A review of energy storage technologies for large scale photovoltaic power plants

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Abstract

Energy storage can play an essential role in large scale photovoltaic power plants for complying with the current and future standards (grid codes) or for providing market oriented services. But not all the energy storage technologies are valid for all these services. So, this review article analyses the most suitable energy storage technologies that can be used to provide the different services in large scale photovoltaic power plants. For this purpose, this article first summarizes the different characteristics of the energy storage technologies. Then, it reviews the grid services large scale photovoltaic power plants must or can provide together with the energy storage requirements. With this information, together with the analysis of the energy storage technologies characteristics, a discussion of the most suitable technologies is performed. In addition, this review also discusses how to locate the energy storage within the photovoltaic power plant. The results show that i) the current grid codes require high power - medium energy storage, being Li-Ion batteries the most suitable technology, ii) for complying future grid code requirements high power - low energy - fast response storage will be required, where super capacitors can be the preferred option, iii) other technologies such as Lead Acid and Nickel Cadmium batteries are adequate for supporting the black start services, iv) flow batteries and Lithium Ion technology can be used for market oriented services and v) the best location of the energy storage within the photovoltaic power plays an important role and depends on the service, but still little research has been performed in this field.

Keywords: Energy storage, PV power plants, renewable energy, grid codes, grid services

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Nomenclature

ES	Energy storage
RE	Renewable energy
PV	Photovoltaic
SOC	State of charge
PHS	Pumped hydro storage
CAES	Compressed air energy storage
FES	Flywheel energy storage
DLC	Double-layer capacitor (supercapacitor)
Pb-A	Lead-acid
NiCd	Nickel-Cadmiun
NaS	Sodium-Sulfur (molten salt)
Li-Ion	Lithium-Ion
VRB	Vanadium redox battery (flow battery)
ZnBr	Zinc-Bromine (blow battery)
NREL	National renewable energy laboratory
ENTSO-E	European network of transission system operators
TSO	Transmission system operator
POD	Power oscillation damping
RoCoF	Rate of change of frequency
HV	High voltage
MV	Medium voltage
LV	Low voltage
AC	Alternating current
DC	Direct current
HVDC	High voltage direct current
VSC-HVDC	Voltage source converter - HVDC
FACTS	Flexible AC transmission system
PCC	Point of common coupling
PPC	Power plant controller
LC	Local controller
PPT	Power point tracking

1. Introduction

The reliability and efficiency enhancement of energy storage (ES) technologies, together with their cost are leading to their increasing participation in the electrical power system [1]. Particularly, ES systems are now being considered to perform new functionalities [2] such as power quality improvement, energy management and protection [3], permitting a better integration of non-dispatchable renewable energy (RE), allowing new operational modes, e.g. microgrid island operation [4], improving system operation by reducing the peak load [5], frequency regulation [6] or providing fault support [7], among others. As a result, new concepts such as hybrid wind power plants with ES [8] or hybrid photovoltaic (PV) power plants with ES [9] are

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increasingly being researched and implemented in the field.

While PV and wind power represented around 6% of the installed electric capacity in 2005 (Europe), their participation raised up to 19.5% in 2017 [10]. Similar trends can be found in other geographic areas [11]. The power system has been traditionally based on the connection of synchronous generators, but PV and wind power plants are typically interconnected through power converters [12]. This leads to the loss of synchronous inertia, which can increase the grid frequency variations and compromise its stability [13]. In addition, the intermittent nature of wind and solar resources is challenging even more the stability and dispatchability [14]. As a consequence, power system operators are updating their standards imposing conditions such as power fluctuation suppression, frequency regulation, inertia emulation or fault support capability, to interconnect new PV [15] and wind [16] power plants. Despite wind farms have asynchronous inertia (the kinetic intertia of the rotating blades and axes is behind the power converter), their controls permit to emulate synchronous inertia providing effective primary control support as demonstrated in [17] and to use the stored kinetic energy to smooth the power variations [18]. Contrarily to wind power plants, PV plants have very little inertia. This, together with the non-dispatchability of the solar resource, makes difficult the controllability of the active power generated [19].

Hybridization of solar based power plants can be presented as a solution to these problems. For example, the study in [20] reviews the status of hybrid wind and PV power systems for stand-alone areas, concluding that the hybridization can reduce the storage and diesel generation needs. In the review [14], the focus is put on the intermittence issue of roof-top PV power plants and the use of energy storage systems for avoiding reverse power flows. In [21], a study of a hybrid PV storage power plant for power dispatching is performed. Particularly, the objective is to reduce the power unbalances between the PV power scheduled in the day-ahead market and the real production. The study is applied to a kW scale PV plant and based on the Italian regulatory framework and shows that ES is not cost effective, but reduction in ES prices could revert this situation. These studies do not focus on analysing the storage technologies and are more oriented on the service they can provide.

As shown, ES systems are presented as a solution to these challenges [22]. On the other hand, ES not only contribute to the standards accomplishment but can also provide other market oriented services that increase the income of the power plant [23]. Considering these services, the cost reduction and the improved capabilities of ES technologies, their utilisation can now turn economically feasible [24]. While the previous references presented the potential role of ES, without focusing on the technology or on the technical requirements, several reviews focus on the ES technologies based on their recent advances and potential applications. Reference [2] reviewed the status of ES technologies and their applications in power system and transportation, updating previous reviews such as [25]. Reference [3] also gives an insight of the storage requirements and the most promising technologies for each application and reference [26] provides a review of real projects considering different energy storage technologies. These reviews do not focus on the specific needs of a particular renewable power plant technology. In this direction, in [27], the short and long term ES requirements for the specific application of mitigating the power fluctuations in marine tidal power plants are reviewed together with the corresponding suitable ES technologies. A comprehensive review of ES technologies for specific wind power applications is presented in [28], where both technical and economic applications and the corresponding ES requirements are defined. The technical applications relate to those required in the present and future grid codes, while economic applications are focused on maximizing the wind power plants income by minimizing the penalties or selling energy during peak prices, among others. In [29], concentrated solar power plants technology and the associated thermal energy storage technology is reviewed. As explained before, PV technology does not have rotating mass nor kinetic energy stored. In addition, the primary resource availability and variability is different. Furthermore, standards are (and will) being updated, defining more services PV power plants shall provide (i.e ramp rate, frequency regulation, power oscillation damping, inertia emulation, etc.). Hence the energy storage needs for PV technology are not the same as in the previous renewable power plant technologies. Reference [30] provides the state of art of the role of ES in the case of distributed PV power plants. It is a synthetic review oriented on small-medium scale PV power plants that does not include specific technical requirements and focuses on the intermittence issue and peak shaving. Also, it doesn't quantify the amount (power and energy) of energy storage required.

In the case of large scale PV power plants, grid codes are currently being updated including challenging active power control requirements [15]. In the UK [31], power reserves are specifically required for providing under-frequency regulation. Also, the power fluctuations must be limited is sites such as Puerto Rico or South Africa among others [15]. In some cases this limitation only applies during curtailment transitions [32], but it can also be required to be applied at any time, for example in Hawaii [33]. These control functions are not easy to comply as the PV power depends on the irradiance availability, which can present large variabilities [34]. As a solution, the integration of energy storage within large scale PV power plants can help to comply with these challenging grid code requirements[1]. Accordingly, ES technologies can be expected to be essential for the interconnection of new large scale PV power plants.

For planning the installation of ES systems together with PV power plants, it is important to know which functionalities ES should have for complying standards requirements, which services they could also provide (despite not required by standards) and which characteristics ES should have for each of these services and functionalities. This way, the most appropriate ES technology can be selected. In contrast to previous works that review ES applications without focusing on a specific generation technology, or reviews that analyse ES applications in wind, marine and concentrated solar power plants,

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[1] Some of the described functions are not new in the grid codes, but the transmission system operators were more permissive. e.g. the under-frequency regulation were not strictly required despite appearing in the grid code [35].

the present article is oriented on ES solutions for photovoltaic power plants, which adds value to the work presented in [30] by analysing the specific energy reserve, power reserve and response time requirements based on the new demanding functionalities defined in the Standards. In addition, this review also considers other features such as the efficiency importance of the ES technologies for each service. So, the contribution of this review article is the analysis of i) the current and new services large scale PV power plants must (or can) provide in which ES can play a fundamental role, ii) the analysis of ES requirements for each service and iii) the analysis of the most suitable ES technologies for each of these services. Furthermore, the ES locations within photovoltaic power plants can also affect the performance of the system. In this direction, the present review includes a discussion of the best placement of ES technologies. Accordingly, this article pretends to be usefull for i) the industry by helping the desision-making on the best ES technologies to be installed in a PV power plant depending on its particular control requirements and ii) for the research by remarking the need of further research in the optimal ES location and the future needs in control services.

This review paper is organized as follows: the energy storage technologies and their characteristics are first presented. Then, the trends in grid code requirements, which are motivating the installation of ES within large scale PV power plants, are explained together with the required ES characteristics. After that, a review of other services ES can provide and the corresponding ES requirements is performed. Then, several possible ES locations within the PV power plant are presented. This is a point that still needs further investigation, but a discussion of the best locations based on literature review is provided. Finally, some project examples are presented and, considering the previous information, a discussion of the most suitable ES technologies for hybrid PV power plants with ES is included.

2. Energy storage technologies

There are various ES technologies available in the market. These can be classified in terms of the media for the energy to be stored. ES technologies can be classified into mechanical, electrical and electrochemical. The focus of the classification here presented is on the storage of electrical energy from PV plants. Accordingly, the field of thermal ES, widely applied in concentrated solar power by means of molten salts, as well as the field of hydrogen storage, are excluded from the following discussion. In addition, given the extensive literature on reviews for ES and the fact that this is not the aim of the present paper, following contents just aim to provide a brief overview of the technologies and summarize their characteristics with key representative and quantitative figures.

2.1. Mechanical

Mechanical energy storage systems can be distinguished in two main groups by looking at their response times, power and energy ratings as well.

Slow, usually large capacity mechanical energy storage systems are represented by Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES), both mature technologies. It is based on pumping water into an uphill reservoir using off-peak electricity and later release it downhill to a lower reservoir to power a generator [3]. PHS makes up between 95% [36] and 99% [37] of the world's energy storage capacity. Similarly, CAES systems compress air and store it in underground caverns, pipes or vessels [38]. When required the air is passed through an air turbine or boosted with fuel into a gas turbine [39], coupled with a generator producing electricity [40].

Fast response mechanical systems are mainly represented by Flywheel Energy Storage (FES) systems, which store electrical energy in the form of rotating kinetic energy [41]. During the charging phase, electrical energy is used to accelerate a motor which is connected to a rotating mass through a shaft. During the discharging phase, the rotating mass transfers the stored kinetic energy to a generator connected to the same shaft [26].

While PHS and CAES can be rated at hundreds of MW in power to be exchanged continuously during several hours [42], a flywheel device is not usually rated above few hundreds of kW, and is able to exchange the rated power during few minutes at most (it has limited energy storage capacity) [41]. Thus, its application in large PV power plants is through the inclusion of several flywheel units in parallel [43], so as to reach the required ratings to have a significant impact on the power output of the plant [44].

2.2. Electric

Supercapacitors, or ultracapacitors, or double-layer capacitors (DLC), are a competitive commercial reality applied in many technological environments. The operating principle of supercapacitors and batteries is totally different. The main difference is the fact that in batteries, voltage between terminals is due to electrochemical reactions in the electrodes of the cell. On the other hand, no electrochemical reactions occur in supercapacitors, but the cell voltage is because of the electro-static field within the cell.

The energy storage capacity of a supercapacitor depends on two factors: the capacity, usually reaching even thousands of Farads, and the square of the cell voltage. In particular, the energy stored E can be calculated as: $E = 0.5 \cdot C \cdot V^2$, where C is the capacitance in Farads, and V is the voltage in Volts.

Supercapacitors can be considered as competitors to flywheels. They permit to develop high ramp power rates, with response times in the range of milliseconds. The lifespan, because no chemical reactions occur, can reach millions of cycles of charge and discharge. There are numerous manufacturers of supercapacitors offering compact products, able to integrate modular systems rated at few MW in power. Supercapacitors are of application in electrical networks, for the frequency control, and of uninterruptible power supply systems for the protection of critical loads against main failures. They are also applied in trains, for regenerative breaking. In renewables, for instance in wind turbines, they are applied for the actuation of blade pitch mechanisms [45].

2.3. *Electrochemical*

A battery cell is an electrochemical device in which the energy is stored chemically. Through reduction and oxidation reactions in a media called electrochemical cell, this chemical energy is transformed into electrical energy. Chemical reactions occur in the electrodes of the cell: the anode and the cathode. From these chemical reactions, an electrical potential between the electrodes appears. This electrical potential drives the movement of the products of the electrochemical reactions, i.e. ions and free electrons, between anode and cathode. In particular, electrons are exchanged between electrodes through an external path to the cell, i.e. the load or the power source the cell is connected to, yielding an electrical current. Ions, in turn, are exchanged internally, through the cell itself and thanks to a media called electrolyte [28].

Batteries are based on the series and parallel connection of cells. The number of cells utilised, depend on the requirements of voltage and current. The voltage of the battery decreases progressively while discharged untill reaching a minimum practical voltage. The capacity of the battery, commonly expressed in Ah, depends on the conditions at which the discharge is performed and is limited by the above mentioned minimum practical voltage. Hence, the state of charge (SoC) is defined as the percentage of energy stored in the battery with respect to that under the conditions of fully charged.

The higher the battery voltage and the lower the weight of the materials participating in the chemical reactions, the higher the specific energy storage capacity, expressed in Wh/kg. Similarly, the specific power is defined as the ratio W/kg. This metric refers to the maximum current a battery can provide with respect to its mass. Looking at these characteristics, others such as operating temperature, safety, cyclability and modularity as well, the industry offers progressively improved new electrochemistries with enhanced performances that facilitate the application of batteries to more and more environments.

In general terms, the available battery types in the market can be grouped into 4 families: lead-acid, alkaline, molten salt and lithium-ion. The main characteristics of each family are summarized in the following:

- Lead-acid batteries (Pb-A) are the most mature options among eligible. Today, these batteries are cost-competitive and robust, also accounting on low maintenance and offering easy scalability and modularity. The nominal cell voltage is 2.04 V. Lead-acid batteries are reasonable options in numerous stationary applications, e.g. uninterruptible power supply systems, telecom, industrial actuators and renewable generating systems. The main drawbacks of lead-acid batteries are a limited specific energy and lifespan.

- Nickel-cadmium batteries (NiCd) –or alkaline ones– are also mature technologies. Along with lead-acid batteries, nickel-cadmium batteries present competitive costs in the market. The main drawbacks of the technology are a very limited cell voltage (just 1.3 V) and lifespan. In addition, self-discharge can be remarkable, even provoking the complete discharge in one month without proper loss compensation mechanisms [3].

- As opposed to cheap (but with limited performance) and mature lead-acid and nickel-cadmium batteries, two young and high performance battery types are coping more and more market share nowadays: molten salt and, specially, lithium-ion types. Molten salt batteries (for instance the ones based on sodium and sulfur, NaS) offer nominal cell voltages around 2.6 V. High cyclability, modularity and very limited self-discharge are their key performing characteristics. In this manner, they are good options for stationary applications requiring tens of MW in power during several hours. A fundamental (and limiting) aspect for this technology though, is the fact that the operating temperature is over 300 degrees Celsius and important preheating periods are needed. This precludes the application of NaS batteries in electric vehicles.

- Finally, lithium-ion batteries (Li-Ion) are the technologies coping the majority of research and development nowadays in energy storage. The remarkable lifespan (exceeding ten years), nominal cell voltage (up to 3.7 V, depending on the lithium-ion subtype) modularity and low self-discharge are key advantages over other battery types. Specially, the capacity of developing very high peak currents and the high specific energy (the ratio Wh/kg) are two of the characteristics that define lithium-ion batteries as particularly suitable for portable applications and electric vehicles. The term lithium-ion comprises a set subtypes depending on the electrochemistry for the electrodes of the cell. A summary of the main characteristics and differences among subtypes can be found in [46].

Apart from the above presented mainstream battery types, the catalogue for secondary batteries is completed by the inclusion of the so-called flow batteries. In flow batteries, the electrolyte is not stored in the cell itself, but in two separate and external tanks. When the battery is being utilised, the electrolyte is pumped into the cell, enabling the electrochemical reactions to occur. Thus, the size of the electrolytic tanks determine the energy storage capacity. The power capacity, in turn, is determined by the size of the electrodes, so for the size of the electrochemical cells. Two electrochemistries can be basically found in the market of flow batteries: vanadium-based (VRB) and zinc-bromine ones (ZnBr). The nominal cell voltage for the first type is around 1.6 V, while it reaches 1.7 V for the second type. In general terms, the self-discharge is almost negligible in flow batteries and can be completely discharged (until reaching a 0% state of charge) without accentuating the degradation. The cyclability is very large. For instance, vanadium-based batteries can be completely discharged more than 10,000 times [26].

2.4. *Summary of ES characteristics*

Table 1 deals with the ES's features regarding rated power and energy, density and per mass unit capacity. In Table 2 other ES technical characteristics are summarized; in here, efficiency is described as discharge efficiency when it refers to the losses tied to the power output process, round-trip efficiency when it also accounts for the losses during the ES's power intake and as daily self-discharge when referred to the power that is lost at the ES while stored. Table 3 shows the costs tied to each ES, both in terms of capital costs and levelized costs of energy. The data included in these tables are adopted from extensive and updated literature on energy storage. In addition, synthesizing a general comparison among technologies, Table 4 summarizes the main advantages and challenges for each one.

Regarding costs, it is worth-noting that because the industry of energy storage technologies is changing rapidly, costs greatly vary in time. This is specially remarkable when it comes to batteries. According to the technology roadmaps of recognized institutions like the European Commission in 2011 [47] and EASE/EERA in 2013 [48], the average cost for lithium-ion cells was around 900 €/kWh. Figures for 2018, according to IRENA [49], are near 200 €/kWh. This means that the cost for lithium-ion cells has been reduced up to 4.5 times in a period of about 5 to 7 years. Also referring to costs trends for lithium-ion cells, according to IRENA [49], by the current year 2020, expected average costs are around 100 €/kWh, and the goal is to reach 65-70 €/kWh by 2030. Such tremendous cost reduction is particularly important for lithium-ion, since being the most promising battery technology for both stationary applications and electromobility. In fact, is the deployment of electromobility one of the main drivers for such cost reduction. According to IEA [50], the number of electrical vehicles in the world in 2018 reached 5 million, and 250 million are expected by 2030. Costs trends for the rest of battery types are harder to estimate. Referring again to the technology roadmaps [47] and [48], the main goal is to fit capital costs below 200 €/kWh by 2030. In terms of levelized costs of energy, or cycle costs, and according to the newest technology roadmap for batteries in Europe (the SET-Plan [51]), the aim is to reach the challenging figure of 0.05 €/kWh-cycle by 2030. Such reduced capital and cycle costs for batteries would definitely boost renewables towards, for instance, 2030 European objectives around the decarbonization of the energy sector (Paris Agreement, in October 2014), and also for the rest of the world.

3. Trends in grid code requirements

The operation of PV power plants is conditioned by the requirements imposed by the regulations put in place by local authorities, which are found in the so-called grid codes. This review is focused on large scale PV power plants. Hence, only those regulations affecting the interconnection to the transmission system (high voltage, HV) are being analysed.

Regarding the operational requirements, grid codes define i) frequency and active power requirements, ii) voltage and reactive power requirements and iii) fault support requirements. The first group affects the active power generated, while the second and the third groups are more oriented to the reactive power. The main objective of ES is to manage active power. Hence, this review is focused on the first group, i.e. frequency and active power regulation. The study done in [61] provides further details for the second and third groups.

Particularly, the main requirements affecting the active power generation can be classified as i) power curtailment, ii) frequency regulation and iii) ramp rate. In addition to these requirements, the response time is also an important characteristic to be considered.

3.1. Power curtailment

Power curtailment consists on defining the maximum active power the large scale PV power plant can generate. Normally, these power plants will try to reach this maximum setpoint as it maximises the income. Nevertheless, the lack of solar radiation may lead the PV power plant to operate below this level. As the power curtailment relates on reducing the active power generation, it does not require any power reserve and ES is not needed. Most of the countries with specific regulations for PV power plants include this requirement. For example, but not limited, in Germany, South Africa, Denmark, Puerto Rico, Hawaii or Mexico. This requirement is basically related to solving congestion problems in the transmission lines [62].

3.2. Frequency regulation

Frequency regulation defines the conditions on how the PV power plants need to react when the grid frequency deviates from its nominal value. Basically, it consists on a predefined droop curve. This curve determines the amount of active power the PV plant has to reduce (over-frequency events) or increase (under-frequency events). An example of a generic droop curve is shown in Figure 1. P_{ini} is the actual power delivered at the moment the frequency deviation occurs. Under-frequency response is one of the most challenging requirements as power reserves are needed. These power reserves could be obtained by operating below the available power. The main problem is that estimating the available power when operating in curtailed mode is not an easy task, specially during cloudy days. The estimation of available PV power for providing power reserves in PV systems is one of the current research topics. For example in [63], the available PV power of a single PV inverter is obtained by curve fitting methods. This study is extended in [64] to consider the effects of partial shading. On the other hand, authors from [65] have presented a promising method to estimate the available power of a pair of PV inverters. This method consists on operating one inverter under maximum power point mode serving as a available power estimator of the pair of inverters, while the second inverter operates under curtailment mode for providing power reserves. This latter method has been extended for an entire PV power plant in [66], where the accuracy of the available power estimation has been also studied. From this latter study, two main problems can been identified: i) high accuracy of the available power estimation can be achieved at the cost of limiting the maximum curtailable power and ii) the operational cost increases because a portion of energy is not delivered. These problems can be solved by ES, which can be used to supply these required power reserves. In fact, the need of including an ES is explicitly included in some grid code, e.g. in

Table 1: Comparison of different energy storage technologies in terms of size: energy storage capacity, power rating, weight (specific energy and power) and volume (energy density and power density). Adapted from [3]

Technology (type)	Energy rating [MWh]	Power rating [MW]	Specific energy [Wh/kg]	Specific power [W/kg]	Energy density [Wh/L]	Power density [W/L]
PHS (mechanical)	500−8k[3]	1−5k[3]	0.5−1.5[3]	0.01−0.12[52]	0.5−2[3]; 0.3 [53]; 0.133−0.5[52]	0.5−1.5[3]; 0.01−0.12 [52]
CAES (mechanical)	<1k[3]	<300[3]; 3−400[54]	30−60[3]	2.2−24[52]	2−6[3]; 12[53]; 0.4−20[52]	0.5−2[3]; 0.04−10[52]
FES (mechanical)	<5[3]; 0.75[52]	0.1−20[3]; 0−0.25[52]	~5 low speed, ~100 high speed[3]; 10−30[26]	400−1.5k[3]	20−80[3]; 0.25−424[52]	1k−5k[3]; 40−2k[52]
NaS (electrochemical)	244.8[3]; 0.4[52]	<34[3]; 0.05−8[52]	100−240[3]; 150−345[52]	90−230[3]; 150−240[52]	150−300[3]; 150−345[52]	140−180[3]; 1.3−50[52]
Pb-A (electrochemical)	0.001−40[3]	0−40[3]	25−50[3]	75−300[3]	50−90[3]; 25−90[52]	10−40[3]; 10−400[52]
Li-Ion (electrochemical)	0.004−10[3]	0.005−100[3]; 0−0.1[52]	75−200[3]; 160−200[53]	150−2k[3]	150−500[3]; 94−500[52]	1.5k−10k[3]; 56−800[52]
NiCd (electrochemical)	~6.75[3]	0−40[3]	45−80[3]; 35−60[52]	150−300[3]; 140−180[52]	15−150[3]	80−600[3]; 38−141[52]
VRB (electrochemical)	<60[3]; 2[52]	0.03−3[3] 0.5−100[53]	10−30[3]; 30−50[52]	166[3]; 150−160[53]; 80−150[52]	16−35[3]; 45−90[53]; 10−33[52]	<2[3]; 2.5−33.4[52]
ZnBr (electrochemical)	0.1−4[3]	0.05−10[3]	30−80[3]; 75−85[52]	45−100[3]	30−65[3]; 5.2−70[52]	<25[3]; 3−8.5[52]
DLC (electric)	0.0005[3]	>0.3[3]; 0−0.3[52]	0.05−15[3]; 20[53]	500−10k[3]	10−30[3]; 2.5−15[54]; 1−35[52]	>100k[3]; 15−4.5k[52]

Table 2: Comparison of different energy storage technologies in terms of technical features: Life, cyclability, efficiency, response time and maturity of the technology. Adapted from [3]

Technology (type)	Life [years]	Cycling capability [cycles]	Efficiency			Response time [-]	Maturity
			Discharge [%]	Round-trip [%]	Daily self-discharge [%]		
PHS (mechanical)	40[3]; 40−60[55]; 30−50[52]	10k−30k[3]; 20k−50k[56]	∼87[3]	65−85[3]	Very small[3]; Almost zero[52]	min (grid synch.)[3]; ≤1min (power variation)[53]	Mature[3]
CAES (mechanical)	20−40[3]	8k−12k[3]; 10k−30k[56]	70−79[3]	42, 54[3]; 70[57]; 70−89[53]; 50−89[54]; 70−80[52]	Small, almost zero[3]	min[3]	Mature[26]; developed[54]
FES (mechanical)	>15[3] >20[58]; 20[52]	>20k[3]; 10^5-10^7[58]	90−93[3]	90−95[3]; 85 instant.[26]	100 (≥20% hour)[3]; 55−100[52]	s[3]; <ms[54]; ms[52]	Early commercialized[3]; demo[54]; commercialized[52]
NaS (electrochemical)	12−20[3]; 10−15[52]	2.5k−4.5k[3]; 1k−5k[52]	85[3]	75−90[3]; 89−92[52]	Almost 0[3]	ms[52]	Commercialized[3]
Pb-A (electrochemical)	5−15[3]	200−1.8k[3]; 200−2k[52]	85[3]	63−90[3]	<0.1-0.3[3]; 12−5 per month[59]	ms[3]	Mature[3]
Li-Ion (electrochemical)	5−16[3]	1k−20k[3]	85[3]	75−97[3]; ∼100[52]	0.1-5[3]; ∼1 per month[59]; 0.03[52]	ms[3]	Demo[3]; commercialized[52]
NiCd (electrochemical)	3−20[3]	2k−3.5k[3]; 1.5k−3k[52]	60−70[3]	65−80[3]; 60−90[52]	0.03-0.6[3]; 5−20 per month[59]	ms[3]	Commercialized[3]
VRB (electrochemical)	5−20[3]	>12k[3]; >16k[52]	75−82[3]	65−85[3]	Small, very low[3]; almost zero[52]	<1/4 cycle[3]; ms[52]	Demo, early commercialized[3]; commercializing[52]
ZnBr (electrochemical)	5−10[3]; 10−20[26]	1.5k−2k[3]; 2k−3.5k[52]	60−70[3]	65−75[3]	Small[3]	<1/4 cycle[3]; ms[52]	Early demo, commercialization[3]; demo[52]
DLC (electric)	10−30[3]	50k−100k[3]	95−98[3]	84−97[3]; 85−98[52]	5−40[3]; 5[26]	ms[3]	Developing, demo[3]

Table 3: Comparison of different energy storage technologies in terms of cost. Dollar-to-Euro conversion rate 0.9 as of 30/07/2019

Technology (type)	Cost			
	[€/kWh]	[€/kW]	[¢€/kWh per cycle]	O&M
PHS (mechanical)	4.5–90[3]	2250–3870[3]; 180–1800[55]; 540–2000[52]; 1800[57]; 450–1350[60]	0.09–1.26[26]	0.0036[€/kWh], ~2.7[€/kW/year][3]
CAES (mechanical)	1.8–225[3]; 1.8–90[54]; 1.8–45[52]	360–1395[3]; 360–1800[54]	1.8–3.6[26]	0.0027[€/kWh], 17.1–22.5[€/kW/year][3]
FES (mechanical)	900–12600[3]	225–315[3]	2.7-22.5[26]	~0.0036[€/kWh], ~18[€/kW/year][3]
NaS (electrochemical)	270–450[3]; 480.6[57]	315–2700[3]; >900[57]	7.2–18[26]	~72[€/kW/year][3]
Pb-A (electrochemical)	45–360[3]; 44.83–538[26]; 270–540[54]; 180–360[52]	180–540[3]; 270–540[52]	4.5–9[26]	~45[€/kW/year][3]
Li-Ion (electrochemical)	540–3420[3]; 807–1300[26]; 202.5–720[53]; 540–2250[52]	810–3600[3]; 1080–3600[52]	13.5–90[26]	N/A
NiCd (electrochemical)	360–2160[3]; 720–1350[52]	450–1350[3]	N/A	~18[€/kW/year][3]
VRB (electrochemical)	135–900[3]	540–1350[3]; 630–2250[52]; 2880[57]	4.5–72[26]	~63[€/kW/year][3]
ZnBr (electrochemical)	135–900[3]	180–2250[3]; 630–2250[52]	4.5–72[26]	N/A
DLC (electric)	270–1800[3]; 5400[53]	90–405[3]	1.8–18[26]	0.0045[€/kWh], ~5.4[€/kW/year][3]

Puerto Rico's [67] and Mexico's grid codes [68]. Table 5 summarizes the frequency regulation requirements of several grid codes around the world.

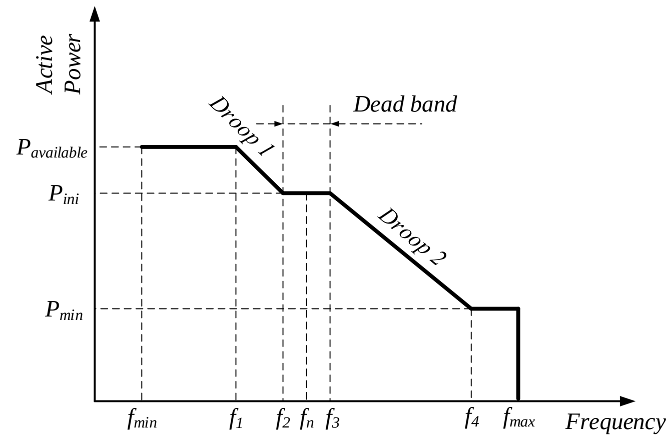

Figure 1: Example of a typical frequency droop curve and their zones. *Droop 1* defines the required power increase in case of having under-frequency events. *Droop 2* defines the required power reduction in case of having over-frequency events. The *dead band* defines the range of frequencies in which no action is required.

Frequency regulation has priority and is not limited by the ramp rate requirement. The required response time should be also considered as an important parameter to decide the energy storage technology. From the analysed grid codes, the frequency regulation response times are between 15 and 30 seconds: 15 s in Denmark [69], 30 s in Germany [70], Romania [71] and Europe in general [72] and 16 s (70 % of the setpoint) - 46 s (100% of the setpoint) in Puerto Rico [33].

3.3. Ramp rate

Ramp rate consists on limiting the power output variations to a maximum value (RR_{max}). The ramp rate constraint differs depending on the country. In countries such as South Africa [32] or Denmark [69], the upward ramp constraint applies at any time while the downward ramp only applies during transitions and shut down. On the other hand, in several places such as Puerto Rico [67], Hawaii [33] or Mexico [68] this constraint can be defined at any time and for both upward and downward ramp rate events, independently of meteorological conditions.

In order to be able to control the ramp rate, the time window in which the ramp rate is evaluated should be larger than the response time of the PV power plant.

Table 4: Main advantages and challenges for ES technologies (based on [45]).

Technology	Advantages	Challenges
PHS	Low operation costs, reliability, flexibility in power regulation.	The scarcity of suitable natural locations suggest the development of new concepts, such as micro-PHS.
CAES	Low operation costs, reliability, flexibility in power regulation.	The development of advanced-adiabatic CAES concept, to avoid the usage of natural gas and overcome the problem of scarcity of natural places to store the air underground.
FES	High power rates, reliability, high cyclability and energy efficiency.	The need of developing solutions to improve energy density, currently very poor, at minimum possible cost.
NaS	High energy efficiency and cyclability. No self-discharge and high energy density.	Thermal management, need to increase the temperature to 300 degrees to start operating the battery. Need to solve safety issues related to the high temperature of operation.
Pb-A	Reliability, maturity, low cost and large number of manufacturers.	Poor performance under high charge / discharge current rates, in terms of energy efficiency and capacity, degradation and the difficulty of ensuring proper balancing of the different batteries in the pack under frequency cycling conditions.
Li-Ion	High energy efficiency, good performance under high power rates, good energy and power density, high cyclability, diversity of electrochemistries (and manufacturers) already in the market.	The need of reducing the cost of the electrodes by adopting cheaper materials. The need of improving safety (for instance, by avoiding the usage of liquid electrolytes). The need of further increase energy and power density. The need of properly characterize degradation mechanisms for businesses development.
NiCd	Mature technology, high variety of manufacturers. Low cost, compared to lithium-ion batteries. Reliability.	Poor performance under high charge / discharge current rates. Poor energy efficiency and degradation. Toxicity of Cadmium, as a heavy metal.
VRB	Energy and power capacity are independent design variables, thus providing high design flexibility. Competitive life costs to well established Pb-A batteries, even for self-consumption applications. Good cyclability and energy efficiency.	Still few manufacturers in the market. Need to increase energy density. Need to increase performance in terms of fast charge and discharge processes, specially when reaching very low or high state of charge condition.
ZnBr	As for VRB, very good design flexibility and competitive life costs. Good cyclability and energy efficiency. Energy density is better than for VRB.	As for VRB, there are still few manufacturers in the market. Need to increase energy density and performance in terms of fast charge and discharge processes. The usage of different electrolytes for the anodic and cathodic parts of the cell suggest possible cross-contamination, thus reducing the life of the battery.
DLC	High power rates, reliability, high cyclability (reaching millions of cycles) and very good energy efficiency. Good modularity (considered as the possibility of serializing and parallelizing DLCs).	Energy density is very poor, thus limiting the application of DLCs to environments in which they have to provide high power but for a very short time (in the range of seconds). A trend is to hybridize DLCs with lithium-ion or Pb-A to increase energy density and still offer good performance in terms of peak power.

3.3.1. Ramp rate calculation methods

Grid codes' ramp rate requirements do not explicitly provide an exact formula for its computation. In [73], the ramp rate is estimated as the difference between consecutive boxcar averaged values whose width is the specific time window. In this review, this calculation method is referred as *ramp rate of averaged values*. The authors claim that slower sampled data results in smaller ramp rates. In contrast, in [74] the ramp rate is calculated as the difference between the maximum and the minimum values measured during the time window, *referred as ramp rate of extrema values* in the present paper. They conclude that the larger the sampling time, the larger the power fluctuations thus the smoothing effect is reduced with the time window. In [75], the ramp rate is computed as the difference between the final and initial value each time interval. This method is referred as *ramp rate of extreme values* in the present review. As the ramp rate's results of [75] are not expressed in an unified time unit, the values are not directly comparable, although it is noticeable that the maximum power change per unit of time decreases with the size of the time window. These are the most used ramp rate indicators in the literature. Due to different calculation methods apparently opposite conclusions are obtained.

Figure 2 shows the ramp rate histograms calculated from one year PV power data series sampled at 1 second resolution. To obtain the power data, irradiance data, corresponding to Oahu, Hawaii, has been obtained from NREL's database [76]. Then, the conversion from irradiance to active power generation has been obtained based on the model developed in [77], where the PV plant dimensions of Milagro PV power plant (Spain) have been used. On the left side of Figure 2, a), c) and e), the effect of the time window on the ramp rate calculation is shown, where each figure shows a particular ramp rate calculation method. It is clear that larger time windows result in smaller ramp rates. On the right side of Figure 2, in histograms b), d) and f), the effect of the ramp rate calculation method is depicted, where each plot shows a particular time window. It is noticeable that the discrepancy between calculation methods is more obvious at wide time windows, where the extreme and extrema difference methods result in higher ramp rates. In contrast, the effect of the computation method is not distinguishable for small time windows and when the rate is small. Currently, it is commonly assumed that time units in the ramp rate limits are scalable, i.e. 10%/min = 0.167%/s. However, as shown in Figure 2, grid codes still need to clarify the proper time window and ramp rate calculation method in order to overcome the current ambiguity.

3.4. Summary on grid code requirements

Table 5 summarizes some of the operational requirements of several grid codes. Regarding the power reserves for frequency regulation, it can be noted that they are being required in several regions. Also note that European countries are subject to the recent ENTSO-E regulation. So, even if the corresponding grid code does not include power reserves for frequency regulation, it is expected to happen soon. Regarding the ramp rate constraints, some countries are requiring they are applied independently of the ambient conditions.

4. ES requirements for grid code compliance

The minimum ES requirements to comply with the ramp rate constraints and the under-frequency regulation will be presented in this section. Then, other preferred features will be explained.

4.1. ES requirements for frequency regulation

Regarding the frequency regulation requirements, some grid codes define $P_{available}$ as a function of P_{ini}. For example, in South Africa $P_{available} = 1.03P_{ini}$. Hence, the ES power rating should be, at least, 3% the maximum power the PV plant will deliver under normal conditions. Other countries such as Denmark [69] or Mexico [68] also specify this data (see Table 5). In terms of energy, the amount of time the PV power plant must provide under-frequency support is also commonly found in the Standards. For example, 15 min in Denmark [78] and Mexico [68] or 9 min in Puerto Rico [67]. Also, in the recent unified European Grid Code, the primary frequency response must be active during 15 -30 min (agreed by the corresponding system operator) [72]. Knowing this amount of time and the required storage power, the energy storage capability can be easily obtained ($P \cdot t$). To sum up, from PV power plants under-frequency regulation viewpoint, the energy storage should require between 1.5% to 10% of the rated power of the PV plant. In terms of energy, it is required, at least, to provide full power during 9-30 minutes (see Table 5).

Considering the response time of the frequency regulation of the analysed grid codes, the ES should be capable to react in less than 15-30 seconds.

4.2. ES requirements for ramp rate limitation

As shown in Section 3.3.1, the ramp rate may depend on the calculation method as well as on the time window. Accordingly, the required energy storage will also depend on these parameters. In this section, the ramp rate of extreme value and instant ramp rate, i.e. 2 seconds time window, is used as a reference. Note that if instant ramp rate is accomplished, then the 10, 30, 60-s ramp rates will be also fulfilled. Hence this section analyses the worst case, i.e. the case that produces larger ramp rates and requires larger storage capacities.

The estimation of the storage requirements for ramp rate compliance is more difficult and depends on the PV plant design. Particularly, the smoothing effect of the geographic dispersion, and consequently the inverse relation between the power fluctuations and the plant size, is a well known phenomenon [79]. ES can help improving both upward and downward ramp rate response. Using ES for the upward ramp rate can avoid PV power losses by storing the excess of PV power, but the energy storage capacity requirements increase. Because of the cost of ES technologies, other solutions such as limiting the upward ramp rate using the PV inverters are preferred [80]. In this case, the ES requirement is reduced by half in terms of energy. Taking this latter approach, the upward ramp rate can be limited at the PV inverter level (local) [80] or at power plant control level (central) [81]. On the other hand, downward ramp events require power reserve that can be obtained

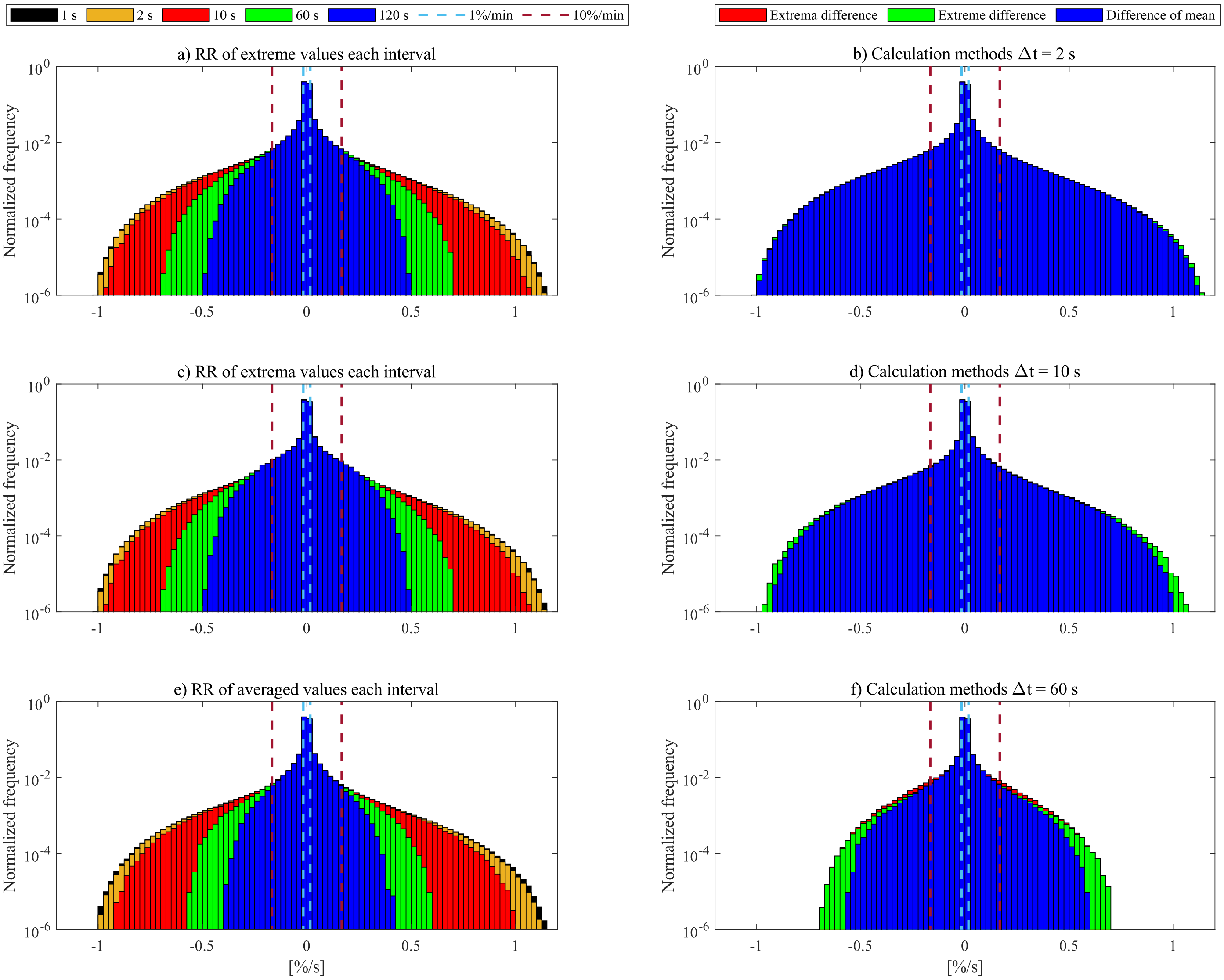

Figure 2: Comparison between different ramp rate calculation methods and the effect of the time window's witdh. Results obtained from 1 year data sampled at the rate of 1 Hz. The dashed lines represent two common ramp rate limits: 1%/min and 10%/min. a) effect of the time window's width on the ramp rate using the extreme values method, c) effect of the time window's width on the ramp rate using the extrema values method, e) effect of the time window's width on the ramp rate using the averaged values method, b) comparison of ramp rate calculation method (time window = 2 s), d) comparison of ramp rate calculation method (time window = 10 s), f) comparison of ramp rate calculation method (time window = 60 s).

by operating below the maximum power point or by ES technologies. This latter approach has been widely studied during the last years [82]. An example of an hybrid PV-storage power plant with ramp rate (frequency support) control functions can be found in [83]. The energy storage requirements for this purpose have been studied in [84] and [85], determining that the required storage ratings depend on the PV plant dimensions, its rated power and the maximum ramp rate limitation. As a reference, a 10 MW PV power plant with 10% ramp rate limitation per minute would require around 7 MW and 700 kWh (0.1h at full power). A comprehensive method to obtain the required ES discharge power and energy is found in [86] and summarized in equations (1) and (2). In equation (2), it is supposed the upward ramp events are limited by the PV inverters, otherwise, the requirement is doubled.

$$P_{ES\,max} = \frac{Pn}{100}\left[90 - \tau \cdot RR_{max} \cdot \left(1 + \ln\frac{90}{\tau \cdot RR_{max}}\right)\right] \qquad (1)$$

$$E_{ES\,max} = \frac{0.9 \cdot Pn}{3600}\left[\frac{90}{2 \cdot RR_{max}} - \tau\right] \qquad (2)$$

being Pn the rated PV plant power in [kW], RR_{max} the maximum ramp rate in [%/s]. τ is calculated in function of the smallest perimeter l as $\tau = 0.042 \cdot l - 0.5$, where l is expressed in [m]. $P_{ES\,max}$ and $E_{ES\,max}$ are expressed in [kW] and [kWh] respectively.

Last but not least, the response time can vary depending on the ramp rate calculation method. The most strict requirement is the instant ramp rate in Hawaii, which is evaluated each 2

Table 5: Mandatory services LS-PVPPs must offer according to the grid codes in different countries

Country	Power Curtailment (y/n)	Frequency regulation				Ramp rate
		Under-frequency (y/n)	Over-frequency (y/n)	Power reserve	Energy reserve[*1]	
Germany [70]	yes	no	yes	n/a	n/a	1 [% Pn/min][*2]
Denmark [69]	yes	yes	yes	yes. Specified by TSO	15 [min] [78]	<100 [kW/s]
Romania [71]	yes	only if there is enough irradiation	yes	no	no	yes. Specified by TSO ~10 [% Pn/min][*2] [35]
ENTSO-E [72]	yes	yes	yes	1.5-10 [% injected power]	15-30 [min]	yes. Specified by TSO
South Africa [32]	yes	yes	yes	3 [% injected power]	yes[*3]	yes. Specified by TSO
Puerto Rico [67]	yes	yes	yes	10 [% rated power]	9 [min]	10 [% Pn/min][*2]
Mexico [68]	yes	yes	yes	10 [% rated power]	15 [min]	1-5 [% Pn/min][*2]

[*1] The maximum time the PV plant must perform the frequency regulation together with the power reserve provide the energy reserve

[*2] Pn = rated power of the PV plant

[*3] The provision of reserves appears in the grid code, but how much time they should be provided is not specified

seconds using a time window of 2 seconds [33]. So, it should respond in less than 2 seconds.

4.2.1. *Other desired ES features*

In addition to the ES sizing and the response time, there are other ES characteristics that should be considered. The high intermittency of the solar resource (due to the clouds covering the power plant) is a well recognised issue [87]. Accordingly, to comply with the ramp rate requirements, having a high cyclability is required and high round trip efficiency is a desired feature.

Normally, the minimum use of ES is desired to avoid excess of ageing and the need of over sizing. So, the controller tries to keep the state of charge at high levels and only use the stored energy in case of being strictly necessary, i.e. lack of available PV power [80]. As a result, low self-discharge rates are desirable.

5. Other potential services of energy storage

ES can be used to provide other services either as individual units or along with generation units. The increase of renewable non-synchronous generation is leading to new grid code requirements where ES can be more relevant. The main potential services to be included in the future grid codes are i) Fast frequency response and inertia emulation, ii) Black start capability and iii) Power oscillation damping (POD) [88]. Requirements for fast frequency response or inertia response from PV power plants or ES are already under discussion or implementation in few countries. Black start and POD have been analysed in the literature, but their introduction into the grid codes is only considered in general terms.

These services (and the ones described in Section 3) are services from the technical perspective in order to ensure a reliable integration of PV power into the current electric system, maintaining its stable operation. In essence, this is the reason why they are progressively being introduced in the Standards and grid codes. On the other hand, from the market and economics perspective, ES can help large scale PV power plants to provide firm dispatchable capacity. In this direction, the following services can be identified i) Capacity Firming and ii) Electric energy time shift [23].

5.1. *Fast frequency response and inertia emulation*

The reduction of synchronous generation is decreasing the total inertia of the power system, which leads to higher and faster frequency deviations. Therefore, additional frequency response services are needed to limit the frequency variations and the Rate of Change of Frequency (ROCOF) during the first seconds after a power imbalance. As a result, two new services have been analysed in the literature: fast frequency response and inertia emulation [89].

Fast frequency response is similar to the primary frequency response, but with an activation time of few seconds and a duration up to few minutes. Battery storage has been already tested as a fast frequency support service in a number of areas, such as Great Britain, Ireland and Texas [89]. For example, National Grid in Great Britain has defined a service called Enhanced Frequency Response, which has an activation time of 1 second, a duration of 9 s and a maximum response of 50 MW per unit [90].

Inertia emulation is used to represent the automatic response of synchronous generators during the first seconds after a power imbalance. This service is specially convenient for wind turbines, which have kinetic energy stored in their rotating mass, but it can also be used in ES systems. The main inconvenient of this service is the recovery power that is required once the inertia support has been ended to restore the rotor speed of the wind turbines. This recovery power must be limited to avoid a negative effect on the frequency. System operators in Canada and Brazil have already defined grid code requirements for inertia emulation [89]. For example, Hydro-Quebec TransEnergie in Canada has defined an inertia emulation service for wind turbines, where the maximum activation time is 1.5 seconds, the minimum duration is 9 s, the minimum response is 6 % of the nominal power and the maximum recovery power is 20 % of the nominal power [91]. General requirements are indicated in the ENTSO-E grid code, but the details must be defined by each European system operator [92]. Also, future inertia emulation requirements for PV are anticipated in [93]. According to this article, an energy storage system should be required with a capacity of 10% of active power during at least 2 seconds.

The definition of fast frequency response and inertia emulation for PV plants is comprehensively discussed in [94]. As defined in [94], the concept of inertia emulation might not be applied for inertia-less system, such as PV power plants. However, fast frequency response represents a more general concept and can be easily extended to any generation source. Accordingly, in case grid codes include these services, the fast frequency response concept for PV power generation is expected to be used.

The ES used for these services must have a fast response time, but the capacity can be small since they are required for a short duration. The ES self-discharge is not as important as in other services due to the small energy required. The frequency deadband defined by the system operators will determine the number of activations for these services, which is directly related to the cycling capability of the ES. Estimating the cycling requirements is difficult as it will depend on the amount of frequency deviations, which will depend on the strength of the network where the PV plant is connected.

5.2. Black start capability

Black start is the procedure to recover the transmission system from a shutdown. This service is included in all the grid codes, but it is not compulsory for all the generators. As indicated in [95], black start capability can be considered from renewable generation, but it is subject to availability of the primary energies. Therefore, ES can be used to ensure that black start is accomplished in PV power plants.

Black start includes requirements for active power, storage and reactive power [96]. The active power and storage requirements depend on the purpose of the black start units. If these units are used to re-energize auxiliary elements of larger black start generator units, the required active power and storage can be low. The reactive power requirements are subject to the energization of grid elements. In case of ES, the reactive power requirements could be accomplished by the associated converters that control the ES power.

A number of studies and real tests have been presented to analyse the viability of ES for black start. For example, in California a lithium-ion battery system of 33 MW and 20 MWh was used to start-up a 44 MW combined cycle natural gas turbine [97]. Also, the ISO New England analysed in [98] the technical and economical viability of VSC-HVDC and ES for black start, where it was concluded that ES are more expensive than conventional solutions if they are only used for black start. However, VSC-HVDC are more competitive since black start is considered as an additional service. Therefore, if ES are planned to be used for multiple services, black start could be also included as an additional service for a relatively low cost.

According to [99], the ES used for black start capability should have a similar response to conventional power plants, a duration between 15 min and 1 h, a power between 5 and 50 MW and a minimum number of 10 - 20 cycles per year. As seen, the number of black start activations is very small. So, as the energy will be stored for long periods, a low ES self-discharge is a desired feature.

5.3. Power oscillation damping

Electromechanical oscillations at low frequencies (0.2 - 2 Hz) [100] might be originated by transient events in the grid such as, line disconnections or faults. Power system stabilizers (PSS) are traditionally used in conventional synchronous generators to damp these power oscillations. PV power plants with ES can provide POD with additional converter controllers that represent a PSS.

In [101], the contribution of wind and PV generation for oscillation damping in the Eastern Interconnection (US) is analysed considering a 5% penetration of these renewable resources. Application of POD for PV generation and ES is equivalent to HVDC systems or wind farms with fully rated converters without considering the contribution of the mechanical control. In particular, POD from wind generation and ES is reviewed in [102]. Active and reactive power control are presented as possible magnitudes to damp oscillations in [102]. However, active power is the most effective solution since the oscillations are produced by active power differences between generation and demand. In [28] it is suggested to use ES with a response time around one minute and a small storage capacity.

At this moment, POD from PV generation, ES or in general from renewable generation is not considered in the grid codes. However, ENTSO-E includes general requirements for HVDC-connected systems [103], where the specifications about the grid conditions and the frequency range to activate POD must be defined by the European system operators.

5.4. Capacity Firming and electric energy time-shift

Capacity firming is defined as the capability of a variable power plant to maintain the generation level during a certain period of time [104]. PV firming capacity can reduce the conventional generation capacity during periods with high demand [105].

Electric energy time-shift or arbitrage is usually referred to the ability of an ES of purchasing electric energy when its cost is low and selling it later at expensive periods, taking advantage of the electric price variability during the day [104]. In the case of renewable power plants such as PV, time-shift does not only take the advantage of the price variability but also includes the capacity to store energy during periods of excessive production, i.e. to store energy that otherwise would be curtailed [104]. Note that, as stated in Section 3.1, providing power curtailment capability at the point of interconnection is mandatory for large scale PV power plants. Despite energy storage is not necessary for curtailment, it could add a value if the curtailed energy can be stored and delivered later.

The economic value of ES, still requires further investigation [23]. A recent study by Energy & Environmental Economics, First Solar Inc. and Tampa Electric Company has found that the operational value of energy storage increases at high PV power penetration [106], when solar curtailment is more significant and time-shift service gets more profit. But the study only considers operational benefits, omitting the capital cost of ES. Hence, no conclusions regarding the full cost-benefit can be drawn. In [107], the economic value of energy storage for capacity firming and electric energy time-shift (arbitrage) have been evaluated. The study is based on a 50 MW PV plant with a 30 MW (charge and discharge) and 120 MWh ES connected to a large utility network. The study concluded that at current costs, the energy storage has a negative value. Nonetheless, it was also estimated that in 2020 these services could be economically feasible for PV power plants. In contrast, in [108], the energy storage value of each of these services (firming and time-shift) were studied for a 2.5 MW PV power plant with 4 MW and 3.4 MWh energy storage. In this case, the PV plant is part of a microgrid. The results in [108] differ from the ones found in [107], as it was concluded that the economic value of energy storage is positive at the current prices. In addition, in the case of [108], the combination of these services together with frequency regulation adds an extra value. These differences could be explained due to the different nature of the network (utility network [107] and microgrid [108]).

According to [104], ES should be able to supply between 1 MW to 500 MW during 1 to 12 h with a response time around minutes for time-shifting service. This service is expected to be used in a daily basis. So, in [104] it was estimated it should require medium cyclability, i.e. > 250 cycles per year. In contrast, according to [105], these requirements range from 1 kW to 500 MW and a discharge time between 3 h and 5 h (nonetheless, kW scale have no sense in large scale PV power plants). Similar ranges are expected for capacity firming [105], but with high cyclability to compensate PV power fluctuations. The energy stored through these services can be sent back to the grid after several hours. Accordingly, low self discharge characteristics would be beneficial.

6. Summary of energy storage requirements for large scale PV power plants

In Sections 3, 4 and 5 different grid support services that large scale PV power plants must offer (Section 3) or potential future services (Section 5) are reviewed together with the potential requirements of ES (Section 4). Table 6 summarizes the energy storage requirements for each of these services.

7. Hybrid PV plants with ES layouts

This section discusses how ES can be interconnected to large scale PV power plants.

7.1. Background

First of all, it is important to understand how PV power plants are built, i.e. the different elements and how they are interconnected. Figure 3 shows a typical large scale PV plant configuration in absence of energy storage [109]. PV panels are normally connected in series and parallel to form PV arrays. Each array can deliver a power of several hundred of kW up to few MW (direct current, DC). Each PV array is controlled by a power converter, which also transforms the DC system to a 3 phase low voltage (LV) AC system. Then, 3 winding transformers are in charge to step up the LV to a medium voltage (MV) level and to deliver the generated power to the PV plant collection grid. This internal grid collects and transmits the generated power to the external grid, where a power transformer steps up the MV to high voltage (HV) level. In addition, there can be other supporting devices such as FACTS, capacitor banks or storage systems to provide grid support functions. As shown, large scale PV power plants have several generation units (generation unit=PV array+converter). But from the transmission system operator viewpoint, it is a single generator connected to the point of common coupling (PCC). Hence, the power delivered to the grid and the grid code fulfilment is checked at the PCC. As a result, there is a need to coordinate all these elements together in order to control the generated power as desired at the PCC. To achieve this, there are two control levels i) local controllers (LC) at the generation unit level and ii) central power plant controller (PPC) at the plant level. First, the LC is in charge to control the active and reactive power generated at the generation unit. Then, the PPC is in charge to control the PCC power fulfilling the grid codes and/or other agreed services to the external grid by measuring the state at the PCC and generating the setpoints to be sent to the local controllers [35].

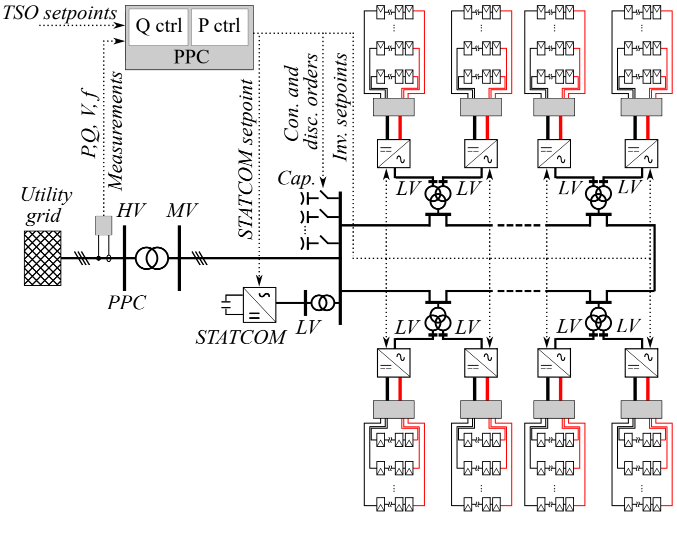

Figure 3: Example of a typical large scale PV plant layout. A set of PV arrays are connected to collection grid, which is interconnected to the external network at te PCC. The compliance of grid service is evaluated at the PCC. So, a central controller monitors the power exchange at this point and coordinate all the PV inverters.

7.2. ES locations

Mainly two configurations for integrating ES systems together with PV systems exist, namely DC coupled and AC coupled respectively, as shown in Figure 4. Configurations where the ES is not electrochemical storage might require different or

Table 6: Energy reserve, power reserve and techincal characteristics that energy storage should have for each grid service according to the analysed grid codes and literature.

Service	Description	Power requirements	Energy requirements	Response time requirements	Cycling requirements	Self-discharge requirement
Power curtailment	Limit power output. Avoid congestions.	Not required	Not required	-	-	-
Under-frequency regulation	Increase power output. Limit frequency deviations.	1.5-10 [% PV rated power]	9-30 [min]	15-30 [s]	Depends on droop dead-band and the network's strength.	Low
Over-frequency regulation	Decrease power output. Limit frequency deviations.	Not required	Not required	-	-	-
Ramp rate	Avoid fast power variations.	equation (1)	equation (2)	< 2 [s] for instant ramp rate.	High	Low
Fast freq. response & inertia emulation	Mimic synchronous generator's behaviour.	6-10 [% PV rated power]	Few seconds (<9 [s])	<1 [s]	Depends on droop dead-band and the network's strength.	Medium
Black start	Recover the transmission system from shutdown.	Depends on the system to re-energize.	15-60 [min]	Few seconds	Low (10-20 [cyc/year])	Low
Power oscillation damping	Damp power system oscillations by injecting pulsating active and/or reactive power.	Very system dependant	Small. Depends on the frequency of the oscillation to damp	Depends on the frequency of the oscillation to damp	High. Depends on the frequency of the oscillation to damp	Medium
Capacity Firming	Maintain constant power generation.	1-500 [MW]	1-12 [h]	minutes	High	Low
Time-shift	Postpone power generation. Economic viewpoint.	1-500 [MW]	1-12 [h]	minutes	Medium (>250 [cyc/year])	Low

additional interfaces, e.g. flywheel energy storage would require, at least, an AC/DC converter for DC coupled configuration. Also, it is worth highlighting that despite many storage technologies have DC output, the direct connection to the DC side of the PV array is not recommended. The DC output of these storage technologies depends on the state of charge and is approximately constant. So, the direct interconnection to the PV array DC link would lead to the loss of PV controllability, which is achieved by a power point tracking algorithm (PPT) regulating the PV array voltage. On the other hand, the power converter of the ES in DC coupling configuration can be cheaper due to the lower number of transistors.

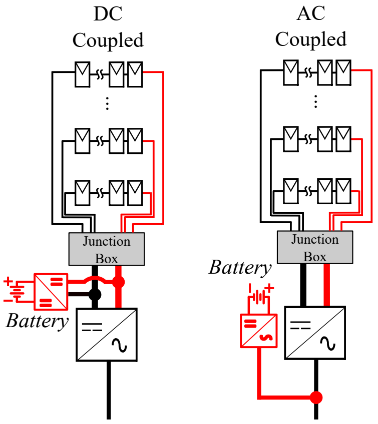

Figure 4: Scheme of a battery energy storage coupled to a PV system through DC and AC approaches. DC coupling is done though a DC-DC converter at the PV array side. AC coupling is done through a DC-AC inverter at the grid (AC) side

Due to the large scale PV plant layout, the DC coupled ES is performed in a decentralized way as shown in Figure 5. In contrast, 3 different approaches might be considered for the ES AC coupled configuration. In the first ES AC coupled topology, which is decentralized, the ES is connected to the low voltage AC side of the PV arrays as depicted in Figure 6. So, each of the PV arrays has an associated ES at its AC side. In the second ES AC coupled topology, the ES is interconnected in a decentralized way at the medium voltage AC collection grid. This topology is shown in Figure 7, where pairs of PV arrays share a single ES unit. As the output of power converters are normally low voltage, an additional transformer is required. Finally, the third ES AC coupling topology is a centralized one, as observed in Figure 8. In this case, the ES is connected through a dedicated feeder close to the PCC.

Very little work has been performed for evaluating the ES locations within PV power plants. In [107] a comparison between the DC coupled and AC coupled topologies is carried out from economical viewpoint. In this case, the energy storage is installed for obtaining benefits from capacity firming and energy arbitrage. In this particular case, in both configurations, the cost-benefit ratio is smaller compared to the ’only-PV’ case due to the high capital expenditure (CAPEX). But comparing AC to DC coupled topologies, DC coupled topology is beneficial from economical viewpoint. As shown in [107], at the current costs the use of energy storage systems is desirable for

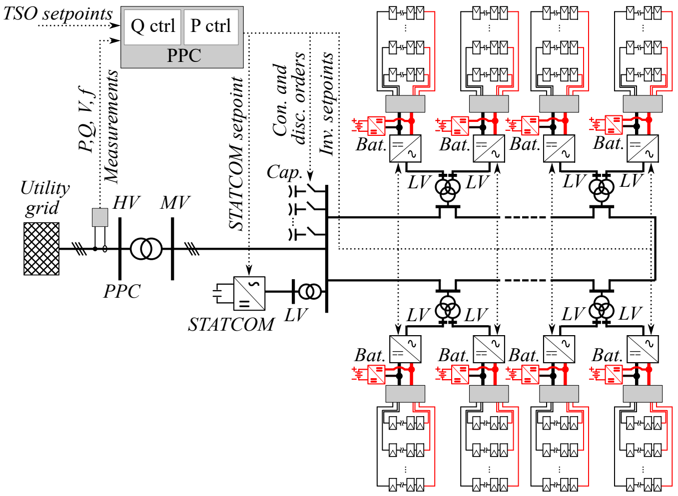

Figure 5: PV plant layout with DC coupled ES topology (decentralized). Each PV array includes an ES device connected to the DC bus

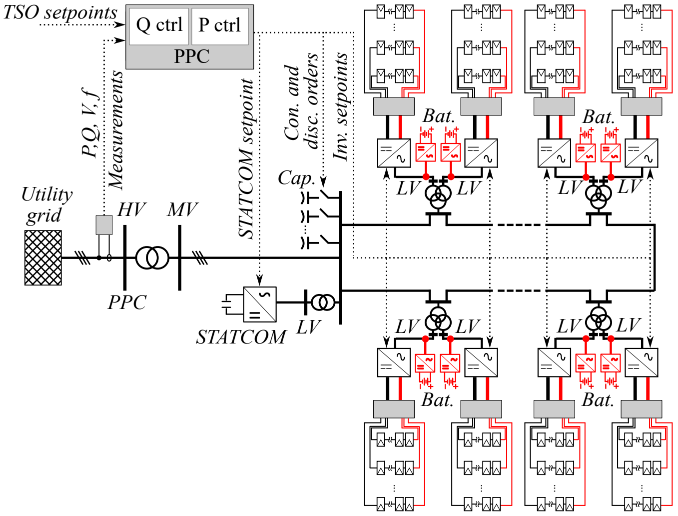

Figure 6: PV plant layout with AC coupled ES topology (decentralized at low voltage level). Each PV array includes an ES device connected to the LV AC bus

complying standards and allowing the power plant connection rather than for economical purposes. In contrast, the study performed in [110] reached opposite conclusions and centralized ES connected near the PCC is recommended. In this case the purpose of the ES was to operate the PV power plant as a constant power generation.

The best ES locations depend on the particular application, but further research in this area is still required to draw reliable conclusions. As shown in [107], ES is not an economical solution, but may be required to comply with standards as explained in Section 3. So, for this particular application (ramp rate and frequency support), the ES requirements in terms of power and energy could be one of the main aspects to decide the most economical topology. In DC coupling approach, the ramp rate control is typically performed at PV inverter level [111]. But as

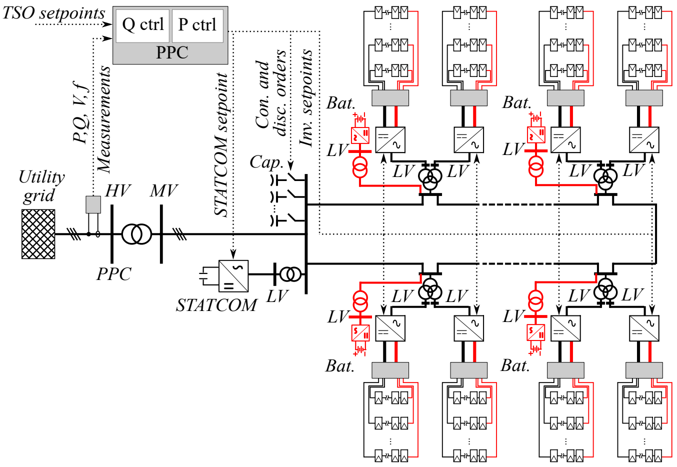

Figure 7: PV plant layout with AC coupled ES topology (decentralized at medium voltage level). Each pair of PV arrays includes an ES device connected to the MV AC bus

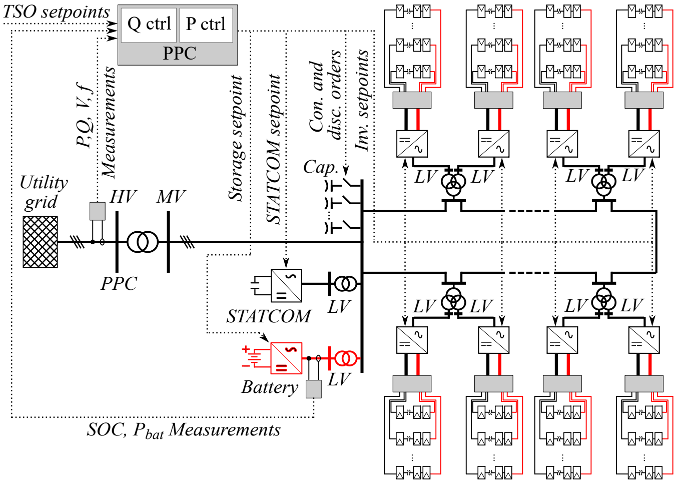

Figure 8: PV plant layout with AC coupled ES topology (centralized). The ES is connected to the collection grid through a single dedicated feeder

explained before, PV power fluctuations are greater for small PV systems. Hence, controlling the ramp rates of individual inverters would led to higher ES requirements in terms of energy and power. On the other hand, one of the main drivers for installing decentralized energy storage systems (in both DC and AC decentralized topologies) is the possibility to reduce the PV inverter size, the LV/LV/MV three winding transformer and the collection grid cable ratings (or to avoid generation curtailment due to excess of power generation) [112]. This assumption can be realistic when the storage is used for decreasing the power output. But now, because of the under-frequency support requirements, the need to increase the output power in some situations could lead to the opposite effect and require over sizing of the equipment. Accordingly, the centralized approach could be beneficial for the current grid codes compliance, avoiding over sizing the PV plant equipment and leading the to minimum ES requirements for ramp rate compliance. In contrast, decentralized approaches could be beneficial for economic oriented grid services. On the other hand, AC coupled topologies (centralized and decentralized) could present an additional benefit. Despite not being the focus of this review paper, grid codes also stablish fault ride through requirements which relate to the reactive current injection. While AC coupled ES could increase the reactive current injection capability through the associated power electronics interface, the DC coupled topology cannot contribute to fault support due to the absence of reactive power in DC systems. Nevertheless, more research is still required to confirm these assumptions.

8. Project examples

Hybrid large scale PV power plants with ES systems are still under development. Up to now, there are several hybrid systems under operation and additional projects that are announced to be built during the next years [113, 114].

Table 7 summarizes some of the reported real hybrid PV-storage power plants according to the size, technology and the main service provided. It is observed that, these hybrid plants have been used to test frequency regulation, ramping, time shifting and capacity firming. The power rating of the PV power plants is up to 71 MW, while the power rating of the storage systems is between 10% to 100 % of the PV power plant size. In terms of storage technology, most of the projects are based on lithium-ion batteries. But other technologies such as Pb-A, VRB or DLC are also being tested. It is worth noting that in the last project in Table 7, the main purpose is to comply the Puerto Rico's grid code. This tendency of requiring storage for complying the control requirements can be expected in the near future as discussed in previous seccions in this review.

9. Discussion

ES, together with PV power plants can be implemented for both, technical or economic purposes. While both approaches are of interest, the technical purposes such as ramping and frequency support have captured more interest during the last years. But due to the PV and storage cost reduction, economic oriented services are also being considered at present [23]. This is confirmed by the project examples given in in Section 8. According to project search results (including those not shown in Table 7), Li-ion is by far the most popular ES technology used in hybrid large scale PV power plants with ES. However, other electrochemical energy storage technologies have also been employed. On the other hand, it is worth mentioning that flow batteries (e.g. vanadium redox based) are also being employed in small and medium scale PV plants [113]. And probably, it will be a good option in the future. Accordingly, in the following discussion, the suitable storage technologies for each service will be discussed. This discussion will be based on the storage characteristics reviewed in Section 2 and the requirements reviewed in Sections 3 and 5. Considering that not all the presented services are (or will be) required in a particular photovoltaic power plant (this will be determined by the

Table 7: Overview of projects related to hybrid large scale PV power plants with ES, showing the purpose of the installation of the ES, its sizing and its technology.

References	Location	Services	PV power rating [MW]	Storage power rating [MW]	Storage energy rating [MWh]	Storage technology
[115]	Puerto Rico	Frequency regulation Ramping	40	19	N/A	Li-ion
[116]	Lanai, Hawaii	Ramping	1.2	1.125	0.5	N/A
[117, 118]	Hokkaido, Japan	Ramping	14.5	10	6.75	Li-Ion
[119, 120]	Tudela, Spain	Ramping Frequency regulation	1.18	1	0.56	Li-ion
[121–123]	Queensland, Australia	Capacity firming Time shift	55	20	80	Li-ion
[124]	Hokkaido, Japan	Capacity Firming	NA	15	60	VRB
[23]	Bedfordshire, UK	Fast frequency response Time shift	10	6	6	Li-ion
[23]	Catania, Italy	Capacity firming Time shift	10[*2]	1	2	Sodium Nickel Chloride
[125]	Zheijiang, China	Ramping Time shift	2	1.2	1	Pb-A
[126]	Kaua'i, Hawaii	Capacity firming Time shift	13	13	52	Li-ion
[127]	Kaua'i, Hawaii	Capacity firming Time shift	20	20	100	Li-ion
[128]	Oahu, Hawaii	Capacity firming Time shift	20	20	80	Li-ion
[129]	Bailesti, Romania	Frequency regulation Time shift Ramp rate Voltage Regulation	3	1	0.95	Li-ion
[129]	La Paz, Mexico	Frequency regulation Time shift Ramp rate Voltage Regulation	10	10	5.605	Li-ion
[129]	HVPS, Spain	Frequency Regulation Voltage Regulation	10	1.65	NA (4s rated power)	DLC
[129]	Oriana, Puerto Rico	Frequency regulation Ramp rate Voltage Regulation PREPA GC Compliance	71	21.6	4.2	Li-ion

[*1] The energy storage system was installed to test ramp rate control algorithms and real implementation using a small area of the PV power plant (122.4 [kW PV])

[*2] 10 MW of PV power installed, but limited to 8 MW due to grid limitations

corresponding Transmission System Operator and the particular needs in the region the PV plant is installed), this discussion will serve as a guidance to select the most appropiate ES technologies for each particular case, i.e. for each large scale PV power plant.

First of all, PHS and CAES are technologies that require specific geographic locations. This limits its applicability in large scale PV power plants for providing services at the PCC. These storage technologies could be used in virtual power plants, but this concept is out of the scope of this article. In general, PHS and CAES would not be recommended to be used in PV power plants because of location issues.

9.1. Energy storage technologies for power curtailment and over-frequency regulation

As explained above, these services do not require storage technologies as they can be provided by PV inverters together with classical central power plant controllers. Note that the use of ES for taking profit of the energy lost due to the power reduction is considered as an economic approach (time-shift).

9.2. Under-frequency regulation

ES for under-frequency regulation can be considered as high power - medium energy application. The active power requirement can reach levels up to 10% of the PV power plant nameplate capacity. This means MW-scale during 30 minutes. In contrast, the response time is relatively slow (15-30 s).

In this case, Li-Ion is the ideal ES technology. Its power, energy and response time capacities comply with the requirements. Furthermore, Li-Ion technology can provide current close to their rated current without excessive loss of efficiency (+ 90% at its rated value) and with less degradation that any other electrochemical technologies. In addition, its low self-discharge (~1%/month) will be an advantage versus other technologies such as FES or DLC. FES could also be an good option. Despite its limited energy capacity, its flexible design permits its power over-sizing in order to provide lower power during longer time. In this case, it can reach up to several minutes (as required by this service). This fact, together with its nearly instantaneous response, makes this technology suitable for under-frequency regulation in large scale PV power plants. The main drawback of FES is its high self-discharge, decreasing the efficiency of the system and its larger capital cost compared to Li-ion technology (this cost could be compensated by the higher durability/cyclability).

Technically, flow batteries could also offer this service. But they are not recommended because at high power levels an over heat occurs, generating gases that require to be extracted and decreasing its effective capacity. Consequently, flow batteries should be over-sized too much. These batteries are more suitable for low-medium power (respect to their rated power) applications with long discharge times. Pb-A and Ni-Cd present large degradation and energy capacity reduction at high power level. Thus, they are not recommended either.

9.3. Ramp rate

Ramp rate control in large scale PV power plants can be considered as a power service with medium energy reserve requirement, as in the previous case. The main differences are: i) in ramp rate service, the response time is more critical (< 2s) and the cyclability becomes more important as PV power ramps are frequent events. The high cyclability limits the suitable ES technologies for this application. DLC and FES are the technologies with highest cyclability (up to hundreds of thousands cycles). While FES can comply with the other technical requirements (power, energy and response time), DLC are limited in power and energy and too many DLC units should be parallelized. Another option is the Li-Ion, whose cyclability can reach up to tens of thousands of cycles considering a low depth of discharge (DOD). This means that for maximizing the lifetime of Li-Ion batteries, they should be oversized avoiding excessive DOD. Despite the potential of FES for this service, this technology is rarely used. Instead, Li-Ion batteries are winning the market for this service (e.g. see Table 7).

Pb-A, NiCd and flow batteries are not an option because of the same reasons than in the case of under-frequency regulation: their low performance at high power levels.

9.4. Fast frequency response and inertia emulation

Fast frequency response & inertia emulation services require similar features to ramp rate but less energy (up to 9 s at full power) and faster response time (< 1s). FES and Li-Ion technologies are still an option. But due to the low energy requirement, DLC would be recommended because of the high cyclability and low cost. Due to the small energy requirement, the high self-discharge of DLC is not specially relevant. Hence, this would be the most suitable technology for this service. Nevertheless, in very large power plants, the required power could limit the use of DLC's. In this case, Li-Ion batteries would be recommended. Due to the low energy requirement, the DOD will be small (i.e. small cycles). Under this situation, Li-Ion batteries are not excessively degraded and their lifetime can be enlarged.

Flow batteries can also be an option for this application. The excess of temperature produced at high power level only occurs at low state of charge (SOC) levels. If flow batteries are oversized in terms of energy, fast frequency response and inertia emulation will produce small variations of the SOC around a constant value (note that small amount of energy is required for these services).

Pb-A and NiCd are not recommended for the same reasons than in the previous services.

9.5. Black start

The power required for black start depends on the system to be supported its duration can last up to 1 h (1 h of energy reserve). In addition black start is a rare event. Consequently, the cyclability and the round trip efficiency would not be relevant. Technically, Li-Ion could be a feasible technology for this purpose, but Pb-A and NiCd too. In fact, Pb-A and NiCd could be recommended due to they lower price compared to the Li-Ion technology. In addition, while Pb-A can be maintained at 100% SOC (floating state) without excess of degradation, the electrodes in Li-Ion batteries degrades at full SOC. Thus, paying for Li-Ion storage in order to be used very few times per year is not reasonable.

FES and DLC technologies are not an option for this application because i) their energy capacity normally lasts up to 30 minutes at full discharge power and ii) their high self-discharge (not reasonable for eventual uses as it will present constant power losses).

9.6. Power Oscillation Damping

Power oscillation damping has similar characteristics to inertia emulation. It is more a power than an energy service. The energy requirements, despite being small, will heavily depend on the frequency of the oscillation which needs to be damped. Something similar happens with the cyclability. Note that charge and discharge time will correspond to the half of the period of the oscillations.

Accordingly, the storage recommendations for this service are the same as for inertia emulation, i.e. DLC, FES, Li-Ion and flow batteries.

9.7. Economic oriented services

The power and energy requirements for economic oriented services can vary in a wide range depending on the specific service. For those services requiring low power and long time (high energy), flow batteries would be a suitalbe option, as their energy capacity can be easy scalable. On the other hand, Li-Ion will also present good characteristics for these services and higher efficiency than flow batteries. But the price of Li-Ion can be higher. While for low power economic services the most recommended technology would be the flow batteries, for high power services these batteries present power limitations. In this case, Li-Ion technology will be preferable.

Both flywheel and DLC technologies are not adequate options due to their low energy capacity and large serf-discharge. In the case of Pb-A and NiCd, their low efficiency together with their low cyclability can turn these services into non-economically feasible.

9.8. Summary of proposed ES technologies for each service

Considering the overall review and the discussion in Section 9, the recommended ES technologies in PV power plants are listed in Table 8.

10. Conclusions

Energy storage can play an important role in large scale photovoltaic power plants, providing the power and energy reserve required to comply with present and future grid code requirements. In addition, and considering the current cost tendency of energy storage systems, they could also provide services from the economic perspective, turning the photovoltaic plant project more attractive. Among the large variety of energy storage technologies, selecting the proper one could not be evident. Accordingly, this article has comprehensively analysed those most suitable technologies to be used in each identified grid service in large scale PV power plants. For this purpose, the present article has identified the features of different energy storage technologies, has defined the energy storage requirements for the different services of photovoltaic power plants and has discussed which of these technologies suits better for each of the services. Furthermore, the placement of energy storage devices within photovoltaic power plants have also been discussed. From this review, the following conclusions can be drawn:

- At present, Lithium-Ion is, by far, the most used technology. This tendency is motivated by its high power and medium-high energy capacities, its acceptable levels of cyclability, its high efficiency and low self-discharge and its fast response time. Nevertheless, due to its cost and the better performance in terms of cyclability of other techologies such as double-layer capacitors or flywheel energy storage, it is not the only option to be considered.
- Grid support services of the current grid codes may require high power - medium energy energy storage technologies. In this case, Lithium-Ion technology is the one that would be preferred. On the other hand, other options are still possible. Considering the flexibility of the design and the power and energy ranges together with its nearly instantaneous response, flywheel energy storage can also be an option for providing under-frequency regulation. Something similar happens in the case of ramp rate limitation. Because of its characteristics and its higher cyclability, flywheel energy storage could also be used for providing this service. Nevertheless, flywheel energy storage are rarely found in current large scale PV power plants projects.
- Inertia emulation, fast frequency response and power oscillation damping requirements are strong candidates to be included in the future grid codes. These services are more oriented at power services rather than energy, i.e. high power - low energy (up to several seconds) with very fast time response. As a consequence, double-layer capacitors would be the ideal energy storage technology, being cheaper than other possibilities such as Lithium-Ion, flywheel energy storage or flow batteries and presenting better cyclability. While flow batteries could be an alternative option, Lithium-Ion or flywheel energy storage could also be used, specially in those particular cases where very high power is required (e.g. very large photovoltaic power plants).
- Black start is also one of the candidates to be required in the future grid codes. Because of black start is expected to be a rare event, the cyclability and round trip efficiencies are not relevant. So, despite Lithium-Ion could be a feasible technology, in this case Lead-acid and Nickel-Cadmiun technologies are preferable because of their low cost.

Table 8: Recommended ES technologies for large scale PV power plants. This recomendation is based on the analysis of the ES requirements of each service and the size, technical and economic characteristics of each storage technology

Service	Recommended ES technology	Other suitable ES technologies
Power curtailment	Not required	Not required
Under-frequency regulation	Li-Ion	FES
Over-frequency regulation	Not required	Not required
Ramp rate	Li-Ion	FES
Fast freq. response & inertia emulation	DLC Li-Ion (in very large PVPPs)	FES, Flow batteries
Black start	PB-A, NiCd	Li-Ion
Power oscillation damping	DLC	Li-Ion, FES, Flow batteries
Capacity Firming	Flow batteries Li-Ion (high power cases)	-
Time-shift	Flow batteries Li-Ion (high power cases)	-

- Economical oriented services can require a large range of power and energy reserves depending on the particular application. In addition, considering its medium cyclability requirement, the most recomended technologies would be the ones based on flow and Lithium-Ion batteries.
- The way to interconnect energy storage within the large scale photovoltaic power plant is an important feature that can affect the the price of the overall system. This is a field still requiring further research. Nevertheless, a trend on installing centralized energy storage for technical services and decentralized for market oriented services can be observed.

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