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Report

Grid integration of big photovoltaic farms with energy storage support

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ABSTRACT

This report deals with two types of network code requirements that apply to big photovoltaic installations and cannot be met with the use of inverters but require energy storage.

The first of these requirements is frequency response. It prescribes how much the active power output of a photovoltaic installation should change when system frequency deviates from the nominal frequency in order to support the grid.

The second requirement is the maximum ramping rate which determines by how fast the active power output of a photovoltaic installation may vary due to changing cloud cover or other factors.

The report classifies the network codes into three grades of severity. Two methods to size the required storage capacity for different grades of severity are explained with corresponding examples.

The report concludes that improved storage sizing methods should be developed as there is clear potential for significant reductions in required storage capacity.

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1 Executive summary

This report is a part of the NEWPLAVOL project. Its objective is to provide guidelines on the employment of storage with big photovoltaic installations (also called power parks in the report) in order to meet network code requirements.

Newer network codes on grid connection of intermittent sources therefore specify stringent criteria similar or equal to grid connection criteria for synchronous generators in the following areas:

- Voltage and reactive power requirements during faults
- Anti-islanding support
- Frequency response
- Ramping

The first two of these requirements can be met with the employment of modern inverters. Island systems such as Puerto Rico as well as bigger countries including Mexico specify stricter codes, particularly those related to frequency response and ramping or changes in the active power output. These require storage capacity.

The sufficient storage capacity for frequency response is simple to determine from two characteristics of a particular power system; the droop characteristic and the expected duration of the longest frequency deviations.

The imposition of maximum allowed ramping rates represents a much stricter requirement than frequency response. A maximum ramping rate of 10% of rated output per minute can require a storage power output in the same order as the actual power plant. This report provides guidelines to sizing storage capacity for different ramping rates based on a method devised by the University of Navarra. It classifies the grid codes into the following three categories:

- Undemanding grid codes; These are grid codes that only impose a frequency ride-through, also called frequency response requirement
- Demanding grid codes; Include a frequency ride through requirement and a maximum allowed ramping rate up to 20%/min of rated output.
- Very demanding grid codes; Include a frequency ride through requirement and a maximum allowed ramping rate below and including 20%/min of rated output.

The report finds that current methods aimed at fulfilling code requirements focus only on the technical feasibility of the solution. An effective storage sizing method is yet to be developed and should be based on a precise analysis of expected output variations and aim at a sufficient rather than full compliance rate.

2 Description of work as provided in the project documentation

2.1 Work plan

This work will focus on alternative grid codes, with special focus on different levels of severity for the connection of PV plants – with corresponding opportunities for energy storage technology. The work will result in a superior description of different scenarios regarding how PV plants and corresponding energy storage technology can be connected to grids with grid codes at different detailing levels. Relevant scenarios with conditions and examples, to be included in the description are

- Very demanding grid codes
- Medium demanding grid codes
- Undemanding grid codes

2.2 Description of activities

- Grid code scenarios
- Huge PV farms impact in grid codes
- Energy storage recommendations

3 European network code general description

In 2007, the European Commission paved the way for an internal EU market. To facilitate the market integration of the individual markets into an effective common market, ENTSO-E[1] was mandated to develop a set of rules - the network codes - that would complement and replace the individual members' rules. Since 2011 ENTSO-E has been drafting the network codes, with guidance from the Agency for the Cooperation of Energy Regulators (ACER). Each code takes approximately 18 months to develop and applies to one of the three key areas:

- Grid connections
- Grid operations
- Cross-border electricity markets

There are altogether 10 network codes dealing with different key areas of network operation. The connection of PV plants to the medium voltage level is covered in the network code on Requirements for Generators (NC RfG) that falls under the Grid connection area [1].

[1] ENTSOG was mandated to draft the rules for the gas market.

4 Types of technical requirements on PV power parks grid code scenarios

4.1 Overview of the types of technical requirements

In order to be connected to the grid, PV facilities have to fulfill a set of technical requirements that are related to the operation of the network. The following is a list of typical requirements imposed by the network operators on PV facilities:

1. **Voltage ride-through;** PV facilities are required to support the grid in case of sudden voltage drops or rises. This requirement specifies the lowest and highest voltage levels as well as related times during which PV facilities need to stay connected – ride through – in case of under- or overvoltage.
2. **Reactive power capability and minimum power factor requirements;** Power factors have to be either fixed or dynamic adapting to network conditions to supply or absorb reactive power.
3. **Frequency ride through / frequency response or regulation;** Power parks need to be able to operate within a given band around the default system frequency. In case of under frequency they are required to supply additional active power output, while in case of over frequency they should reduce the active power output to restore the system frequency.
4. **Rate of change of active power output / ramp rate control;** Active power output should not change faster than specified.
5. **Capability to operate in island mode;** if an area is disconnected from the main grid, PV generators can be required to continue operation within the active and reactive power output limits as specified for normal operation. They can be required to reduce their active power output in these cases in order to support voltage and frequency levels in island operation.
6. **Reactive power current injection;** to help maintain voltage stability, PV generators can be required to provide reactive current injection.
7. **Black start;** PV generators can be asked by the TSO to provide black start capability after a blackout.

These requirements can be further split into subcategories, but only those pertaining to points 3, 4 and in future perhaps 5, 7 are of relevance for energy storage. To fulfill these requirements a generator needs to supply active power, whereas the others only require reactive power. We will look at requirements 3 and 4 in more detail. Requirement number 4 is the more significant of the two when it comes to storage sizing. It is perhaps important to note, that this requirement is not included in the European network code.

5 Frequency ride through / frequency response or regulation (point 3)

This is the first of the two types of requirements for which energy storage is employed as mentioned in Section 3. System frequency can drop due to a sudden loss of a generator or rise in case of an unexpected loss of load. In order to stabilize or restore the frequency the TSO requires generators to change their active power output. For this purpose, network operators auction or mandate frequency reserves which are traditionally provided by synchronous generators. Increasingly, however, large PV generators are required to provide frequency response or frequency containment. The exact terminology can vary from system to system and can be divided into under and over frequency, but the principle remains the same. In case of under frequency PV generators are required to increase their active power output and in case of an over frequency they are required to reduce it.

Figure 1 depicts a generalized frequency response curve with frequency f on the x-axis and corresponding change in active power output ΔP on the y-axis. The characteristic can consist of two droop curves, one for the under frequencies and one for over frequencies. The droops can be equal in magnitude or differ and can be separated by dead band. In the simplest case the characteristic can be a given by a line passing the x-axis at $f_{nominal}$. The droop can level out below or above a certain frequency as depicted in the under frequency area in Figure 1. On both extremes lie the trip frequencies f_{trip1} and f_{trip2}. Below and above, generators are allowed to trip or at least stop adjusting their output.

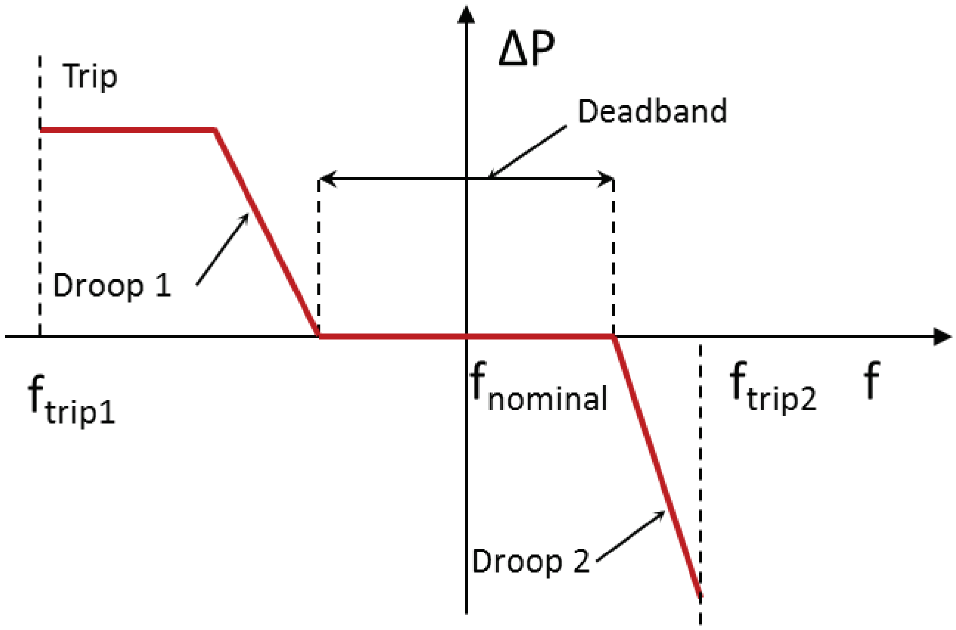

Figure 1: Frequency response of a power park

As an example the ENTSO-E code specifies that the droop in the under frequency (Droop 1 in Figure 1) should start on the interval between and including 49.8 and 49.5 Hz [1]. The droop should be set between 2 and 12% per Hz. Before the trip in the under frequency area ENTSOE-E specifies that the active power can be reduced as given by Figure 2. TSOs can set the droop in the range between 49.5 Hz (f_1) and 49 Hz (f_2) while the magnitude of the droop can range between 2% (s_2) and 10% (s_1).

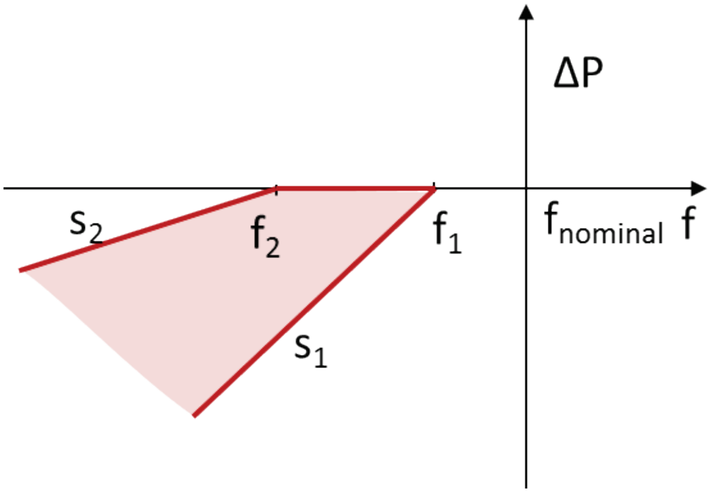

Figure 2: Range of allowed droop characteristics for under frequencies

To size the storage for frequency response we need to know the maximum required power output of the storage and the longest duration of a big frequency deviation that we can expect in a system. PREPA, the Puerto Rico Electric Power Authority, prescribes an increase of 10% of rated output over the operating point at the time of the event for 9.5 minutes [2]. The ENTSO-E code allows some freedom in determining the droop characteristics as shown above. The strictest requirement in line with the grid code would be a 12%/Hz droop in under frequency that starts at 49.8 Hz and applies down to 49 Hz (Figure 1). This would require a maximum increase of

$$\textbf{Maximum change in active power output} = -\mathbf{12\%}\ /\mathbf{Hz}\ \times (\mathbf{49.0\ Hz} - \mathbf{49.8\ Hz}) = +\mathbf{9.6\%}.$$

Per MW of installed capacity this means

$$\textbf{Maximum change in active power output per MW} = \mathbf{1MW} \times \mathbf{9.6\%} = \mathbf{96kW}.$$

The mildest case in line with the ENTSO-E code would have Droop 1 in Figure 1 begin at 49.5 and droop S_1 in Figure 2 at the same frequency. This would require no frequency response at all. ENTSO-E does not specify the duration of the frequency response. A study [10] from the University of Stuttgart states that durations of over 30 min are common in the European power system.

Assuming a 30 minute constant negative frequency deviation at 49 Hz would in the above mentioned worst case scenario necessitate an energy reserve per MW of installed power of

$$\textbf{Energy reserve per MW} = \mathbf{1MW} \times \mathbf{9.6\%} \times \mathbf{30\ min} = \mathbf{48kWh}.$$

For a precise estimate of the required energy reserve we would need a thorough analysis of the size and duration of frequency deviations. In case battery systems are used for frequency response one can expect the power output to be the determining factor in storage sizing. Batteries usually have energy to power ratios (number of kWh per kW) above 1. Considering that durations of frequency responses should mostly be well below one hour, the full energy reserve will probably never be fully used. For example, the energy to power ratio of 1 would in the above case of a 96 kW storage output provide 96 kWh, which is double the 48 kWh that are actually needed.

6 Rate of change of active power output (point 4)

The changing cloud cover causes the output of a power park to rise and fall. The resulting up and down ramps can be of the order of a few tens of percentage points in a matter of seconds, which would significantly impact network stability. In addition to the frequency response, the TSO can prescribe the maximum ramp rate which limits the speed at which the active power output of the power park is allowed to fluctuate. The ramp rate is usually given in percentage points of the rated power per minute. For example a maximum ramp rate of r_{max} = 10% / min means that the output of a 10 MW power park cannot drop or rise from the current operating point by more than 1 MW per minute. If the actual output drops faster than the maximum ramp rate, the difference will have to be supplied by the storage.

6.1 A simple method to size energy storage

In the extreme case of an instantaneous active power drop of ΔP (Figure 3), the storage will have to deliver the power ΔP in the first instant and drop linearly at rate r_{max} to 0 (blue line). During the time Δt it will have delivered an amount of energy equal to ½ x ΔP x Δt (shaded area in Figure 3) where Δt is equal to $\Delta P/r_{max}$.

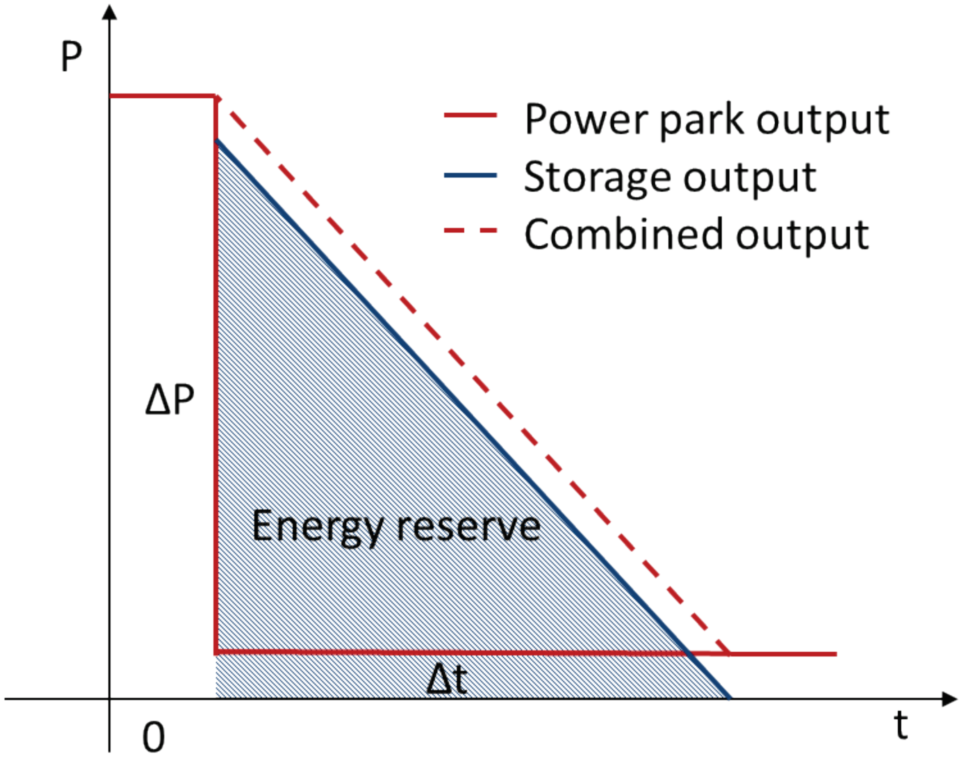

Figure 2: Required energy reserve in the extreme case of an instantaneous output drop

For example, if r_{max} = 10% / min and we assume the most extreme case of the active power output dropping from 100% to 0% for more than 10 minutes that will mean that the storage will have to supply 95% of the rated output in the first minute, 85% in the second minute, 75% in the third and so forth. Sizing the storage by this reasoning is a simple task.

The storage energy reserve per MW of rated power has to be equal to

$$\textbf{Energy reserve} = \frac{1}{2} \times \mathbf{P} \times \frac{100\%}{\mathbf{r_{max}}} = \frac{1}{2} \times \mathbf{1MW} \times \frac{100\%}{10\%/\mathbf{min}} = \mathbf{83.3kWh}$$

The required power output of the storage is equal to the rated output of the power park, that is, 1 MW of storage output per 1 MW of installed generation capacity [2]. A lower allowed maximum ramp rate means a stricter requirement. For example a maximum allowed ramp rate r_{max} = 2% / min would according to the above sizing method require an energy reserve that is five times greater than in case of the 10% / min ramp rate.

$$\textbf{Energy reserve} = \frac{1}{2} \times \mathbf{P} \times \frac{100\%}{\mathbf{r_{max}}} = \frac{1}{2} \times \mathbf{1MW} \times \frac{100\%}{2\%/\mathbf{min}} = \mathbf{416.7kWh}$$

6.2 Storage sizing for an exponential drop of 90% of rated output

A more advanced method based on the shortest perimeter of the power park requires a much smaller energy reserve. The decisive parameter is the shortest perimeter of the power park since it determines how fast cloud cover over the entire area and consequently the output of the installation can change. The method proposes using a drop from 100% to 10% of rated output as the worst case scenario. Instead of an instant drop it assumes an empirical exponential drop with a time constant that depends on the shortest perimeter of the power park (Figure 4).

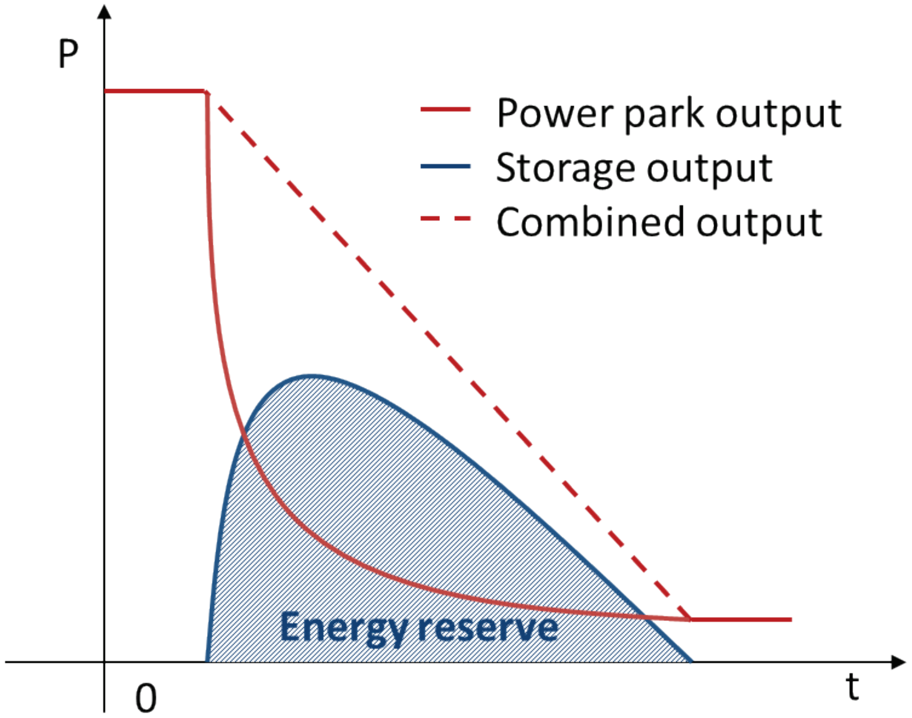

Figure 3: Energy reserve and power output for an exponential output drop

[2] The example is taken from [5], where the 10% per minute requirement is effectively applied to two second intervals.

Compared to the simple method described in 6.1 both the required maximum storage power output and energy reserve are somewhat less. The required power output of the storage is according to this method equal to

$$\textbf{Storage power output} = \frac{P}{100} \times \left[90 - \tau \times r_{max}\left(1 + \ln\frac{90}{\tau \times r_{max}}\right)\right]$$

where P stands for the rated active power output of the power park in kW, and r_{max} the maximum ramping rate in %/s. The last value is the time constant τ given in seconds. It is calculated from an empirically estimated relation between the shortest perimeter of the installation **l** in meters and the time constant **τ** in seconds as

$$\tau = a \times l + b, \qquad \text{with } a = 0.042\frac{s}{m}, \qquad \text{and } b = -0.5s.$$

The values **a** and **b** were obtained for the geographic area of the installations studied in Spain and probably need adjustment in other areas. The corresponding energy reserve is estimated with the following expression

$$\textbf{Energy reserve} = \frac{0.9P}{3600} \times \left[\frac{90}{2 \times r_{max}} - \tau\right]$$

For the example power parks used in the article the resulting storage sizes are reproduced in Table 1. The time constants used for the calculation of storage sizes in Table 1 are calculated using the expression $\tau = a \times l + b$. For completeness, Table 2 lists the ratings of the power parks the article analyzed, corresponding shortest perimeters and measured time constants.

Table 1: Example storage sizes for different ratings of power parks in Spain

Power [MW]	Calculated τ [s]	Required storage reserve / Storage power output		
		r_{max} 10 %/min	5 %/min	2 %/min
0,55	6,1	36 kWh / 465 kW	73 kWh / 478 kW	185 kWh / 487 kW
1,1	6,1	72 kWh / 929 kW	147 kWh / 956 kW	370 kWh / 974 kW
2,2	12,9	141 kWh / 1,76 MW	290 kWh / 1,85 MW	735 kWh / 1,92 MW
6,6	25,8	403 kWh / 4,81 MW	848 kWh / 5,28 MW	2185 kWh / 5,63 MW
11,5	37,1	669 kWh / 7,78 MW	1446 kWh / 8,82 MW	3774 kWh / 9,61 MW
38,5	74,5	1882 kWh / 20,6 MW	4480 kWh / 26,0 MW	12277 kWh / 30,3 MW

Table 1 shows that a maximum ramping rate of 10%/min already represents a very demanding requirement. The energy reserve for the 38,5 MW installation at 1882 kWh corresponds to about 3 minutes of production at rated capacity, but the required power output stands at 20,6 MW which is more than half the rated output of the power park. At a maximum ramping rate of 2%/min the energy reserve is significantly higher at 12277 kWh but the decisive factor remains the required storage power output at 30,3 MW.

Table 2: Ratings, shortest perimeters and measured time constants for the used example power parks [11]

Power [MW]	Shortest perimeter l [m]	Time constant τ [s]
0,55	158	8
1,1	158	9
2,2	318	11
6,6	626	25
11,5	896	32
38,5	1786	77

7 Grid code scenarios

Most countries' grid codes impose only a frequency ride through or frequency response requirement. The proposed EU grid code for example does not foresee a special requirement for the change of active power output or so called ramping. These are, however imposed in island countries such as Puerto Rico, as well as larger countries such as Mexico. As the report shows in section 6, an imposition of a maximum ramping rate is a much more severe requirement than frequency response that is analyzed in section 5. Below are a few examples to demonstrate the effect of the severity of codes.

The storage capacity required for frequency response depends on the longest expected duration of frequency deviations and the droop characteristic as explained in section 3. Table 3 lists example energy reserve values for maximal frequency responses of 5% and 10% of rated output. We can see that with a required response of 10% of rated output and a frequency deviation of 60 minutes the installation requires 100 kWh of energy reserve per MW of installed capacity. This corresponds to 6 minutes of operation at rated output.

Table 3: Required storage capacity for different durations of frequency deviations

Duration of frequency deviation	Required storage capacity per MWp	
	50 kW or 5% of rated output	100 kW or 10% of rated output
15 min	12.5 kWh	25 kWh
30 min	25 kWh	50 kWh
60 min	50 kWh	100 kWh

Frequency deviations of 60 minutes can be considered very long and are added to the table in order to demonstrate how much milder frequency response is as a requirement than ramping rate. Table 4 lists example values for storage energy reserve and active power output calculated for a 40 MW plant for different ramping rates and maximum output variations.

Table 4: Energy reserve and active power output of storage per MW of installed power for different ramping rates

Maximum variation	Ramping rate 20%		Ramping rate 10%		Ramping rate 2%	
	Energy	Power	Energy	Power	Energy	Power
90%	16 kWh	359 kW	50 kWh	550 kW	320 kWh	793 kW
60%	3 kWh	151 kW	18 kWh	296 kW	138 kWh	503 kW
30%	0 kWh	9 kW	2 kWh	76 kW	32 kWh	218 kW

The method used to calculate the values is the one described in section 6. The value for the time constant is hypothetical at 70 s. In the first row we have a 90% variability of output for which the method was designed. The energy reserve at a conservative 20% ramping rate is small at 16 kWh per MW of installed power. The power output at 359 kW per MW, however, is already high compared to what is required for frequency response (100 kW in the extreme case). At a ramping rate of 10% the corresponding values are 50 kWh and 550 kW per MW.

As was mentioned, the method is based on a 90% maximum output deviation. If a lower value is taken, for example 60% or 30%, required storage capacity should be much lower and comparable to that necessary for frequency response. Though, an appropriate method should be designed to take these factors into account first. At this point we can only base the grid code scenarios on the 90% output variability and the 60 or 30 minute frequency deviation. The cost of fulfilling even the mildest ramping rate requirements is in this case considerable. We therefore omit the category moderately or medium demanding requirements as stated in the description of work and divide the grid codes scenarios into the following three categories:

1. Undemanding grid codes; These are grid codes that only impose a frequency ride through also called frequency response requirement
2. Demanding grid codes; Include a frequency ride through requirement and a maximum allowed ramping rate higher than 20%/min of rated output.
3. Very demanding grid codes; Include a frequency ride through requirement and a maximum allowed ramping rate lower or equal to 20%/min of rated output.

8 Discussion

8.1 The combined storage capacity for frequency response and rate of change of active power output

As this report shows, the storage capacity required to provide frequency response represents only a fraction of the amount required to fulfill the requirements that can apply to the rate of change of active power output. In the most unfavorable case, a frequency drop can coincide with a downward ramp. In that case the power park will have to respond to both demands. PREPA, the Puerto Rican regulator, mandates that both services be provided by a screening that is frequent enough to determine whether that is actually the case. The total required capacity for both services is therefore a sum of the individual capacity requirements.

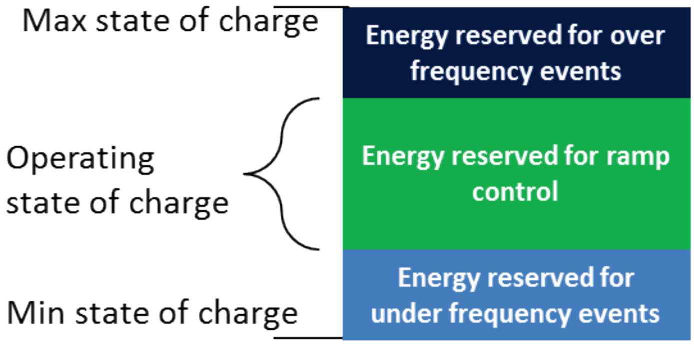

Figure 5: Breakdown of available energy [5]

In fact, the Puerto Rican Association of Producers of Renewable Energy (APER) recommends that energy reserve be divided into the energy reserve for under frequency, energy reserve for over frequency and energy reserve for ramp rate control (Figure 5).

8.2 Compensating upward ramps with inverters

The fact that the inverter can be used to reduce active power output could be usefully employed in the storage control strategy to avoid fast storage charging. It might also result in lower required storage capacity or an extended storage lifetime due to the fact that storage could be used less for upward ramping. In fact the method described in 6.2 originally envisaged double the storage capacity that is calculated in this report. The amount of energy reserve for frequency response as recommended by APER can also be halved by using inverters to curtail active power output in case of over frequency.

8.3 Efficiency of the storage control strategy

The control strategy can result in different levels of energy losses and required energy capacity with a trade-off between the two. Control strategies with higher losses not only imply a loss of revenue but also a higher operating cost due to the decreasing lifetime of the storage. Economic considerations should be taken into account when developing an effective control strategy. Also, it seems that common control strategies that both provide frequency support and limit ramping have not yet been developed. It should be investigated whether there is a synergy between these two services or whether the capacities are independent as is stated in the previous paragraph.

8.4 Size of power park

Clouds moving at the same speed require more time to cover a larger area than a smaller area. It is also less probable that a larger area will be fully covered or uncovered than a smaller area. A greater power park will therefore show smaller output variation than a smaller power park. As reported in the article indirectly [11] and directly in [3] a 1 MW power park can experience fluctuation of up to 90% of its rated output while a 38.5 MW power park only up to 54% of the rated output. This fact should further reduce the required storage capacity. A storage sizing method such as the one described in section 6.2 should be adjusted to correspond to actual maximal output variability that is expected from a plant of a given size.

According to this method the required storage capacity would represent a very significant additional cost. Using an example from Table 1, the 38.5 MW installation has a required energy reserve of 12277 kWh. At a price of 300 EUR / kWh of storage capacity this amounts to 3.7 million EUR. Assuming installation costs of 900 EUR/MW for the 38.5 MW power park, the storage would represent an additional 10.5% of the investment cost.

The authors of the method report in a recent publication [3] the highest measured variability of 54% for the large 38.5 MW power park. Other studies report much lower values for smaller installations and the following may be a pessimistic estimate of the required storage capacity [9]. Adjusting the expression for energy storage from above for 54% instead of 90% we get the following expression

$$\mathbf{Energy\ reserve} = \frac{\mathbf{0.54P}}{\mathbf{3600}} \times \left[\frac{\mathbf{54}}{\mathbf{2} \times \mathbf{r_{max}}} - \boldsymbol{\tau}\right]$$

For larger installations this method would result in a required energy reserve that is about one third of the one obtained with the original expression adding around 7% instead of the previous 21% to the investment cost. The limiting factor, however, is the power output of the storage. If we adjust the expression for the required power output of the storage we obtain

$$\mathbf{Storage\ power\ output} = \frac{\mathbf{P}}{\mathbf{100}} \times \left[\mathbf{54} - \boldsymbol{\tau} \times \mathbf{r_{max}}\left(\mathbf{1} + \mathbf{ln}\frac{\mathbf{54}}{\boldsymbol{\tau} \times \mathbf{r_{max}}}\right)\right]$$

We can expect an approximately 44% reduction compared to the original expression. This would result in an energy to power ratio (number of kWh per kW) of below one. Battery technologies usually have high energy to power ratios. The time intervals during which maximum power is required are in the order of a few minutes. Whether this kind of operation is technically feasible for currently available battery solutions should be assessed further. Flywheels could turn out to be a more appropriate solution due to a more favorable energy to power ratio.

The chance of a 90% output drop does exist even for larger power parks, though, the costs of the additional storage capacity to cover these rare events would probably outweigh the penalties that would be incurred if storage capacity were sized for lower output variability.

8.5 Yearly distribution of fluctuations and compliance threshold

Sizing the storage for the highest possible output variation will result in a too high storage capacity. The TSO, might not require a 100% compliance level. The Puerto Rican regulation for example requires a 98.5% compliance rate on a weekly basis. This means that ramp rates need to be lower than 0,167%/s (10%/min) in 98.5% of all 2 second time intervals in a week. If one were to strictly follow economic considerations, storage capacity should be sized so that the expected penalties of eventual non-compliances equal the marginal cost of additional storage capacity that would reduce the frequency of non-compliance. Battery storage offers some flexibility in this respect. In order to increase battery lifetime, batteries are usually operated within a lower and a higher state of charge limit (for example 20%-80%). In case of rare extreme fluctuations, batteries can be driven outside of that range at some detriment to their lifetime. The optimal size of battery storage should equalize the cost of non-compliance with the cost of operating outside the prescribed state of charge limits and the cost of additional storage capacity.

8.6 Portfolio factor

Individual power parks show much greater output volatilities than clusters of power parks [3]. This is simply due to the fact that when a cloud covers one facility only this single facility's output drops. The probability that multiple geographically separated facilities will experience a change in cloud cover at the same time diminishes with the number of facilities. Combining power parks results in the cluster having a variance of output that is smaller than the individual power parks' variance by a factor of $\frac{1}{\sqrt{N}}$, were N is the number of power parks in the cluster. Ramping requirements apply to individual power parks and thus require much greater storage capacity than would otherwise be required if applied to a cluster of power parks. Whether regulation will in future apply to clusters instead of individual power parks remains to be seen.

8.7 Black start capability

Black start capability is usually required by synchronous generators. With a growing share of renewables and falling share of synchronous generators one could expect that in future power parks will as well be required to provide black start capability. As the report shows, the required storage capacities to fulfill the variability of the active power output are very high and might prove sufficient to provide black start capability at very low additional cost.

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APPENDIX A: Related requirements in selected countries outside Europe

A.1 China

The Chinese standards do not prescribe a droop characteristic. They do require that power parks be able to run for at least two minutes above the 50.2 Hz threshold before disconnecting. Above the 50.5 Hz threshold power parks should disconnect within 0.2 seconds.

A.2 Puerto Rico

Frequency response
PREPA, the Puerto Rico Electric Power Authority, prescribes a 5%/Hz droop characteristic for frequency deviations below 0.3 Hz. For deviations higher than 0.3 Hz a response of 10% of rated power within 1 second is required that has to be sustained for 9 minutes. After the ninth minute the output can ramp down at 10%/min [2].

Ramp rate control
The active power output is required to transition from one output level to another at a rate no higher than 10% of rated output per minute. The rate is screened in 2 second intervals, which means the ramping rate should not exceed 0.33% per 2 second interval [2].

A.3 Mexico

Frequency response
The droop characteristic prescribed by the Mexican regulator, Comisión Reguladora de Energía (CRE), should have a maximum dead band of 0.02% of system frequency corresponding to 0.012 Hz on each side. The power park should have an adjustable doop characteristic between 1 and 10%/Hz. For large negative frequency deviations above 0.3 Hz a minimal increase of 10% of the rated power output is required for a duration of at least 15 minutes [6].

Ramp rate control
CRE, prescribes a ramping rate between 1 and 5%/min. The exact value is determined on an individual basis. Some states, including Baja California, require positive ramping rates lower than 3.5%/min, and negative ramping rates of below 5%/min [6].

A.4 United States

ERCOT, the Electric Reliability Council of Texas, requires a maximum 20%/min ramp rate, though different sources provide different values.

A.5 South Africa

The National Energy Regulator of South African (NERSA) requires that a power park be able to receive and follow a given operating set point above which a reserve of at least 3% should be available. From the available documents it is not clear whether the maximal required power can be above the actual production. NERSA does not specify a maximum ramping rate [7,8].

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