotational kinetic energy. PHS and CAES are considered technologies suited for energy management whereas flywheels are more suitable for power applications.

ii. Chemical energy storage. Hydrogen energy storage is a chemical storage technology. Hydrogen is used as an energy carrier for electricity storage through a process such as electrolysis [14].

iii. Electrochemical energy storage. Electrochemical energy storage technologies convert electricity in chemical energy during charging. Batteries are considered electrochemical energy storage systems. Power converter interfaces for electrochemical energy storage systems have been reviewed in [15]. Innovation in electrochemical energy storage technologies has been monitored in [16].

iv. Electrical field storage. Capacitors are considered electrical field storage systems. Capacitors consist

of two electrical conductors separated by a dielectric material (non-conducting). The electric field is created when applying voltage across the conductors causing opposite electrical charges build up on the conductors. The surface area of the conductors and the distance between them determined the capability of energy storage. In general capacitors consist of two plates separated by a thin dielectric. The capacitors can be electrostatic, electrolytic and electrochemical. The difference between electrostatic and electrolytic capacitors is that the electrolytic uses a liquid electrolyte as one of the plates.

v. Magnetic energy storage. This form of energy storage consists in storing energy in a magnetic field. The flow of direct current in a super-cooled coil creates a magnetic field capable of storing energy. Superconducting magnetic energy storage (SMES) is an example of magnetic field storage technology. In SMES, the magnetic energy can be stored indefinitely once the superconducting coil is charged. Cryogenic refrigeration is required to maintain the magnetic coil so cool as to have superconducting properties [10, 14].

### 2.2 Characteristics of energy storage systems

The potential of energy storage technologies for the demands of different applications is determined by their characteristics. This subsection defines classical properties according to the existing literature.

The characteristics of energy storage technologies such as discharge duration, power rating, energy storage capacity, response time and costs in the context of benefits determine the applications they are most suited for. The criteria for the selection of energy storage technology are divided into 4 aspects [1]:

- Design: Power rating, Storage capacity, Discharge duration, Response time, Energy density per unit area, Energy density per unit volume, Technology maturity, Reliability, Modularity, Siting requirements, Portability, Synergies with other energy applications.
- Operation: Overall cycle, Efficiency, Lifetime/maximum number of charge-discharge cycles, Parasitic losses.
- Financial: Capital cost per energy stored, Capital cost per power rating, cost for Fixed O&M, Variable O&M, Replacement, Disposal, and Commercial risk.
- Other aspects: Health and safety aspects, Environmental impacts, Synergies with other sectors.

The ideal characteristics of storage technologies would be low capital and low operating and maintenance cost, have a long life and high efficiency, be flexible in operation and have a fast response and be environmentally friendly. The main characteristics for choosing energy storage have been defined in [17] and [10].

### 3 Wind Energy Time Shift Simulation

The problem with renewable generation is that it often does not match demand. Peak demand and renewable generation typically occur at different times in the day and year. Renewable energy generation is also dependent on weather and geographic conditions. When generation exceeds the need for serving load, energy storage could be used to store energy for times when generation is not enough to serve the load. Storage helps removing time specific constraints [10].

Energy prices in Spain are set for the Day Ahead Market (DAM), which means the hourly prices are known the day before. This represents an opportunity for wind power plant owners [4, 5, 6]. Wind energy generated in hours when demand and prices are the lowest could be stored and sold in hours when demand and prices are higher. Wind energy time shift has been simulated considering two scenarios, a day with low wind energy generation and a day with high wind generation. The level of wind energy generation influences energy prices. When wind energy generation levels are high, the prices are lower and vice versa.

The low wind day selected for the time shift simulation is May 19, 2015 (see Figure 1). The lowest hourly price registered was 34.40 €/MWh between 4:00 and 5:00 am. The day with high wind energy generation levels selected for the wind energy time shift simulation is May 05, 2015 (see Figure 2). On the day with high wind energy generation levels, the minimum price registered during low demand hours was 14.95 €/MWh (between 3:00 and 4:00 am) while the highest price was 62 €/MWh (between 21:00 and 22:00 pm).

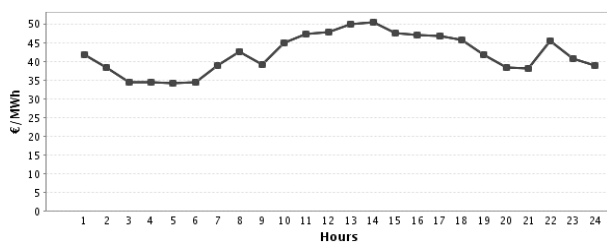


Figure 1. Hourly marginal prices in Spain and Portugal (case of day with low wind, 19/05/2015).

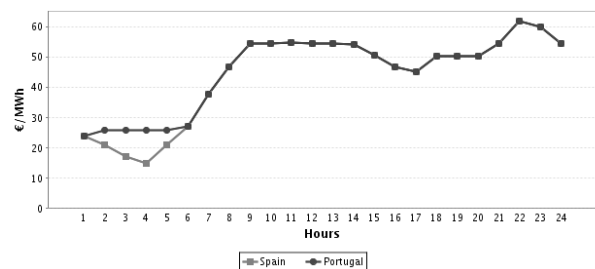


Figure 2. Hourly marginal prices in Spain and Portugal (case of day with high wind, 05/05/2015).

The energy storage technologies considered in the simulation are CAES, PHS, Hydrogen Fuel Cell Storage Systems (HFCSS), Lead Acid (LA) batteries, NiCd batteries, Li-ion batteries, NaS batteries, Vanadium Redox Battery (VRB), Zinc–Bromine flow Batteries (ZBB) and Zero Emissions Batteries Research Activity (ZEBRA) batteries. Flywheel Energy Storage (FES) systems and ultracapacitors (UC) have been discarded due to their short duration storage (below 1 hour) and high self-discharge rates (hourly self discharge of FES is higher than 20%).

Based on the findings in the existing literature regarding energy storage system (ESS) cost, round trip efficiency (RTE), storage duration and self discharge, the following assumption were made (see Table 1), obtained from a deep analysis developed in [1].

These technical characteristics of the energy storage systems will for sure improve with the advance of the technology, but the methodology presented in this paper will be still valid, just adapting the study with the new values. The technical and economic feasibility of storing 1 MWh of wind energy for several hours has been studied. The economic merit of time shift consists in the difference between energy purchase cost, store and discharge energy cost.

#### 3.1 High wind day scenario

The time shift of 1 MWh of wind energy for one or several hours has been made considering the hourly prices registered on May 05, 2015. The lowest price per MWh on that day was registered at 3:00 am. The price escalated continuously until 10:00 am when it reached 55.08 €/MWh. The gain achieved by time shifting 1 MWh of wind energy for up to 7 hours using different energy storage technologies can be seen in Table 2, where it can be seen that the difference between the lowest price and the highest price goes from 29% up to 73%.

ESS	RTE	Cost (€/MWh)	Self-discharge (%/hour)	Storage duration
CAES	71%	0,05	0%	2-50 h
PHS	75%	0,3	0%	h-days
HFCSS	40%	0,01	0%	h-days
FES	90%	3	20%	<1h
LA	80%	0,35	0,01%	min-days
Ni-Cd	85%	1,5	0,02%	1-8h
Li-ion	90%	2,5	0,17%	m-days
NaS	85%	0,45	0	10 h
VRB	75%	1	0,42%	s-12h
ZBB	75%	0,5	0,00%	h-months
ZEBRA	85%	0,65	0,63%	hours
UC	95%	10	0,83%	ms-1h

Table 1: Assumptions regarding the energy storage technologies considered in the time shift simulation.

Hour of the day	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11
€/MWh	14,95	21,00	27,13	37,7	47,02	54,6	54,74	55,08
Hours of storage	0	1	2	3	4	5	6	7
CAES		-0,5	22,2	44,1	55,2	61,4	61,5	61,7
PHS		3,7	25,7	46,7	57,3	63,3	63,4	63,6
HFCSS		-78,1	-37,8	0,8	20,5	31,5	31,7	32,1
LA		9,5	30,2	50,0	59,9	65,5	65,6	65,8
Ni-Cd		9,8	31,3	51,4	61,3	66,9	66,9	67,1
Li-ion		9,9	32,2	52,5	62,4	67,9	67,9	68,1
NaS		14,4	34,1	52,8	62,2	67,5	67,6	67,8
VRB		-0,4	22,9	45,0	56,0	62,2	62,1	62,2
ZBB		2,8	25,1	46,4	57,2	63,2	63,2	63,5
ZEBRA		12,6	32,5	51,6	61,2	66,6	66,4	66,4

**Table 2:** Time shift simulation results for high wind day scenario in time period 03h-11h (in %).

The following conclusions can be drawn regarding the energy price and time of storage (Table 2):

- Time shifting 1 MWh of wind energy for 1 hour reported economical gain with all the energy storage technologies except for CAES, HFCSS and VRB due to low RTE efficiencies or higher cost of the storage system. An important factor influencing the gain is the considerable energy price difference (29% higher).
- After 2 hours of storage and an increase of energy price of 45%, only the time shift with HFCSS does not provide gain. This is due to the low round trip efficiency of the system (40%). During the following hours, all the energy storage technologies used for time shift report benefits.
- The energy price difference increases significantly over the 7 hours: 45% (3 hours); 68% (4 hours), 73% (5, 6 and 7 hours). The gain obtained by time shifting 1 MWh of wind energy increases as the energy price increases. The highest gain is obtained with the Li-ion battery energy storage reaching 68,1%.
- Between 16:00 and 17:00 pm on the same day (May 05,2015, energy price was 45.25€/MWh and it reached 62 €/MWh at 21:00 pm. A time shift simulation was made given the considerable price difference.

In Table 3 it can be seen that the energy price difference is much lower compared to the first time period simulated. The price is steady for the first three hours with a difference of 10% compared to the lowest price. The fourth hour the difference reached 17% while the fifth hour the difference is 27%. As it can be seen, the price difference is not enough for the first three hours to produce economical gain by time shifting 1 MWh of wind energy.

Only Li-ion and NaS battery produce economical gain with an energy price difference of 17%. This is due to their high round trip efficiencies.

With an energy price difference of 27%, except for CAES, HFCSS and VRB, time shifting 1 MWh of wind energy with the rest of energy storage technologies provides economic benefit. The highest gain is achieved with Li-ion battery energy storage.

### 3.2 Low wind day scenario

Time shifting of 1 MWh of wind energy has been simulated for a day with low wind energy. The low wind day chosen is May 19, 2015. Energy prices are higher, and the energy price difference registered in this day with low wind is considerably smaller (32%) compared to the difference registered in the high wind day (73%).

The lowest energy price registered on May 19, 2015 was at 5:00 am while the highest was registered 9 hours later at 13:00 pm. The gain achieved by time shifting 1 MWh of wind energy for up to 9 hours using different energy storage technologies can be seen in Table 4.

From the results it can be seen that time shift does not report benefit with any of the energy storage technologies with small energy price differences (1% to 12%). When energy price increases by 19% (3 hours), time shifting with NiCd, Li-ion, NaS and ZEBRA batteries produces economic benefit. NiCd batteries have maximum storage duration of 8 hours. Time shift with HFCSS does not report benefits at all due to the very low round trip efficiency.

Hour of the day	16-17	17-18	18-19	19-20	20-21	21-22
€/MWh	45,25	50,50	50,5	50,5	54,74	62,00
Hours of storage	0	1	2	3	4	5
CAES		-26,3	-26,3	-26,3	-16,5	-2,9
PHS		-20,2	-20,2	-20,2	-10,8	2,2
HFCSS		-124,1	-124,1	-124,1	-106,7	-82,5
LA		-12,8	-12,8	-12,8	-4,0	8,2
Ni-Cd		-8,7	-8,7	-8,7	-0,1	11,9
Li-ion		-4,9	-5,1	-5,2	3,3	15
NaS		-6,4	-6,4	-6,4	1,9	13,5
VRB		-22,4	-22,8	-23,1	-13,6	-0,5
ZBB		-20,7	-20,7	-20,7	-11,2	1,9
ZEBRA		-7,4	-7,9	-8,4	-0,2	11,2

**Table 3:** Time shift simulation results for high wind day scenario in time period 16h-22h (in %).

Hour of the day	05-06	06-07	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15
€/MWh	34,4	34,60	39	42,71	39,21	45,1	47,4	48	50,2	50,6
Hours of storage	0	1	2	3	4	5	6	7	8	9
CAES		-40,2	-24,4	-13,6	-23,7	-7,5	-2,3	-1,0	3,4	4,2
PHS		-33,7	-18,5	-8,2	-17,9	-2,4	2,6	3,8	8,1	8,8
HFCSS		-48	-120	-101	-119	-90,7	-81,5	-79,2	-71,3	-70,0
LA		-25,6	-11,3	-1,5	-10,7	3,9	8,6	9,7	13,7	14,4
Ni-Cd		-22,3	-8,0	1,7	-7,4	7,1	11,7	12,8	16,8	
Li-ion		-19,3	-5,1	4,4	-4,9	9,5	14,0	14,9	18,7	19,3
NaS		-18,5	-5,0	4,2	-4,4	9,4	13,8	14,9	18,7	19,3
VRB		-37,1	-21,7	-11,4	-22,1	-6,3	-1,4	-0,6	3,5	3,8
ZBB		-34,5	-19,1	-8,7	-18,5	-2,8	2,2	3,4	7,7	8,4
ZEBRA		-20,0	-6,9	1,9	-7,7	6,0	10,0	10,6	14,0	14,1

**Table 4:** Time shift simulation results for low wind day scenario in time period 05h-15h (in %).

## 4 Results

After simulating the time shift of 1 MWh wind energy for periods of time of 1 hour up to 9 hours in a low wind day scenario and a high wind day scenario using several energy storage technologies including CAES, PHS, HFCSS, LA, Ni-Cd, Li-ion, NaS, VRB, ZBB and ZEBRA batteries, the following can be concluded:

- i) In the scenario with high wind energy levels, time shift with energy storage reported gains up to 68,1%.
- ii) In the scenario with low wind energy, time shift with energy storage reported gains up to 19,3%.
- iii) All the selected storage technologies are technically suitable for this service in terms of storage duration and selfdischarge. Ni-Cd has storage duration up to 8 hours. The hourly selfdischarge of the batteries is not significant; however it affects the possible gain when energy is stored for several hours.
- iv) Energy price is the most important factor in terms of benefit. The difference between the energy price during low demand and the energy price during high demand hours determines the economic feasibility of the time shift service.
- v) The efficiency and cost of the energy storage system are very important. Low energy efficiency and high system costs affect the possible gain that can be obtained with time shift. When energy price variation in time is low, low round trip efficiencies and high storage system costs make this service economically unfeasible.

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