European Distributed Energy
Resources Laboratories

European White Book on Grid-Connected Storage

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Abstract:

In the context of electrical networks mutation and of higher penetration of DER and RES, there is an increased awareness of stakeholders that storage is needed to increase the network's flexibility and reliability, providing ancillary services and helping DER deploy. However, in spite of several studies on the possible applications of storage, and of several ongoing demonstration projects, important information is still missing. Issues such as technical requirements, especially interconnection issues, tariff structures and more generally economical aspects, test procedures for selecting storage, etc. are still unclear.

This White Book, prepared by the DERlab consortium, has the ambition of contributing to the clarification of all these complex issues. It is focussed on storage systems as seen from the grid (including converters), rather than on the storage technologies, and tries as far as possible to remain technology-neutral.

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ABSTRACT

In the context of electrical networks mutation and of higher penetration of DER and RES, there is an increased awareness of stakeholders that storage is needed to increase the network's flexibility and reliability, providing ancillary services and helping DER deploy. However, in spite of several studies on the possible applications of storage, and of several ongoing demonstration projects, important information is still missing. Issues such as technical requirements, especially interconnection issues, tariff structures and more generally economical aspects, test procedures for selecting storage, etc. are still unclear.

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CONTENT

INTRODUCTION

The liberalisation of the electricity market, combined with the international pressure to reduce CO2 emissions, lead to new architectures of the future electricity networks with a large penetration of Distributed Energy Resources (DER), in particular from Renewable Sources (RES).

The new architectures are driven by two factors: the integration of DER including bi-directional flows of both energy and information, and the unbundling of the networks related to liberalization, where producers, transmission system operators and distribution system operators are different and independent key players.

In addition, the end users position will change from passive to active towards the network, both in terms of production and of demand control.

All these changes must happen with ongoing requirements in terms of power quality and of security of supply.

In this context of networks in mutation and of higher penetration of DER and RES, there is an increased awareness of stakeholders that storage is needed to increase the network's flexibility and reliability, providing ancillary services and helping DER deploy. Storage systems can provide various services and can be considered in different ways:

- as distributed energy resource simply. In this case, they will compete with other technologies on the only basis of their cost and technical adaptation,
- in association with a renewable energy system in order to maximise the production of the system and the penetration of DER by shifting the produced energy,
- as a tool for power quality and for smoothing of load curves. Distributed generation options can be used as backup power, but energy storage systems are needed for "ride through" power until the backup system can be brought up to capacity. Downtime translates to loss of business, costly equipment damage, and equipment and network repair time and therefore such short storage time can have a very rapid payback time. In addition, storage will enable the customer to shift its peak loads and become predictable. From the grid side, he will become an "ideal customer" with a constant load profile. Both the utility and the customer should benefit from such a win-win approach.

In spite of several studies on the possible applications of storage, and of several ongoing demonstration projects, important information is still missing. Issues such as technical requirements, especially interconnection issues, tariff structures and more generally economical aspects, test procedures for selecting storage, etc. are still unclear. Besides, the recent focus on electro-mobility, i.e. using the storage systems included in the electric vehicles for grid services, is raising new technical and economical issues which add further complexity. The main issues addressed in this document are:

- the selection of storage applications, based on existing classification studies but with the view from the storage system point of view, rather than from the grid operator,
- the selection of relevant descriptive parameters for each of these applications,
- guidelines to proceed with measurement and monitoring,
- guidelines for dealing with economical aspects.

This White Book, prepared by the DERlab consortium, has the ambition of contributing to the clarification of all these complex issues. It deals with grid issues specific to the use of grid-connected storage systems. It is focused on storage systems as seen from the grid (including converters), rather than on the storage technologies, and tries as far as possible to remain technology-neutral.

Before discussing about the different applications where a storage system could be very useful, we will see on the next chapter the differences between a classic DER and a storage system.

0 CHAPTER 0 – MOTIVATION: WHY STORAGE IS A SPECIFIC CASE OF DER

0.1 Introduction

For a large number of people, storage systems are not so different from a conventional DER power plant. Despite apparent similarities such as location on the grid, nominal power, etc., storage systems are much more different. In the way to argument these differences, this chapter answers to the following question “why do storage systems represent a specific category from the grid viewpoint, compared to conventional power plants?”

The first answer that comes is that the specificity of storage is bi-directionality: it can both produce and absorb energy. This gives a very high potential for network balancing, but a much higher complexity in energy management.

The second one is that the electricity is, a priori, not storable; from this assumption, it appears that we can store the electric energy in different form (chemical, mechanical,…) and so the management will change a lot depending on the storage system technology.

Because most of the characteristics and test procedures must be technology-neutral (in order to simplify the comparisons), some of them will be relevant only to some applications and, therefore, to a range of appropriate technologies.

We will now describe the basic assumptions in order to define “what a storage system is” before making inventory of the important parameters and the apparent difficulties for their assessment.

0.2 Outline of a grid-connected storage system

A preliminary step is to define the main boundary conditions of these grid-connected storage systems. Based on a flexible but already restrictive analyse, the two following points fix this border:

- a storage system is a bidirectional device, connected to the grid (permanently or temporarily), controllable and able to communicate,
- it is connected to the distribution network, thus with a maximum voltage of 35 kV, and has a maximum power of 20 MVA [1].

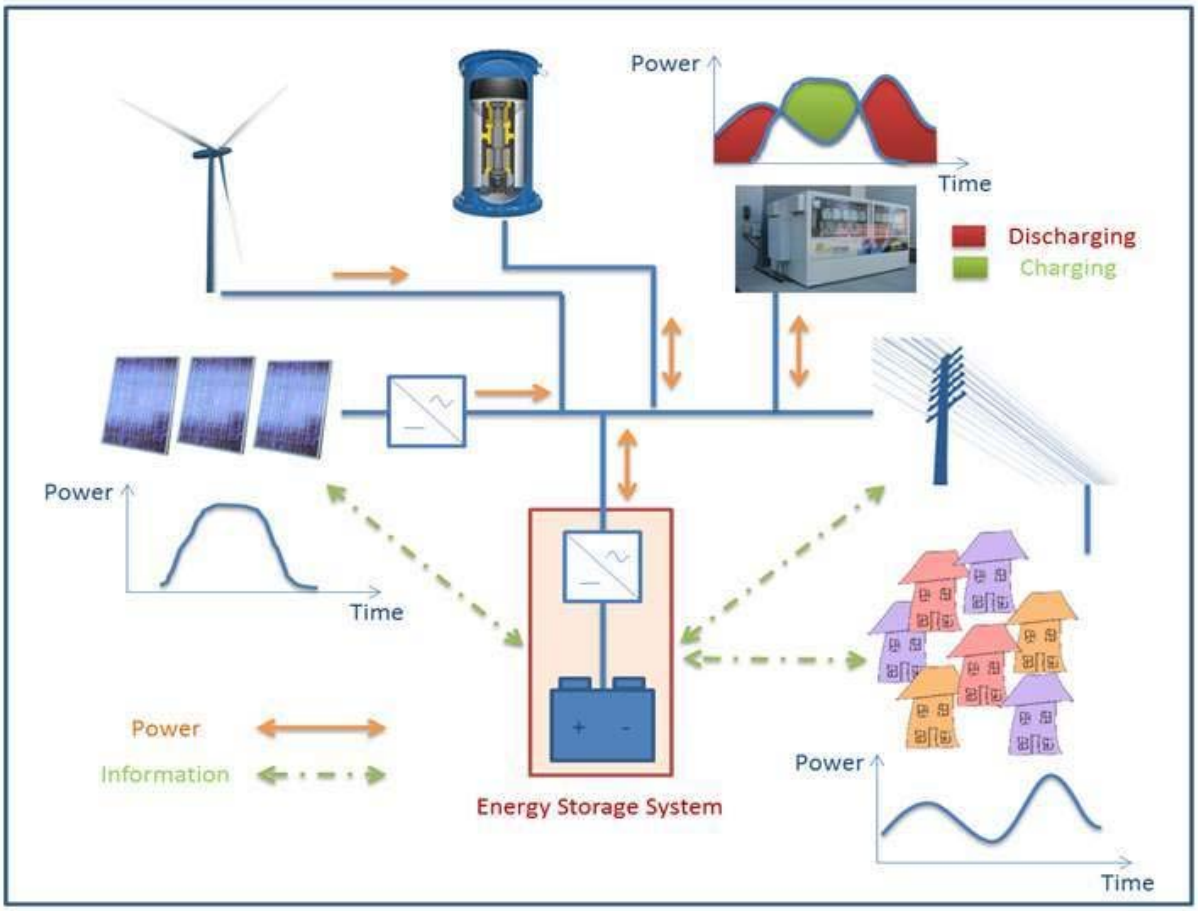


Figure 0.1: Energy storage systems in the framework of smart grids

Like a standard power plant, the storage systems have a number of characteristic parameters that need to be known:

- minimum and maximum power available,
- energy content,
- efficiency in load and supply modes,
- response time for availability (load & supply modes),
- size/area needed, weight,
- possible safety issues,
- variation of the parameters values with time, temperature,…
- delay for switching between the two modes.

These parameters, even if they are quite basic, can be difficult to evaluate. In most of the cases, it is due to the distinctiveness of storage systems. Here is a non exhaustive list of the different specificities of storage systems compared to conventional power plants:

- they can operate in two different modes: energy generators (supply function) and energy receptors/consumers (storage function),
- the technologies on which they are based can be very different, and the energy can be stored after transformation to chemical, mechanical, thermal energy,…

- even if the assessment criteria have to be common to all storage systems, independently of the technology they are based on, the measurement methods may differ,
- for some technologies, the characteristic parameters have a strong variation during the life of the storage system,
- some of these criteria are vey difficult to measure, especially lifetime,
- the energy available varies a lot when changing the discharging rate, the “ageing” of the system, the temperature,…

In addition, especially for electrochemical storage, energy content is most often expressed in Ah, while network operators need to know Wh. These two values differ by voltage, which is not constant during operation.

All these differences induce technical difficulties that do not exist anymore for conventional power plant.

0.3 Conclusion

Storage systems are the only grid-connected devices capable of being a load and a power supply: they have very high potential for grid management and operation and can be envisaged in a large number of configurations.

However, important features are to be known for grid operation:

- electrical features may change according to the charging/discharging operation,
- some technologies will change smoothly from one mode to another, whereas other technologies will need a delay between the two operating modes,
- or some technologies, the available power can depend on the state of charge of the storage, while the available energy can depend on the requested power.

Their complexity requires the setup of an appropriate methodology for the system design and sizing: this is the purpose of this document.

The first step of this process is to clarify the different system configurations where a storage system could have a strong added value, which is the subject of the next chapter.

1 DEFINITION OF APPLICATION CATEGORIES

Numerous studies have been published about the various applications that storage systems could be used for [ ]. We have selected some here, representing as far as possible a large panel of the different business model cases.

1.1 Analysis of the storage applications in grids

Among the huge number of applications for which storage systems could be used, a large panel representing the different business model cases has been selected.

For each of the applications listed in the next paragraphs, the added value that the storage system could provide is shortly described. Then, when necessary, one or two figures illustrate the application and the storage system standard solicitation profile associated.

1.1.1 Electric energy time shift

This service is also known as arbitrage [2, 3, 4, 5, 6]. The energy storage unit (ES) can purchase energy at off-peak times when prices are low, and resell the energy when prices are high. This resale is used to generate a profit for the owner of the ES, but may also have a wider benefit in protecting consumers from price spikes [6]. This “buy low”/”sell high” use for ES may be performed profitably by either the utility company or by an end-user [4,7]. ES used for arbitrage must be capable of charging and discharging for several hours at a time, typically ranging from 4-5 hours [4] up to 8 hours [6] or, in some cases, more than 20 hours [6]. At the end-user side, ES could be effective at smaller timescales of 2 hours – with the optimal usage depending on local tariffs [7]. High ES efficiency is very important to profitable arbitrage services [6].

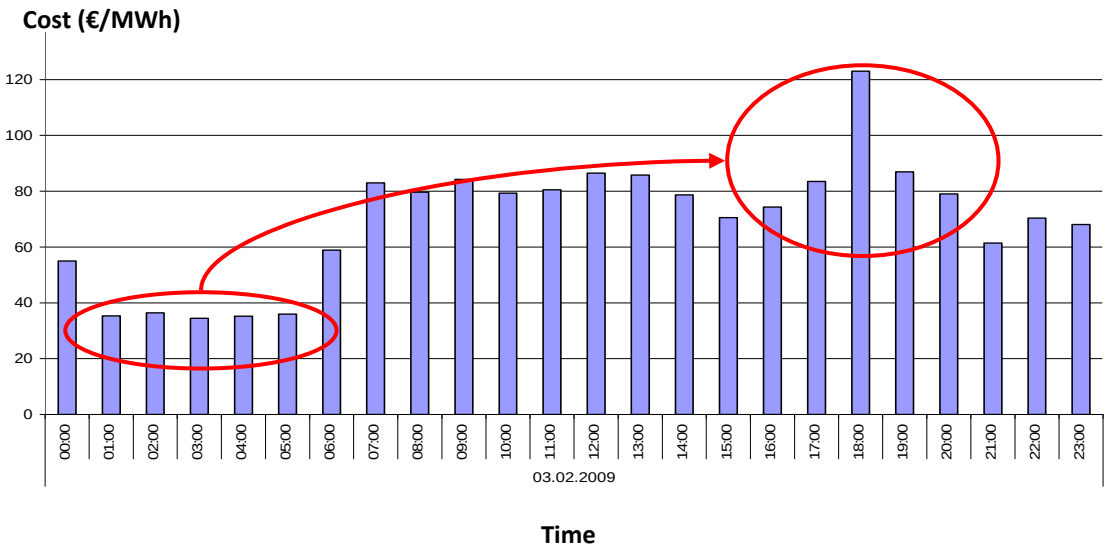


Figure 1.1: Electric energy time shift

1.1.2 Investment deferral

If a substation is overloaded, the power requirements cannot be met and the lifetime of the substation is decreased. Adding a storage system between substation and consumers can solve the problem and allow us to avoid substation upgrading [8].

The storage is charged during a few hours at a constant rate when substation is under loaded; some hours later, it is discharged also at a constant rate during a few hours when the substation is overloaded. Generally, this overloading appears a few times a year (during winter or summer peak consumption period).

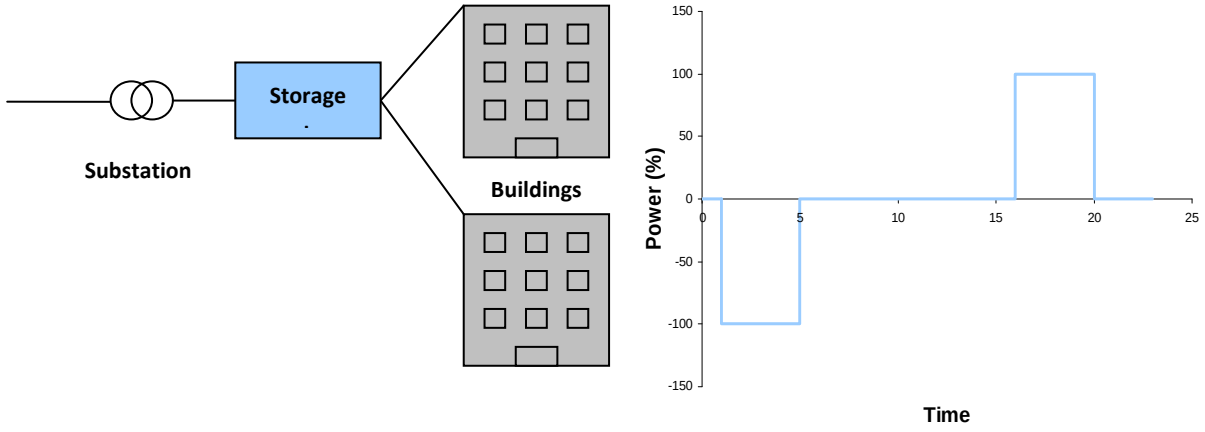


Figure 1.2: ***Left: Scheme representing the location of the storage system Right: The associated storage system standard solicitation***

1.1.3 **Peak-shaving**

Peak-shaving is a method to prevent high peaks of consumption. By charging the storage when demand is low and discharging when demand is high, we can decrease cost of electricity using an undersized electrical power contract [9].

Despite the storage system profile solicitation depends on the load consumption (see red curve in Figure 1.3). It is generally composed of two steps: a charging process of several hours when the demand is far away from the maximum power allowed, and a discharge during peak power consumption for a couple of hours as illustrated in Figure 1.3.

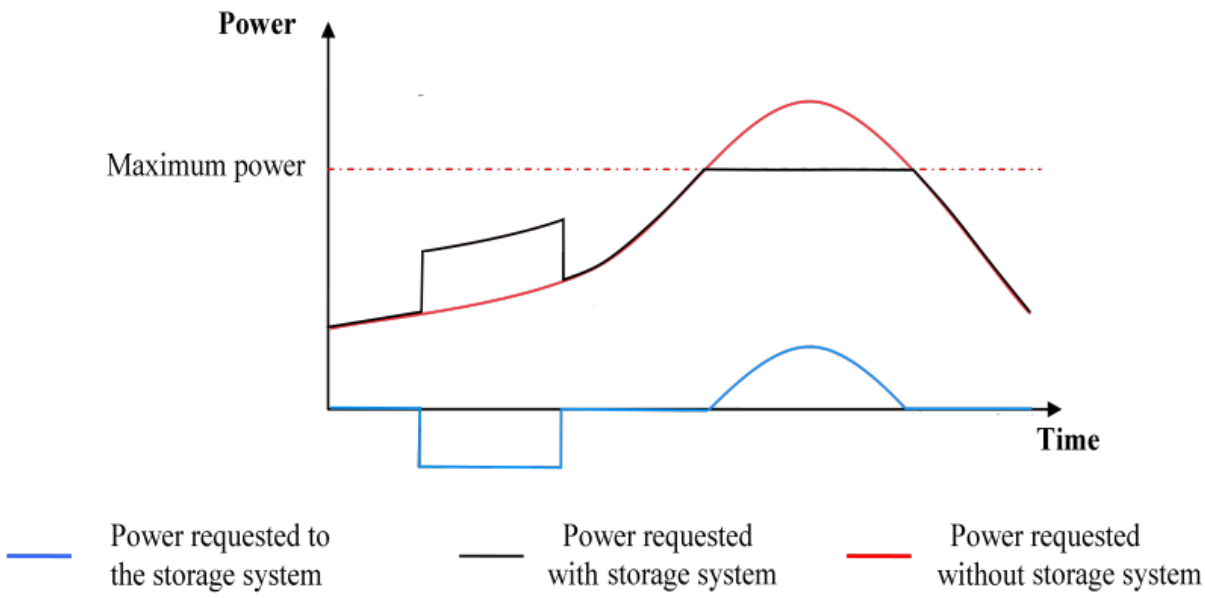


Figure 1.3: ***Comparison between power requested to the grid with and without the use of a storage system for peak shaving. Blue line: standard storage system profile solicitation***

1.1.4 **Load following**

The balance between production and consumption is of vital importance in the electric network because unbalance can cause islanding and black-out. Usually, this balance is provided by varying the output power of a conventional generator in order to fit the load.

An important ability of storage systems is that they can both produce and absorb energy. So, a storage system with 1 MW output power can provide 2 MW load following capacity [10].

Load following application is characterized by power output varying in periods of minutes/half an hour. The output changes in response to the changing balance between generation and demand are shown in Figure 1.4.

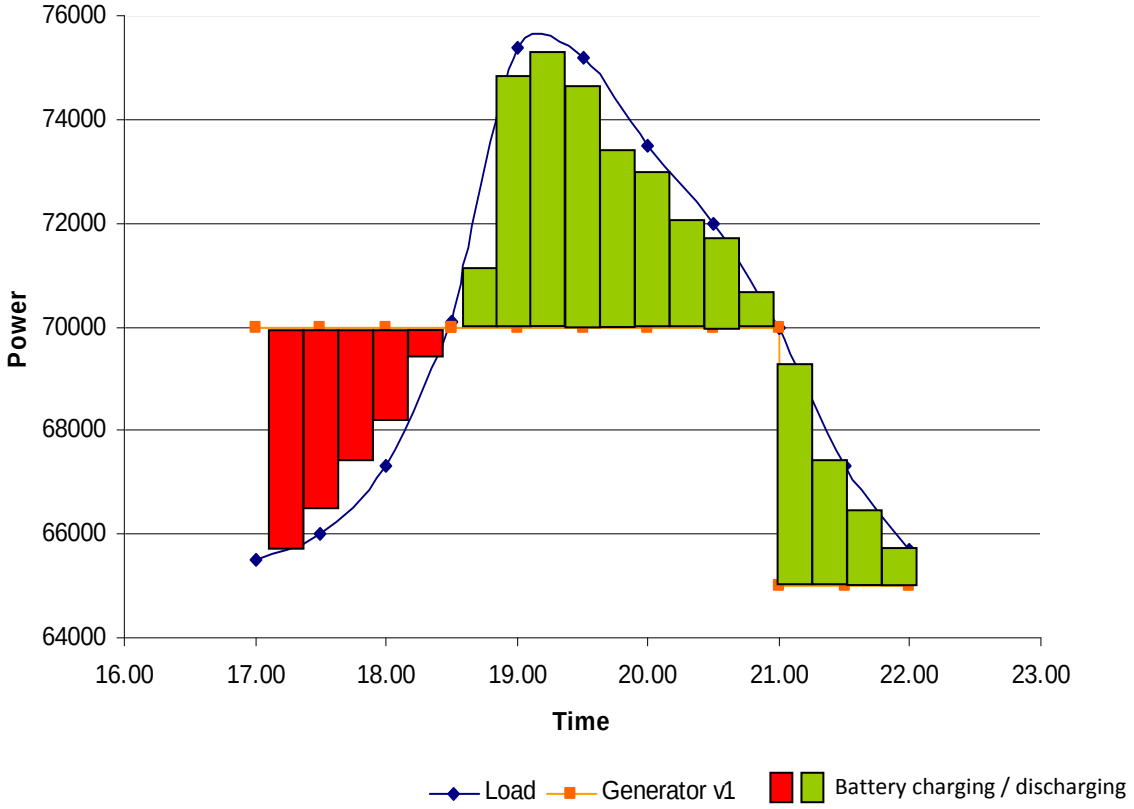


Figure 1.4: ***Illustration of a storage system used to fit the load (load following). The output from storage system + generator equals the load consumption Blue line: load; orange line: constant output power from a generator; bar chart: storage system solicitation***

1.1.5 **Spinning reserves**

Spinning reserves are generators kept in readiness to provide power on short notice, such as with large spinning but part loaded steam powered generators. ES could replace open cycle gas turbines for this purpose [2, 3, 11]. This application is characterized by fast time response (1 s) and discharge duration of approximately 15-60 minutes.

ES could also be used for standing reserve services, which have a longer lead-time than spinning reserves [12, 13]. This ancillary service is expected to require operations times of 1 to 5 hours for the ES [7].

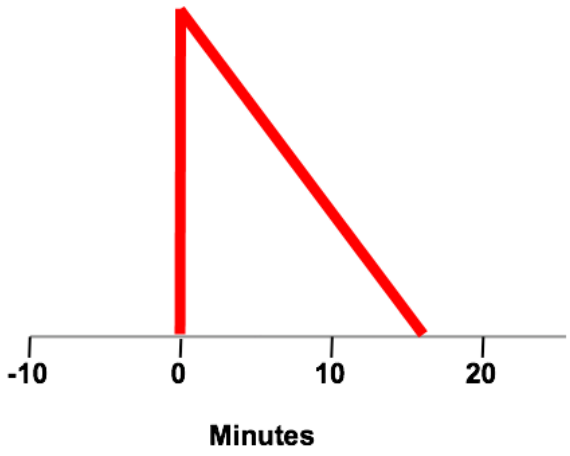


Figure 1.5: ***Time response, discharge duration and power output profile solicitations of a spinning reserve used in case of transmission/generation outages for frequency***

1.1.6 **Black start**

After a black out (an area remains without any electricity), a step-by-step restoration of the electricity supply is required. The paradox is that most generating units require electricity to start-up. Emergency diesel generators can provide the so-called “black start capability”. But also electricity storage systems can provide this electricity needed to start up the generators.

The storage needs high power for a short time (seconds to minutes).

1.1.7 **Integration of non predictable sources**

Energy storage systems may be used to ensure a smooth power output from a variable energy source [14, 15, 16, 17]. This is particularly important for renewable energy sources connected to the grid, so that they can meet power delivery contracts if the forecasted supply of renewable resource (e.g. wind or sunlight) is not available. Energy storage can also store excess energy produced by renewable sources, which otherwise would be wasted [12, 18]. When used to meet contractual obligations, ES is expected to have an operation period of 6 to 10 hours [7].

The storage system profile solicitation depends mostly on the nature of the generation unit. Yet, in all cases, it is characterized by fast changes between charge and discharge and frequently changing output (from every minutes to one hour).

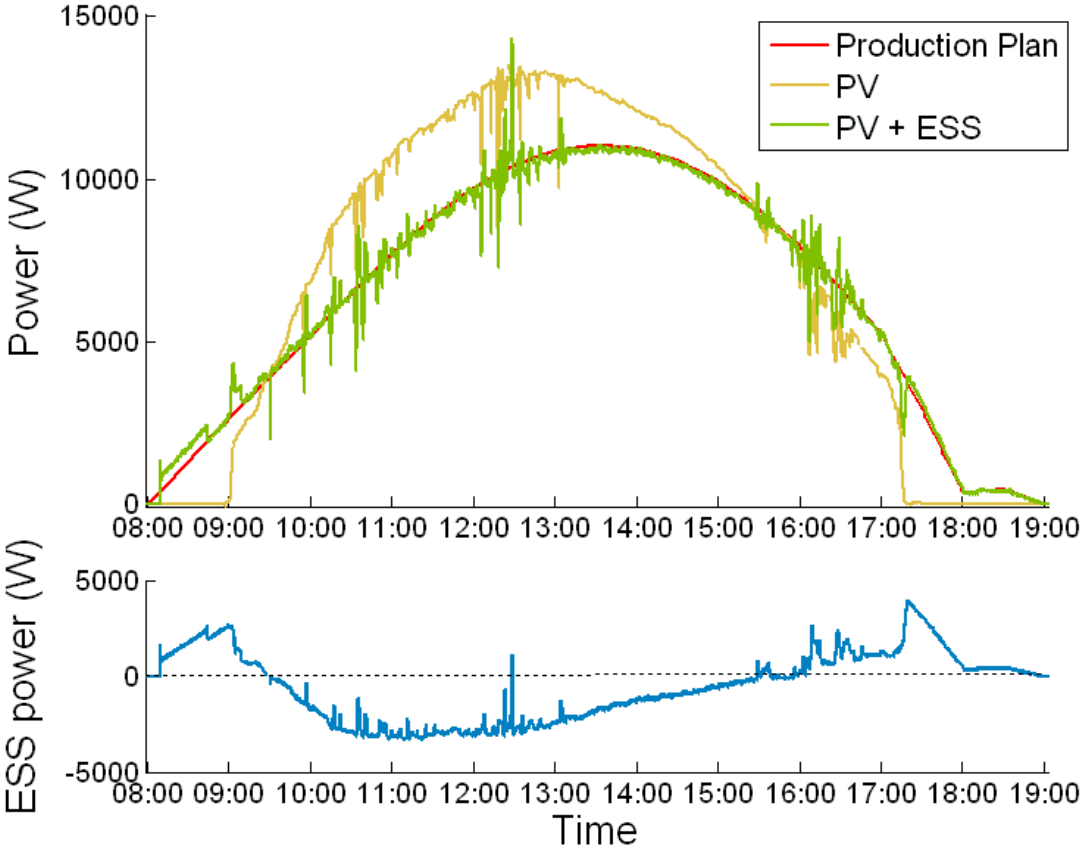


Figure 1.6: ***Top: Classic PV production (yellow) and PV + storage system used to smooth the production (green)***

Bottom: Charging/discharging power of the storage system (associated with the PV profile on the top plot)

1.1.8 Control power/regulation

Regulation is used to reconcile momentary differences between supply and demand. This application shows strong similarities with the "load following application"; the main difference is located on the time scale of the application (longer for load following) [10].

The standard storage system profile solicitation is characterized by:

- outputs that change as frequently as every "second to minute" depending on the balance between load and generation,
- fast switch between charge and discharge.

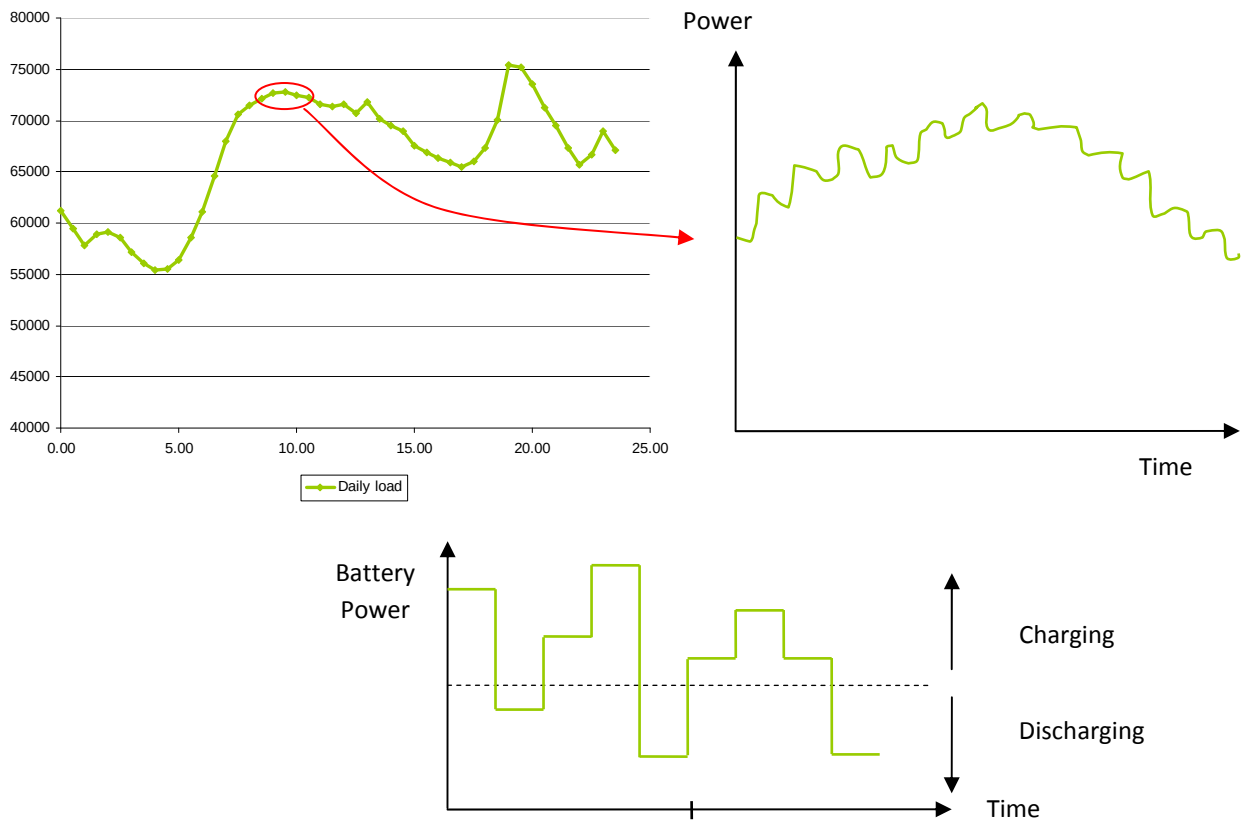


Figure 1.7: ***Top: standard load profile for a day (left). Zoom on the daily load profile (right)***

Bottom: Classical power profile solicitation of a storage system used for regulation

1.1.9 Power regulation with intermittent sources

When RES such as PVs are integrated in a power system, an efficient energy management between PV production and storage is essential to resolve issues related to the provision of ancillary services in a modern electricity system. Power balancing at local level through an appropriate control of the storage component can become beneficial for the TSO as well as for other stakeholders including energy providers. Storage can be placed in order to regulate the flow of active power between the feeder and the distribution system and provide local reactive power compensation at the point of storage connection.

In this case, simulation results show that, with this control scheme, it is possible to minimize active power exchanges between the feeder and the distribution system due to fluctuations of the power injected from PV systems. The important contribution of the storage equipment is to offer the capability of regulating the power exchange with the upstream network.

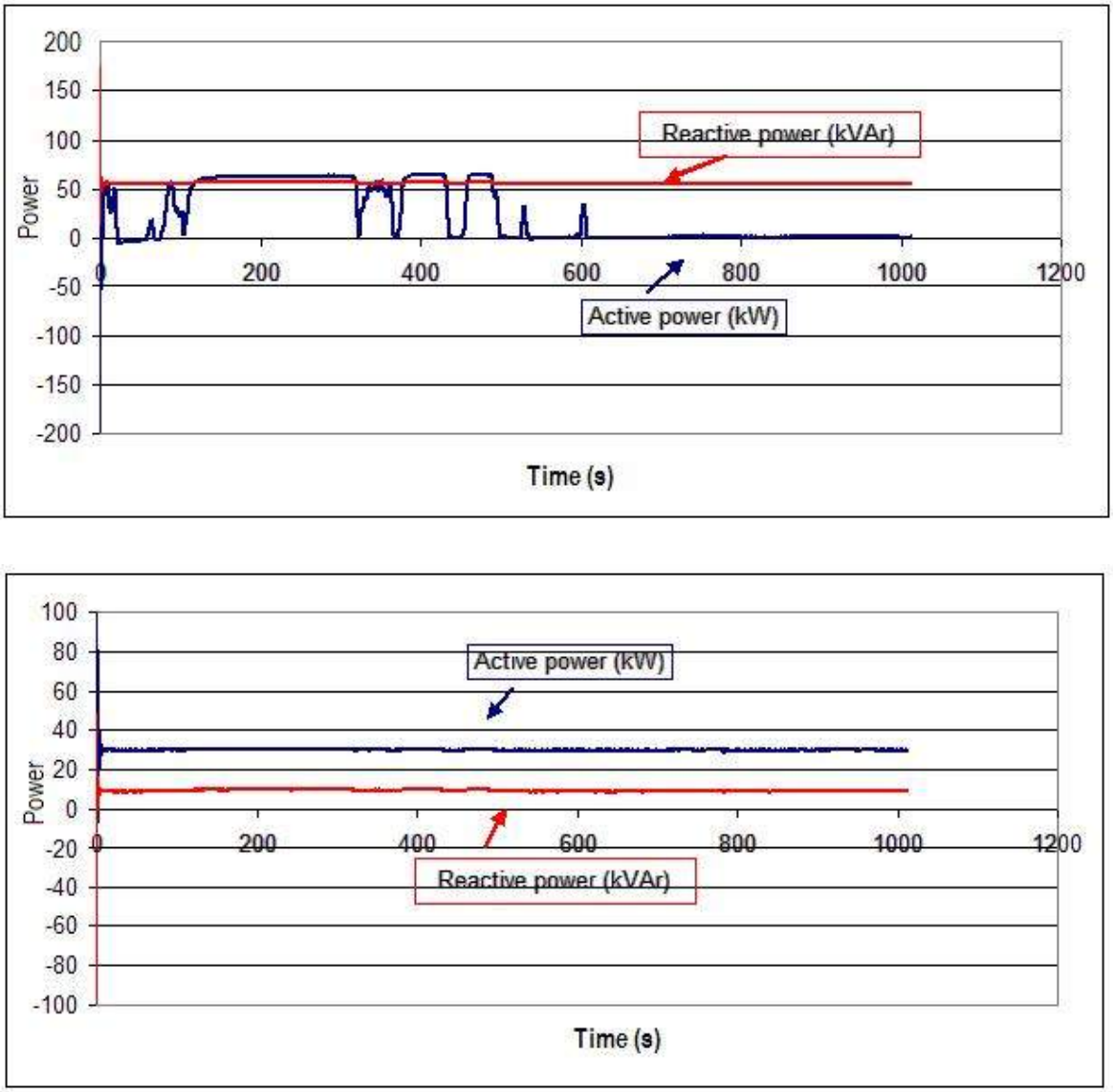


Figure 1.8: Top: power flow in the battery inverter; bottom: power flow in the main grid

1.1.10 **Power quality and stability**

Utilities dealing with generation, transmission and distribution of electrical energy are under an obligation to provide customers with energy of good quality in an effective and reliable manner. Maintaining the required power quality is an issue to which power system operators pay much attention. It needs a proper operation of the power system and some measures to be taken to compensate for disturbances that deteriorate power quality. Traditionally, such measures were compensating devices, like for example, DSTATCOM or APF, among other “custom power” devices. Networks with distributed generation provide the operator with new possibilities and solutions.

A storage system can improve transmission performance by compensating for electrical anomalies and disturbances such as voltage sags, noise, harmonics,... The result is a more stable system with improved performance.

The expression “power quality” covers in fact different aspects such as harmonics, transients, etc. [2-34]. This is generally a medium timescale use for ES, requiring operation for 15-60 minutes at a time

[4], or it may operate on a shorter timescale of 10 seconds to 1 minute [7]. This application needs sub-second response, partial state-of-charge operation, and many charge-discharge cycles of the storage system.

The storage units may be located wherever power quality is to be improved, for example in a customer's UPS system, or on the utility side working with a FACTS device [19].

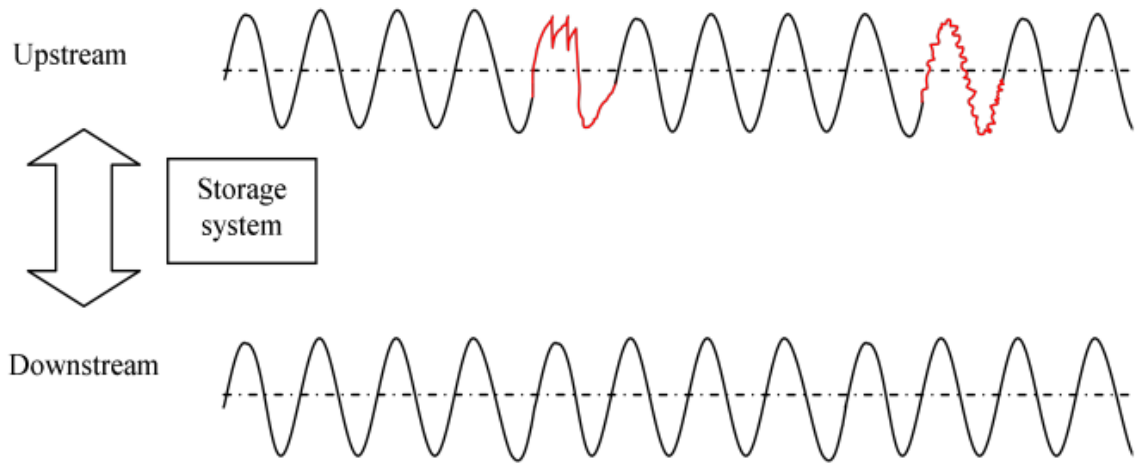


Figure 1.9: Illustrated objectives of a storage system used for power quality

This "global" application can be divided in several ones that are described in the next paragraphs.

1.1.11 Voltage Support – Long timescale

The ES may be used locally to provide voltage support, helping to keep the grid within the acceptable voltage ranges [2, 3, 18, 20]. This may be important in situations where energy supplied by a renewable source exceeds demand or when demand is very high– for example a town with a large number of PV panels at noon on a sunny day [18] or a couple of houses during peak winter time.

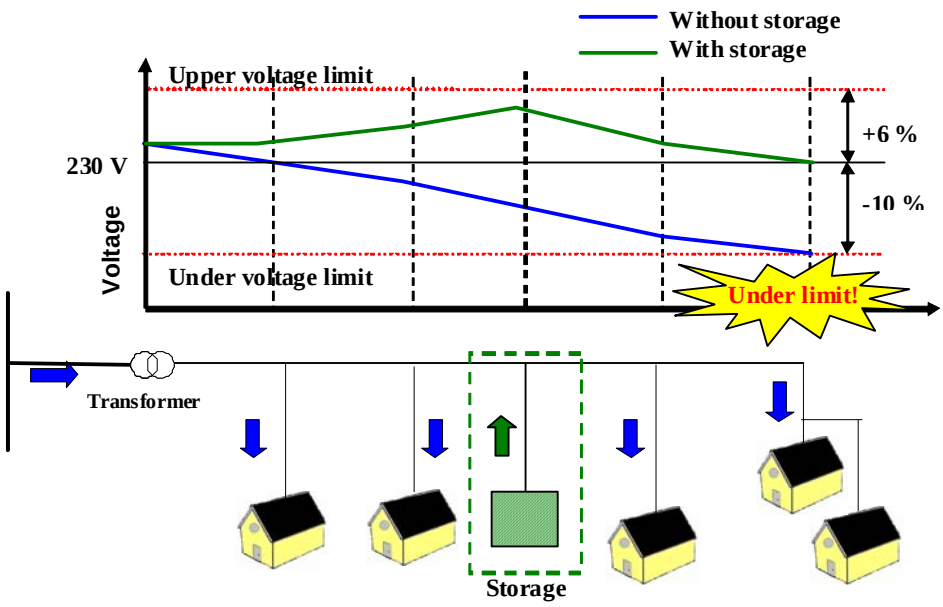


Figure1.10: Illustration of a storage system used for voltage support

1.1.12 Voltage Support – Short timescale

Voltage support may also be operated at a very short timescale of 2-5 seconds [7]. This specific task performed by the unit depends on its operation mode.

In current control mode, which is assumed for load compensation, the inverter must inject to the network currents such that undesirable components of the load current; for example, in the case of harmonics, reactive and negative sequence ones are cancelled and the network current becomes the fundamental harmonic and the positive sequence. At the same time, the inverter is expected to generate active power to meet requirements of the management system. It is also possible to stabilize the voltage at the point of connection. To stabilize the voltage, the inverter must inject a reactive current of fundamental frequency and positive sequence which gives an appropriate voltage drop on the reactances of the supply network.

As an example of load compensation, Figure 1.11 illustrates the possible operation of the storage system in current control mode. The system compensates for the reactive power and load unbalance. In 0.5 s, active power set value was decreased from 50 kW to 30 kW (load power constant), then in 1.25 s load power was decreased by 30% proportionally in each phase. Load and network currents are presented in Figure 1.12.

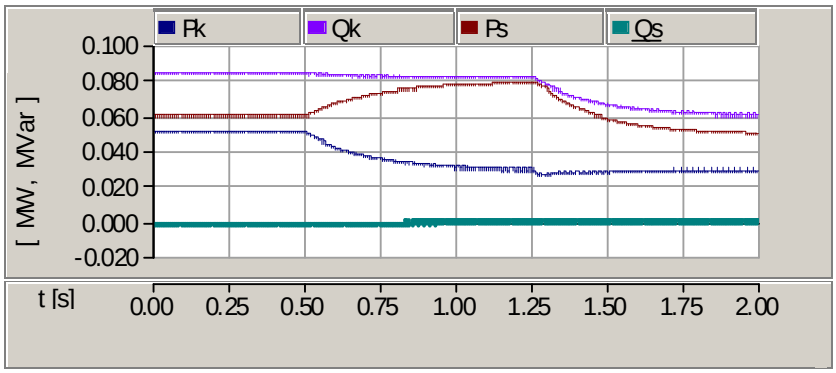


Figure 1.11: ***Operation of a storage system in current control mode Pk – inverter active power, Ps – network active power Qk – inverter reactive power, Qs – network reactive power***

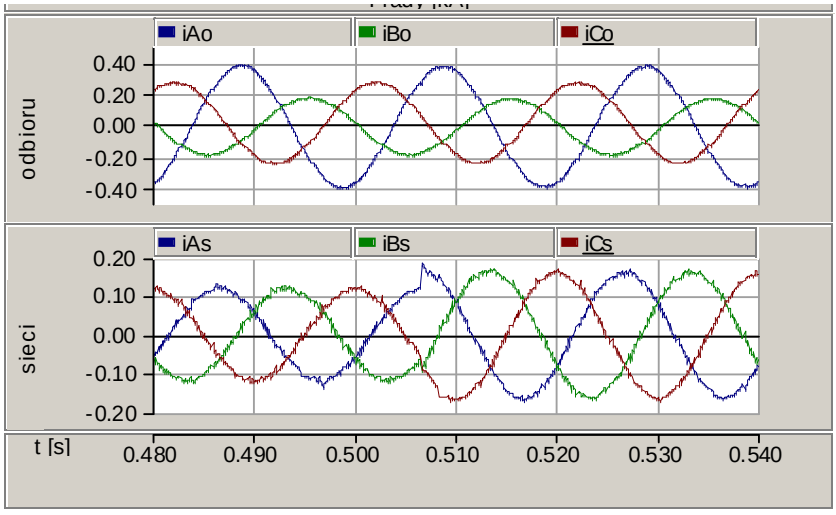


Figure 1.12: ***Load and network currents - storage system used for load unbalance compensation Change in set active power in 0.5 s***

In voltage control mode, the inverter has the task to produce active power and stabilize the supplying voltage at the point of connection. Control scheme applies typical active power and voltage control. The system may provide a mean for voltage dips reduction. This type of application is presented in Figures 1.13 and 1.14.

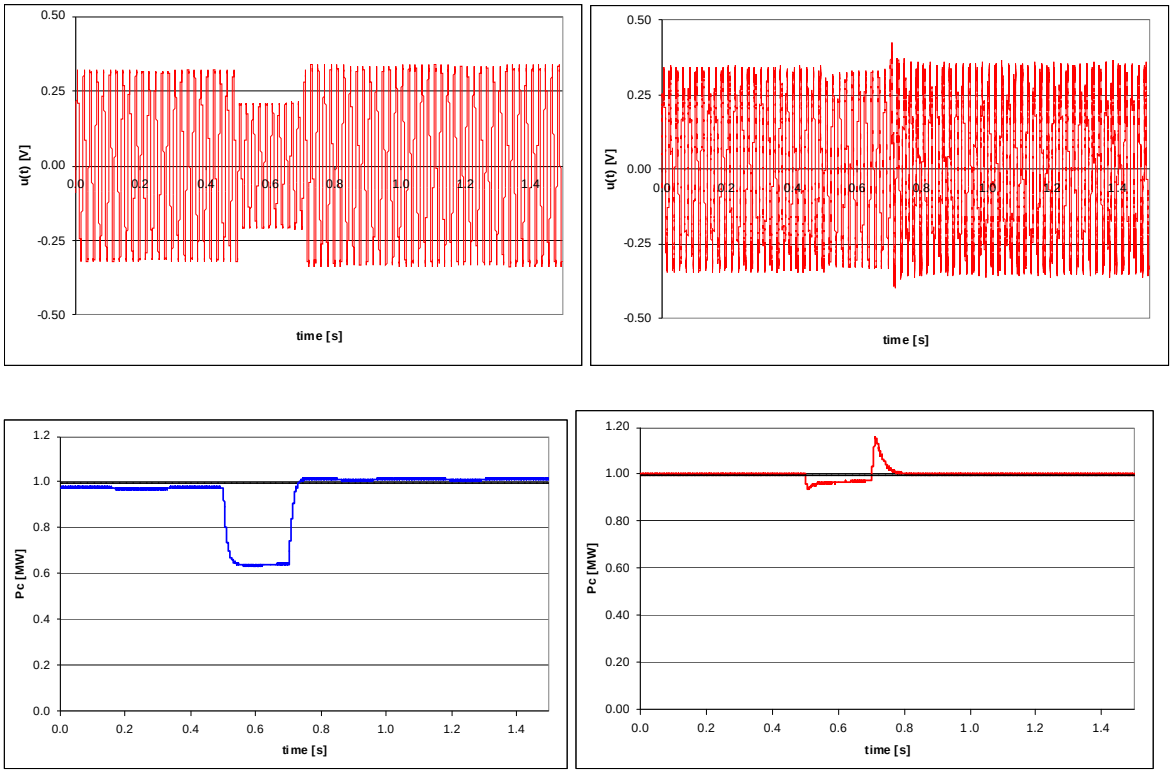


Figure 1.13: ***Voltage dip on LV busbars under a symmetrical short-circuit in the supplying HV network. From the top to the bottom: voltage waveforms, voltage RMS values Left) without compensation; right) with compensation by storage inverter***

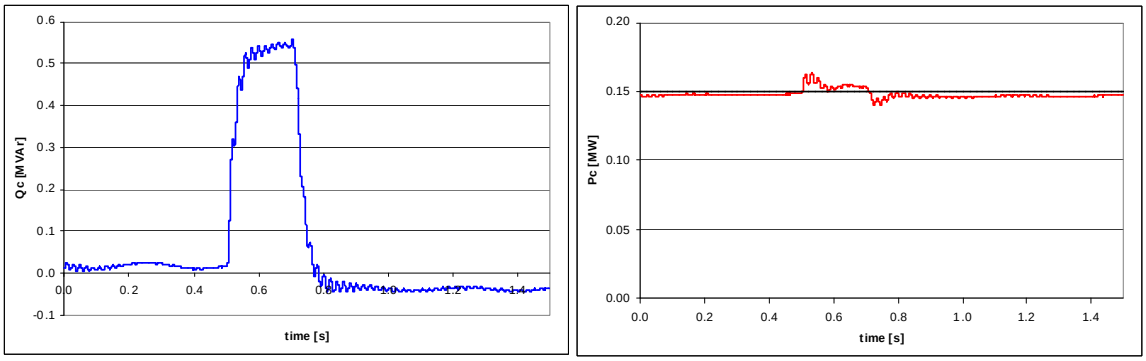


Figure 1.14: ***Inverter reactive (left) and active (right) power***

The effect of compensation is dependent on the coupling impedance between LV and MV networks resulting from the power of a distribution transformer.

PQ control applications require storage systems of high peak power discharge for a few milliseconds up to several minutes.

1.1.13 Frequency support

The grid must also be kept within a specified frequency range [2, 20, 21]. The frequency of the grid may be altered by short-term, random fluctuations in demand which requires energy provision to be regulated, therefore this service is also known as continuous regulation [3, 5, 21]. This is a short-term service, lasting up to 30 minutes. Storage units can be located anywhere on the network with regard to this service as the frequency is common throughout the power system.

Frequency is one of the power quality indices and should be kept within the permissible range of variations. According to the European standard EN 50160, in normal operation conditions the frequency value should be:

For synchronized networks:

- 50 Hz ±1% (49.5 – 50.5 Hz) during 95% of week
- 50 Hz+4%/-6% (47.0 – 52.0 Hz) during 100 % of week

For island operation:

- 50 Hz ±2% (49.0 – 51.0 Hz) during 95% of week
- 50 Hz ±15% (42.5 – 57.5 Hz) during 100 % of week

In the state of equilibrium, generated power complies with demand power. However, active power demand varies in time resulting in frequency variations. Maintaining frequency in the required range needs an appropriate generation capacity and proper control system. In the power system, some generators operate below their power capacity, so disposable power (the maximum active power which can be generated at the moment) is larger than generated power. The difference between disposable and generated power makes up spinning reserve.

Spinning reserve is at the disposal of power system operator and is necessary to follow load changes and to maintain frequency in a given range. Normally, it is provided by thermal or hydro generators synchronized with the network and is categorized on primary, secondary and tertiary power reserve. Primary control is the control of active power of individual generating units by means of their rotational speed regulators. Its aim is to maintain the balance between generation and demand. Primary control action starts after a few seconds from a disturbance (0-5 s) and finishes when the balance between generated and consumed power is re-established. Secondary control takes its action afterwards, 30 s after a disturbance at the latest, and lasts for a maximum of 15 minutes until the frequency is stabilised. Secondary control is power and frequency control by means of coordinated effect on individual controllers of selected generation units. Its aim is to maintain the frequency constant value.

Recently, battery storage systems have been used for frequency regulation offering reserve power for primary control. Battery is discharging when the system frequency is below the lower limit and charging when the frequency is above the upper limit. When frequency is within the permissible range, the battery neither absorbs nor supplies any power. However, to control the state of charge, the operation strategy may include battery recharging or discharging during those intervals. Control algorithms as well as a method for battery dimensioning have been presented in [22].

Batteries used in frequency regulation should respond in a time of 3-5 seconds, be fully activated within 30 seconds and according to the UCTE regulations have to supply primary reserve for at least 15 minutes. For a given nominal power, this time determines the battery minimum capacity. This type of applications requires typically batteries of 1-10 MW power and 30-60 minutes storage time [22, 23].

In many European countries ancillary services are offered under free market conditions. It means that availability of reserve power is paid for and economic viability of storage applications can be determined by comparing total revenue from selling the reserve power with total costs of the storage system operation.

1.1.14 **Power reliability**

Power reliability refers to the number of interruptions to the delivery of electric power that are experienced per unit of time; this could potentially be improved with ES [2, 3]. Energy storage for this service would operate on time scales from 15 minutes to one hour [7].

1.2 Definition of three generic applications

Indeed, from a "grid point of view", it is possible to select and cluster applications looking at:

- their location on the grid (e.g. end user, distribution network,…),
- the amount of energy or power required,
- the kind of service requested (energy, grid support,…),
- the added value to the grid.

In the present work, among all these different ways to cluster applications, we are focusing on the similarity between applications from a "**storage point of view**". This is characterized by the fact that **we do not look at** the:

<u>Sizing of the application</u>

For example, we do not consider any differences between peak shaving applications for end users or for a transmission substation (even if the difference between the two storage sizings is huge).

<u>Location on the grid</u>

The frequency and the kind of ancillary services will be different depending on the location (distribution substation, end user,…). This factor is not taken into account.

<u>Added value to the grid</u>

For example, investment deferral application has the benefit to avoid system upgrading, and electric energy time shift application allows earning money depending on the electricity market. As different as their added value could be, the storage system solicitation is very similar (i.e. we store energy for a couple of hours for then discharging it latter).

Starting from these assumptions, we selected and cluster applications looking at different storage solicitation criteria. The criteria of interest for clustering applications from a “storage point of view” are the discharge duration and the power profile solicitation (not the average value, only the profile).

The chart below shows the different applications and their associated **discharge duration**. Looking only at this plot, we can cluster the applications in, at least, two categories:

- applications with short discharge duration (from milliseconds to a couple of minutes),
- applications with higher discharge duration.

Indeed, this criterion involves large differences between storage systems on several points:

- need (or not) of fast time response (if the discharge is not scheduled),
- high power or high energy storage systems abilities.

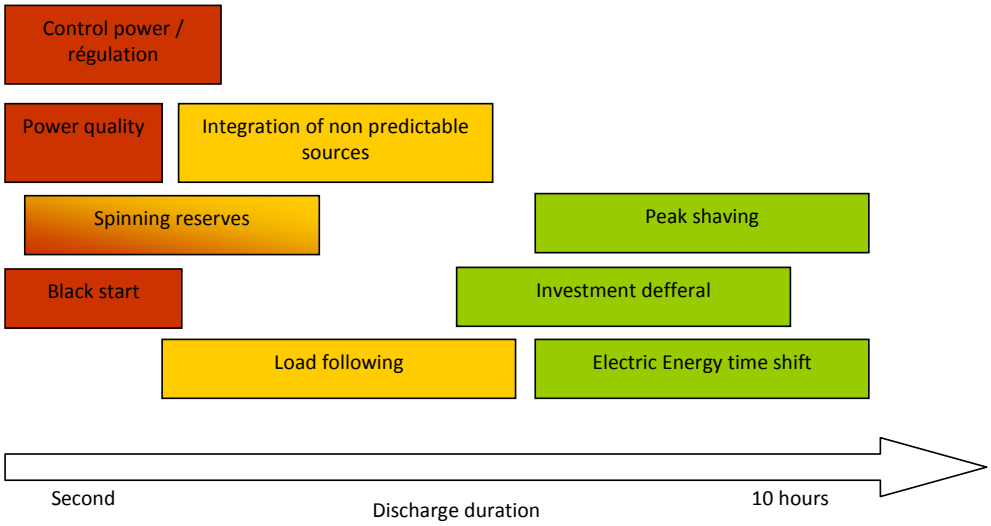


Figure 1.9: Comparison of the discharge duration for the different applications listed above

The second criterion of interest is the **storage system profile solicitation**. Among the listed applications, two categories are of interest. The one corresponding to applications with few “steps” in the power profile requests (electric energy time shift or black start for example), and other with lots of variations in the power profile (integration of non predictable sources or load following). This criterion involves rapid change in power profile and fast commutations between charge and discharge mode.

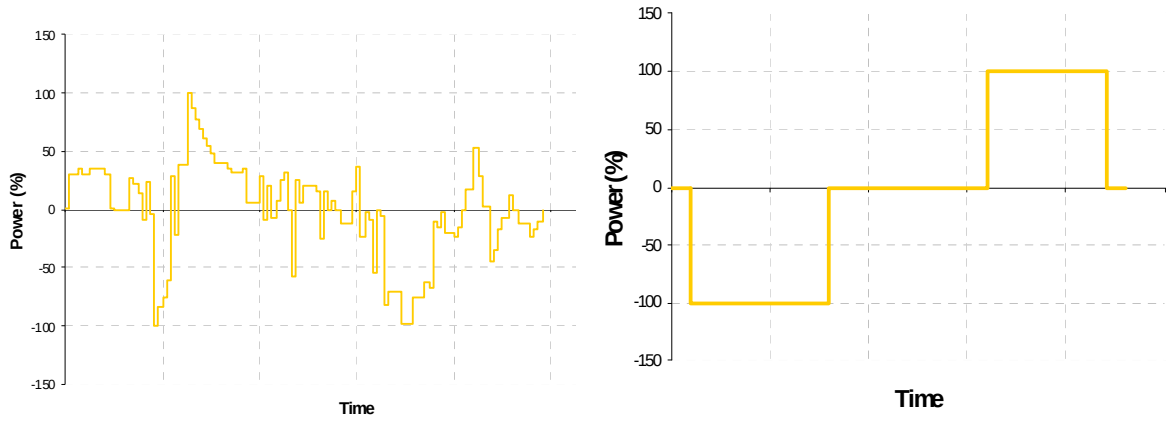


Figure 1.10: ***Comparison of the storage systems solicitations on two applications Left: integration of a PV source; right: peak shaving***

This clustering analysis leads to the clear identification of three main categories:

- **time shift applications**: a storage system is used to store energy in order to be discharged later (generally several hours later),
- **power balancing**: a storage system is used to smooth production/consumption. This involves both energy and power ability and fast changes between both charge/discharge and discharge/charge,
- **power quality support**: a storage system is used to provide pulse power for ancillary grid services depending on grid conditions.

2 CHARACTERISATION OF CATEGORIES

In the previous chapter an overview of the different applications of large scale grid connected energy storage systems is presented. From the overview it becomes clear that for a first order categorization of the applications the following properties of the storage system can be used:

- response time,
- power rating,
- energy rating.

where the energy rating is a measure for the amount of time a given power has to be applied by the storage system. For the different applications, the relative importance of these three properties differs. As such the applications can be divided into three categories where one of these three properties is dominant:

- power quality support (named FAST hereinafter),
- power balancing (named POWER hereinafter)
- time shift applications (named ENERGY hereinafter).

In this chapter these three categories will be characterized in terms of limitations of storage system properties that apply to that category and load cycles that represent a standardized cycle pattern to the

applications in that category. For the categories POWER and ENERGY a sub-categorization is made to cater to the differences in the applications.

Per category the important properties are given. This description includes a summary of the possible applications for that category of storage systems, the business case rationale for that application, the requirements for that type of application, the testing pattern or representative loading cycle and the most important parameters to measure.

2.1 Application category FAST – Power quality support/fast response

In this category the response time is the dominant property of the storage system. Different types of storage systems will have different response times, or ramp times. For example while an electrochemical battery has a near instantaneous response to an applied load, a pumped hydro storage system has a ramp time in the order of minutes. When the response time matters for the application, this parameter must be taken into account when selecting the most suitable storage system.

FAST 1

Application:	Automatic, fast high two-way power response to frequency change (corresponding to the inertia behaviour of synchronous generators).
Objective/business case:	Automatic power regulation. The service can be traded as 'regulating power' at the power exchange markets.
Requirements:	Automatic, fast two-way power response to frequency changes, high power during short time.
Testing pattern:	Cycling triangle change of frequency, corresponding to 20-80% power and 20-80% energy.
Measurements:	The power response to ramping frequency (up and down). Energy efficiency.

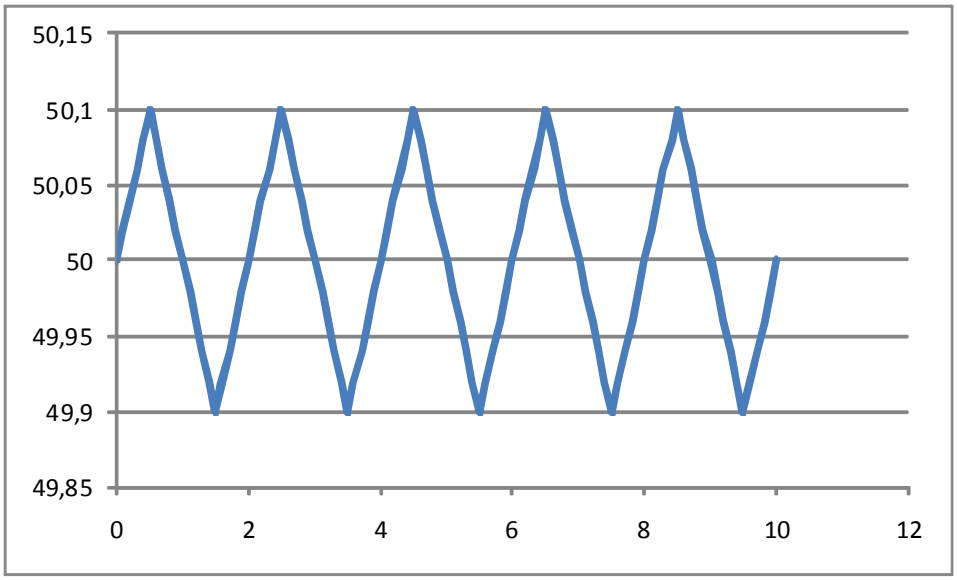


Figure 2.1: FAST 1 testing pattern. X: time (minutes). Y: Frequency (Hz)

2.2 Application category POWER – Power balancing

Energy storage systems with a focus on their power rating are typically used to balance an offset between the power generated and consumed on a time-scale of minutes to an hour. Balancing can be done both on the transmission level as well as on the distribution level, where the different implementations require different system sizes and power ratings. Smoothing the output of a wind farm or PV system influenced by wind or clouds is a typical application on distribution level scale. The storage system in this application acts mainly as a short term buffer. As such, the round-trip efficiency of storing and retrieving the electrical energy must be high or the price per kWh of storage dirt-cheap. An expensive storage system which wastes a significant part of the energy will probably not be cost-effective.

POWER 1

Application:	Automatic two-way power response to frequency deviation.
Objective/business case:	Automatic contribution to system power balancing. The functionality could be mandatory, e.g. as part of a grid code.
Requirements:	Automatic two-way power response to frequency deviation, following a specified response curve.
Testing pattern:	Slow triangle change of frequency, corresponding to the range specified by the response curve and implying a 50% change in SoE.
Measurements:	Relation between (steady state values of) frequency and power.

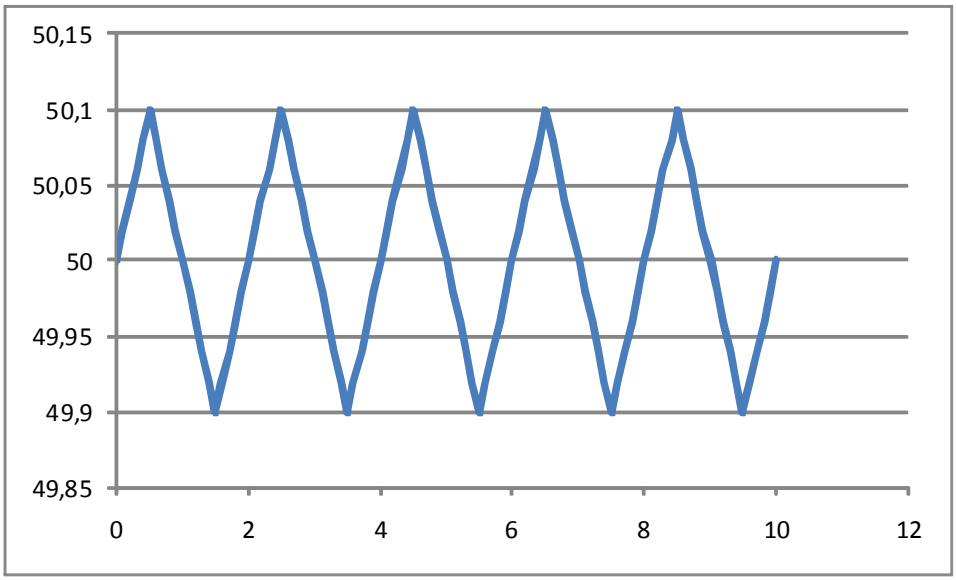


Figure 2.2: Testing pattern for POWER 1. X: Time (hours). Y: Frequency (Hz)

POWER 2

Application:	Smoothing the power fluctuations from a wind farm.
Objective/business model:	Reducing the power fluctuation from a wind farm can reduce the flicker level (increase the power quality) and reduce the need for rapid, compensating power regulation in the power system.
Requirements:	Many small cycles.
Testing pattern:	Controlled 'stochastic' small triangle cycle power loadings (1-10%), over-loaded by a deep triangle cycle loading (80%).
Measurements:	Power response to the reference signal in Figure 2.3. Energy efficiency.

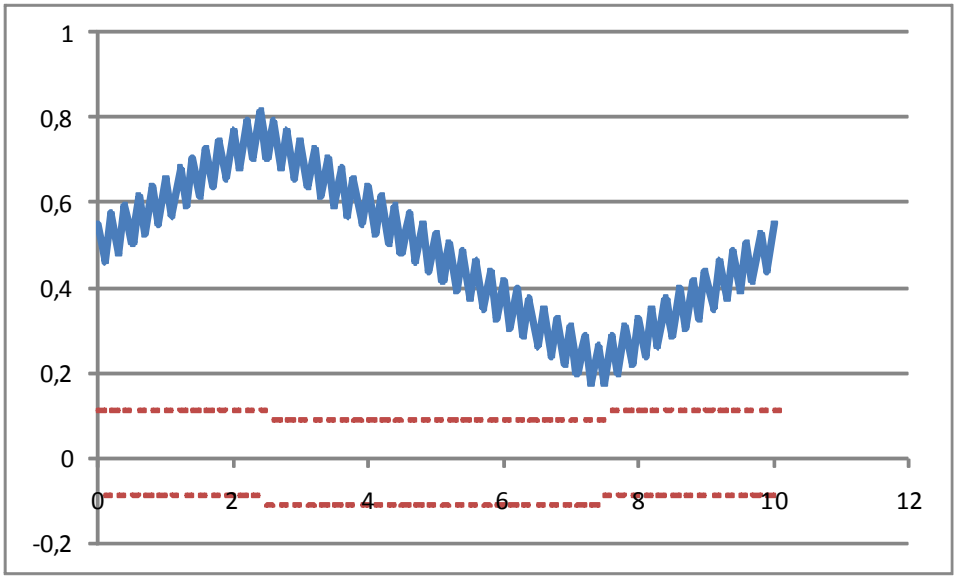


Figure 2.3: ***Power reference signal (lower) and resulting SoE (upper) of POWER 2. X: Time (hours)***

POWER 3

Application:	Smoothing the power fluctuations from PVs.
Objective/business case:	
Requirements:	Many full power cycles.
Testing pattern:	Controlled full power loadings with 'stochastic' filling/emptying time periods corresponding to 1-100% of the storage capacity.
Measurements:	

POWER 4

Application:	Balancing area-to-area power exchange in the power transmission system. (DK – DE case)
Objective/business case:	
Requirements:	High power, high energy.
Testing pattern:	?
Measurements:	

2.3 Application category ENERGY – Time shift

Energy is stored for a duration of hours to days when day/night demand and generation patterns are compensated. Examples are the storage of the French nuclear base-load power generation in Norwegian pumped hydro basins during the night and storage of excess solar power in thermal storage for use in the evening. Again round-trip efficiency is an important parameter in selecting a storage system. The aforementioned options of pumped hydro and thermal storage are mainly interesting in this category as the economy of scale applies.

ENERGY 1

Application:	Shifting energy in time – wind power.
Objective/business case:	To compensate for prediction errors in time (a change in weather occurs before or later than predicted). Reducing the need for compensating power regulation. Reducing the penalties for not following the agreed power generation/balancing pattern.
Requirements:	Full power (in or out) during few hours, once a day.
Testing pattern:	Starting at 50% SoE. Repeat: full power in until 80% SoE, 10% power out until 50% SoE. Pause. Full power out until 20% SoE, 10% power in until 50% SoE.
Measurements:	Energy efficiency.

ENERGY 2

Application:	Shifting energy in time – solar power (day to night).
Objective/business case:	To compensate for the non-generation during the night. The storage will replace the use of the grid as energy buffer. This may reduce the cost related to selling and buying electricity.
Requirements:	Full energy in/out during 10 hours.
Testing pattern:	Starting at 10% SoE. Repeat: 80% energy in during 10 hours (until 90% SoE). Pause 2 hours. 80% energy out during 10 hours (until 10% SoE). Pause 2 hours.
Measurements:	Energy efficiency.

3 MEASUREMENTS

In this chapter, we discuss the determination of main characteristics/parameters of the storage (including nominal capacity and energy efficiency).

As for the other sections of this White Book, we limit our analysis to systems below 20° MVA and 35° kV. The parameters to be assessed/measured are numerous:

- footprint and weight,
- maximum (dis)charge rate,
- safety (fire, overcharging, deep discharging, reversed charging, impact, vibrations),
- operator safety,
- efficiency,
- temperature range,
- EMC,
- availability,
- calendar/cycle life,
- dynamic performance,
- short circuit behaviour,
- communication,
- specific) power density,
- fault ride through,
- (specific) energy density,
- controls check.

For these different issues, we will discuss measurement and calculation methods and equipment, and try to identify development needs.

Different applications of electrical energy storage systems give different requirements, leading to a performance evaluation which can be based on any combination of the quantities detailed in this chapter. By measuring the value for these quantities, different options for a certain application can be ranked to find the most eligible candidate.

There are many aspects of an energy storage system that are quantifiable. These measurements can partially be done on individual components of storage systems. Many of them, however, arise from the integration of the different components into a single system. An example is the energy density. The energy density of the storage medium may be readily available (ex. the energy density of a prismatic Li-ion cell). Nevertheless, in the storage system the raw storage medium is combined with safety electronics, control electronics, current and measurement leads, possibly a cooling system and an enclosure suited for the environment the storage system will be situated in. All these additional components add to the weight of the system, thus reducing the energy density metric.

We will now discuss some of the many quantities related to storage systems.

3.1 Footprint

Storage systems in most cases include a transformation of electrical energy into a different medium. Batteries store the energy chemically, compressed air and pumped hydro use the transfer of air and

water from one place to another, etc. In any conversion step, some of the energy will be lost and converted to heat. Especially for batteries, maximum throughput is strongly related to the maximum power generated in the storage medium which may lead to overheating and degradation of the storage system up to catastrophic consequences. Batteries may have different power ratings for charging and discharging which should be taken into account when designing a storage system.

In mechanical storage systems the maximum throughput depends on the size of the generators and electric motors used to transfer the medium, both with their maximum power rating.

For battery storage systems the power-to-energy ratio has a maximum value. If more power is required the only option is to increase the storage size as well. For mechanical systems as well as for flow battery systems, power is independent of the storage capacity to a certain degree, of course. It makes no sense to use a high power generator with a small storage capacity for most applications.

Maximum power thus can be a matter of cooling or a more physical limit of the conversion process, being it chemical conversion rate or generator size.

Measurements of the maximum power of a storage system is a combination of assessing the maximum power of the individual components and determine whether the cooling capacity of the system can sustain the heat generation in the conversion.

3.2 Maximum power throughput

The footprint of a storage system relates to the weight and dimensions of the storage system. For different applications, restrictions arise with respect to the weight or size. Think for example about the battery pack in an electric vehicle which should be as light and small as possible. But also inclusion of a storage system in an existing substation site may give rise to stringent occupied area requirements due to the limited area available in the substation site. The footprint of a storage system is readily measured but, as mentioned above, should include all components and especially balance-of-plant items.

3.3 Safety systems

Different applications require different safety precautions. Any storage system contains a large amount of potential energy and most systems are inherently capable of releasing that energy in a short time. This might be through fire, explosion or electrical short circuiting. Storage systems in the vicinity of people will require more stringent precautions but in any case care should be taken to identify possible risks, and assess the possibility and the effect of the said risks to quantify them. Any reasonable risky situations should be addressed and safety mechanisms should be set up accordingly by means of fuses, over/undervoltage protections, rugged enclosures, cell balancing, thermal safety switches, etc.

3.4 Operator safety

A major difference from an operator/maintenance point of view is the effect that storage systems (and especially batteries) have no off-switch. Any other piece of grid equipment can be powered down for maintenance. Additional care should be taken as batteries are always active and can pose serious high voltage exposure risks to operators and maintenance workers. Additional protocols and education is needed in the field.

Operator safety is a design issue, but requires safety measurements on site to double check whether the equipment that is being worked on is 'hot'.

3.5 Efficiency

Efficiency is a major parameter to determine. When half the energy is thrown away for transfer from and to the storage medium, storing energy quickly becomes expensive. Efficiency for storage system is usually measured as the roundtrip efficiency, taking into account the losses for both transfer between electricity and the storage medium. The higher the value, the better. Typical roundtrip efficiencies for Li-ion batteries are in the order of 95%. Other battery systems and mechanical storage like CAES are somewhere between 50 and 95%. Efficiency is measuring the total energy going into the storage system while charging a fully empty energy storage system and the total energy extracted out of the fully charged energy storage system. Most energy storage systems however will have a temperature and rate dependency with respect to the roundtrip efficiency. Typically, a colder system will have a lower efficiency, and a faster charge or discharge rate will have associated a lower efficiency as well. Especially for batteries like lead acid, discharging in one hour yields significantly lower total energy discharged compared to a discharge in 20 hours. When doing a synthetic measurement of the roundtrip efficiency this should be done as close to the dynamics of the actual application as possible regarding rate and temperature.

Another part of efficiency is related to the fact that some energy systems cope better with shifted voltage/current AC input than others. This of course is more related to the AC/DC converter used than the actual storage system which is typically DC driven.

3.6 Temperature dependency

As mentioned in the efficiency section, most storage systems and especially batteries have a significant temperature dependency. Depending on the application, this is something that could have a big impact on the performance. For batteries it is common to publish test data for the entire applicable temperature range, which can differ from a wide range of -40 to +85 °C to much smaller ranges. Also for charging and discharging different temperature ranges can apply. For example Li-ion batteries are typically charged above 0 °C only, while discharging is possible at -20 °C.

As a chemical system, batteries are prone to self-discharge due to unwanted side reactions that take place all the time in the battery. These reactions are also temperature dependent and generally will have an Arrhenius-like temperature rate relation. This means that for every 10 °C increase in temperature, the reaction rate doubles. The value of 10 °C is a rule of thumb however. Especially NiCd and NiMH are chemistries that have a large self-discharge rate. This means that even if the storage system is not actively used, e.g. transferring power in or out of the system, it will still consume energy due to self-discharge. So the aforementioned chemistries are less suited for systems in which energy will be stored for several days to weeks before being utilized.

3.7 Electromagnetic Compatibility (EMC)

Energy storage systems, being large DC systems with low voltage per cell (typically tens of cells in strings), will generate significant electric fields through all interconnections and DC bus-bars. It is a recurring problem in designing a battery system that temperature probe signals or per cell voltage measurements used by the battery management system, are disrupted by the fields generated by the large currents flowing nearby the measurement lead. Proper care should be taken that these leads are sufficiently shielded. Another option is to use optical signal transfer, which requires higher per cell

safety circuit investments to translate the electrical signal to optical signals. Also auxiliary systems nearby can be influenced by the fields generated, so for all components used in a energy storage system the electromagnetic susceptibility of the components should be measured.

3.8 Availability

Any battery can be discharged down to the low voltage limit set by the manufacturer. It is a fact that for most chemistries, large cycles (between fully charged and fully discharged) cause more degradation of the cells (i.e. more capacity loss and more increase in internal resistance) than small cycles. Actually, in order to transfer 100 Ah in and out of a 100 Ah capacity Li-ion cell, it will cause significant less damage to do 5 cycles of 20 Ah in and 20 Ah out, than one cycle of 100 Ah in and out of the cell. The cell can for example sustain 1000 100%-DoD cycles, but 6000 20%-DoD cycles. For the 100 Ah cell, this means a total throughput of electrons of 120 kAh instead of 100 kAh during the lifetime. It does mean that at every moment only 20 Ah capacity is available. This is one of the most interesting parameters to play with, with respect to selling the stored energy. One could set price levels for discharging down to a certain DoD. Cheap electricity prices: only down to 20% DoD, high electricity prices: down to 80% DoD. The battery will be worn down more quickly but more money is made as well. The one who masters this game the best, will earn the most.

3.9 Calendar vs cycle life

As detailed above in the availability section, the battery will degrade with a rate depending on the use. On the other hand, a battery will also degrade when not used, similar to the self discharge. As soon as a battery is in operation, different clocks start to tick and any one of those clocks could signify the end of the battery. For some chemistries it is already determined that because of the rate of degradation in storage, it is purely a matter of 'use it or loose it'. Even continuous 100%-DoD cycling will cause less degradation than the storage.

The different clocks will tick with different rates depending on the chemistry of the battery, the design, the operating conditions and the actual materials used. To determine the merit of implementing an energy storage system depends largely on in-depth knowledge of the degradation rates, which can even differ between different generations of batteries from the same manufacturer.

3.10 Dynamic performance

Typically a storage system, transforming electrical energy to and from chemical or mechanical energy, has a non-linear power versus efficiency behavior. This behavior also depends on the state-of-charge of the system. As such, modeling the impact of implementing a storage system in the network should take into account these parameters. Measuring the dependency could be done by performing microcycles at different state of charge with different power draws.

3.11 Short-circuit behaviour

A short-circuit, or a fault, could occur either within the storage system (internal fault) or within the grid (external fault), as shown in the Figure 3.1. The behaviour of the system and its corresponding reaction differ depending on the location of the fault.

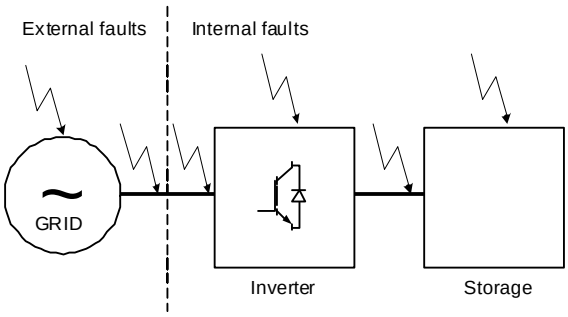


Figure 3.1: Different possible fault locations

Internal faults within the storage medium or the grid inverter is considered a safety issue and should be included in the design of the system (see also 'safety systems' and 'operator safety' sections). Common system behaviour during internal faults within the grid inverter is to isolate the fault (if possible), disconnect both the AC and DC terminals (using a suitably rated fuse, contactor or breaker) and then de-energize the DC link capacitors (using a thyristor crowbar circuit). During a fault situation the energy storage system is disconnected from the grid and therefore not operational until the fault has been cleared. With severe faults, (human) intervention is typically required to reset the system after the fault has been cleared.

External faults in the grid result mainly in a voltage dip on the AC terminals of the grid-inverter. Other phenomena include voltage unbalance and frequency variation. The severity and duration of the voltage dip depend on the nature of the fault and the distance thereof from the terminals of the grid inverter. The closer the fault is to the terminals of the grid-inverter, the more severe the voltage dip would be; a fault exactly on the terminals would lead to a 100% voltage dip (residual voltage of 0 V). The required behaviour of storage systems under these fault conditions is largely defined in the prevailing grid codes of the network operator in which the storage system is being operated. It could either be required to disconnect from the grid completely, or to ride-through the fault whilst still being active (see ‘fault ride through’ section).

3.12 Fault ride through

Fault ride through is a concept that is mandatory for large generators in power systems. It requires that such generators remain active during an external fault and support the grid during the fault and subsequent recovery period. Due to increasing levels of DG penetration, the trend is that also smaller generators and storage systems will need to satisfy such criteria.

If the contribution of the grid inverter towards balancing of the grid is small, the storage system would be allowed to disconnect during an external fault and be reconnected after the external fault has been cleared and the voltage has been restored to its nominal value. However, as the contribution towards grid balancing of such systems increases, its significance in supporting the grid becomes larger and the connection requirements dictate that the grid-inverter should support the grid during a fault. This is commonly performed by the grid inverter remaining connected to the grid during an external fault and providing reactive power to the grid in order to stabilise the grid voltage quicker. For this purpose, the storage system itself is actually not required as the grid-inverter is capable of controlling the reactive power.

The DERlab White Paper on grid-connected inverters [24] describes these requirements (specific voltage dip depth and durations) and its recommended behaviours in more detail.

Furthermore, if the grid-code does not allow for an energy storage system to maintain an island grid, the system should also disconnect, usually based on a Rate of Change of Frequency (RoCoF) protection algorithm (so called “anti-islanding”) implemented in the protection system of the grid-inverter.

3.13 Communication system

A grid connected storage system comprises a number of different communication levels. The primary level is the battery management system (BMS), with communication and information exchange on component level between the storage medium (either cell or battery level) and its direct supervisory equipment. Typical measurement values here are battery temperatures, actual voltage and current levels and cooling unit parameters such as air-flow or cooling water temperatures.

The energy management system (EMS) complements the BMS by incorporating the management of many BMS systems together, including their overall protection systems. If applicable, the EMS allows redundant storage units to be managed for increased availability of the system, as is often critical for utility application. The EMS could also be integrated as part of the grid-inverter control. Typical measurement values here are state-of-charge and voltage distribution amongst many cells or batteries.

The system management is implemented as the top layer of communication. The system management incorporates the main functionality of the storage system with the external market players, using for example price signals. All the functionalities to perform ancillary services are provided within this communication layer. Also control signals from the grid (power curtailing, or set-point deviations) are controlled in this layer.

Similar levels of communication are applicable for mechanical storage systems, as appropriate.

Typical measurement values here are system availability, grid usage load profiles, curtailment information and market signals.

3.14 Controls validation

The services that can be provided by grid-connected storage systems are largely ensured by intelligent software control of the system. In grid applications it is vital to validate, if not certify a system before any connection to the public grid is allowed. This validation covers both the hardware and the software aspects of the system. To validate the control architecture and algorithms, also during worst-case conditions, control systems are extensively tested in simulation as well as laboratory or factory testing. The control system also has different levels, starting from the primary control of the active elements (for the grid-inverter this would be the semiconductor devices) up to the higher level control, responsible for system stability.

The control system can be simulated using either off-line simulation tools or alternatively real-time hardware simulation platforms (see the DERlab White Book on real-time power hardware in the loop testing [25]). The latter provides substantial benefits as regards the validation of the system interaction, and if the grid is suitably modelled, also the system response of control signals of the storage system to the connected grid. This valuable information is of course important during development of the system, but even more during the factory (FAT) and site acceptance tests (SAT) of such systems.

Typical measurement values here are controller bandwidths, controller speed on grid disturbances or set-point variations and controller stability under all circumstances.

4 ECONOMIC ASPECTS

Different storage devices, may be used in combination with other distributed generation energy sources in a variety of grid connected or stand alone applications. Along with the alternative energy resources and the corresponding topology, the storage system, is the next most important technical decision that might affect the overall impact and system performance.

An intelligent energy management system functions in order to optimize generation in accordance with forecasting of the renewable energy resources, and optimizing demand of controllable and switchable loads in accordance with demand forecasts. The best scheduling of energy, and ecological and economic constraints will define the optimized storage scheduling. The goal of the module is to optimize energy flows between generation, supply and points of use, to minimize the operating cost or to maximize the profit on systems with DG. The goal function usually compromises the cost of generation, the cost associated with the grid, and penalty costs.

Although a number of technical challenges related to the integration of storage have to be addressed, this chapter discusses the importance of the storage integration within a consistent commercial framework. It has been recognized that the present arrangements and mechanisms for pricing of distribution services do not treat DG and storage adequately and systematically. Issues related to charges of losses, connection and the use of network along with the use of storage are subject of negotiations between stakeholders, where many different arguments are used. Network operation and practices, together with adopted pricing policies, define the level of access available to participants in the electricity marketplace and therefore make a considerable impact on the amount of storage and generation that may be accommodated. In other words, as adopted technical and commercial arrangements actually dictate the degree of openness and accessibility of networks, it is vitally important to establish a coherent and consistent set of rules on both technical and commercial fronts.

As the different chapters are going to treat storage according to application-driven appropriate technology, economics are going to coincide with this approach. Depending on the technical solution that the storage will provide in each case (such as active-reactive injection, energy efficiency, ‘shallow’ or ‘deep charges’, ancillary services provision, reliability, power quality) a set of economic rules and cost functions, are going to be linked, concerning the customer and/or the energy provider.

4.1 Electric energy time-shift

4.1.1 Application overview

Electric energy time-shift involves purchasing and storing electricity from wholesale markets during lower cost time periods and discharging the stored energy for resale in wholesale markets when prices are high. Generation resources can also use stored energy to offset its need to purchase electricity from higher priced wholesale markets. However, cost savings depend upon wholesale markets as opposed to retail electric tariffs.

4.1.2 Technical considerations

In this application the storage discharge duration is mainly affected by the ability to make “buy low”/”sell high” transactions during the year versus the incremental cost for additional energy storage (discharge duration). Taking into account the Variable Operating Cost (VOC) of the storage system (i.e. the maintenance and replacement cost), the equations of the storage system ‘profit’ can be written as follows:

$$Profit = \frac{Cost\ x\ Energy\_Purchased\ \ - Price\ x\ Energy\_sold}{incremental\_cost\_for\_discharge\_duration}$$

Under the prerequisite, Profit – VOC > 0

The storage *minimum* discharge duration for this application is supposed to be two hours. What is critical for this storage service provider is the incremental cost that is the increase of the amount of energy that can be stored (to increase discharge duration). The demand of the system is probably five or six hours (the typical duration of a utility's daily peak demand period). The profit of the transactions from these applications is based on the difference between the cost of buying-storing energy and the benefit from discharging-selling. Critical factors for the above transactions, with sensibility involved, are the variable operating cost and the storage efficiency. When the variable operating cost increases, or the efficiency decreases, this reduces the number of transactions for which the benefit exceeds the cost reduction.

4.1.3 **Application synergies**

When storage is used for electric energy time-shift it could also provide the following services: investment deferral, transmission congestion relief, reliability, power quality and ancillary services.

4.1.4 **Benefit**

4.1.4.1 Description

The more transactions that can take place within a year operation ("buy low"/"sell high"), the bigger income the service may provide. To this perception every stakeholder may have a different benefit. A utility may gain by providing or buying the service. For other stakeholders, the benefit is internalized as profit. To estimate the time-shift benefit, simple estimations can be used. The algorithm should contain what is needed to determine when to charge and when to discharge storage in order to optimize the financial benefit.

Specifically, it determines when to buy and when to sell electric energy, based on price. In simplest terms, the dispatch algorithm evaluates a time series of prices to find all possible transactions in a given year that yield a net benefit (i.e. benefit exceeds cost).

The algorithm should sum up the net benefits from all such transactions for the entire year to estimate an annual time-shift benefit. Of course in case of a market operation the real time market prices should be used since the estimations are based upon the known market prices.

The data needed for the dispatch algorithm are the following:

- Storage system discharge duration
- Energy storage efficiency
- Hourly price data for one year (8,760 hours)

The hourly price data that can be used are the hourly electric energy prices (Electric System prices). For example, Figure 4.1 shows prices for some hours of the year from the Hellenic Power System.

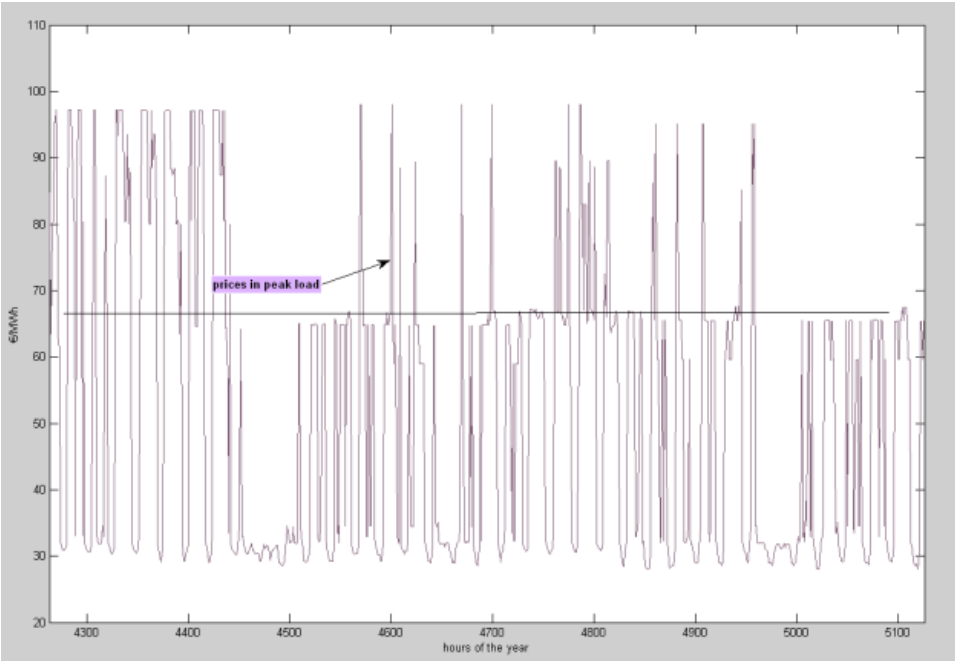
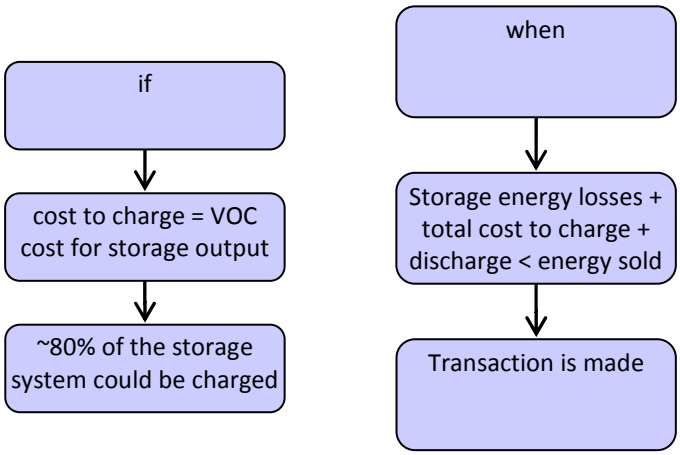


Figure 4.1: System prices from HTSO

Based on the markets data, it is observed that certain hours per year are considered as peak hours, when the price is above a certain point (68° €/MWh). During off peak periods (when storage plants are charged), the price is taking values at about 40° €/MWh to 50° €/MWh.

The income of the service is calculated as variable cost. So the decision is made comparing the cost of buying, storing energy versus the profit of selling energy according to the following diagram:



4.1.4.2 Estimate

The storage dispatch algorithm can be used to estimate the electric energy time-shift benefit for a given year. Figure 4.2 shows what can be the outcome of the estimated net electric energy time-shift benefit for storage systems.

The three plots in Figure 4.2 are for storage with the following (non-energy) variable operating costs (maintenance and replacement cost per kWhout): 1) nothing, 2) 1°C/kWhout, and 3) 2°C/kWhout. Note that if that non-energy variable operating cost (VOC) exceeds 2°C/kWh, then the number of cost-effective transactions in a given year drops precipitously.

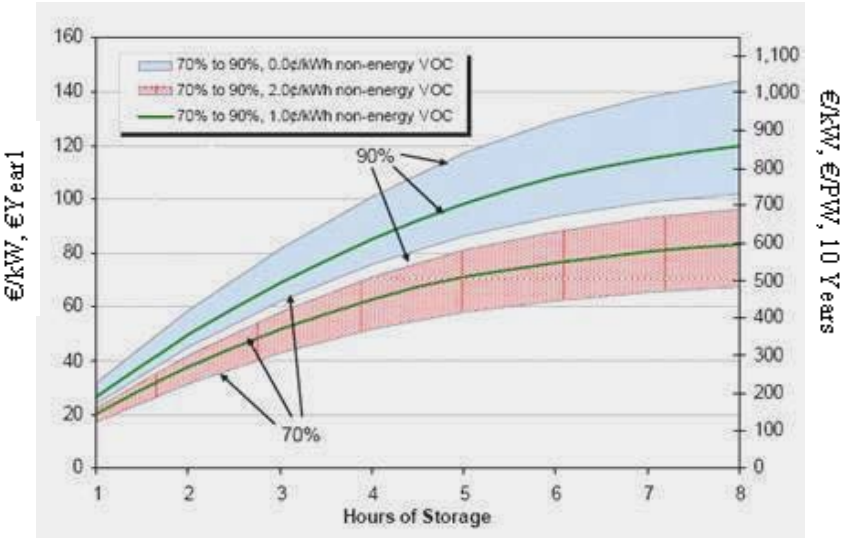


Figure 4.2: Annual and 10-year present worth time-shift benefit

The spread shown for each plot in Figure 4.2 reflects the net benefit for storage efficiencies ranging from 70% to 90%, and for storage whose discharge duration ranges from one to eight hours. As the hours of storage discharge duration increase, initially the incremental benefit increases too, but the increase eventually levels off. That reflects the diminishing benefit per “buy-low”/”sell-high” transaction. The benefit decreases because storage with longer discharge duration requires charging during more hours per year. It also decreases because the additional energy used for charging is probably more expensive and the selling price is probably lower, yielding a diminishing benefit per kWh discharged.

With this method, the outcome of the analysis can be presented as it is shown as present worth of benefits in Figure 4.2 on the second Y axis. In this example, the generic benefit estimate for electric energy time-shift ranges from 60°€/kW-year to 100° €/kW-year for lifecycle benefits ranging from approximately 400°€/kW to 700°€/kW.

4.2 Investment deferral

4.2.1 Application overview

Transmission & distribution (T&D) assets are sized to meet peak demand, but are rarely used at those levels. As demand increases, T&D assets need to be upgraded to serve growing peak demand, while maintaining all assets in the T&D delivery chain within their ratings.

The cost of adding T&D assets, which includes the capital cost of equipment, an annual financial carrying charge and operation and maintenance fees, can be significant. In most cases, however, the total capacity of the T&D asset increase is not needed immediately as the upgrades are generally planned to support projected demand several years ahead of time and typically come in large incremental blocks of added capacity.

In addition to mitigating the significant costs associated with T&D asset investment, deploying advanced energy storage for T&D deferral can increase asset utilization by eliminating the need for capital upgrades to meet brief duration peak system loads. The ability to “peak shave” at the circuit, substation and even system level through aggregation, will offer utilities a reliable and effective new alternative to increasing total system asset capacity factor, which measures asset utilization.

Storage could be used to avoid congestion-related costs and charges. In this application, energy would be stored when there is no transmission congestion, and it would be discharged (during peak demand periods) to reduce transmission capacity requirements.

4.2.2 **Technical considerations**

The design of this application must be very careful since the need for congestion relief may have short duration throughout a year. The same problem occurs with transmission and distribution upgrade applications. The system charges for the use in congestion hours can be calculated separately taking into account maximum charges for these hours. The discharge duration assumed that would be needed for this service is five hours, i.e. the time that congestion phenomena are lasting as in peak demand hours.

4.2.3 **Application synergies**

The use of storage for congestion relief can be combined with electric energy time-shift, ancillary services, possibly renewable energy time-shift depending on location and the discharge duration.

4.2.4 **Benefit**

4.2.4.1 Description

The charges for the provision of the service are not as precise as desired, since the marketplace where transmission and distribution congestion occurs is not concretely formed, and the major problem to be faced is the location of the congestion phenomena. Probably the problem will be greater since the renewable energy resources will compete for the existing transmission capacity. The benefit of the service is based on the congestion charges for the users of the grid and the transmission upgrade for the developers.

4.2.4.2 Estimate

Transmission congestion charges are becoming more common. In case these charges are known as well as the percentage of congestion hours, then the table describing the characteristic values can be Table 4.1, assuming congestion present for 20% of all hours during the year, and congestion charges in those areas range about 45° €/MW per service hour (for the Hellenic power system):

Table 4.1: Characteristic values for investment deferral

	Assumptions
Percentage of year congestion	15%
Hours per year	1314
Transmission access charge (€/MW per hour of service)	15
Annual cost (€/kW-year)	19.71

The calculations for the annual benefit of this type of application can be as follows:

Annual_benefit = (annual_cost + transmission_cost_avoided_per_year
- (investment_cost_per_year + VOC_cost_per_year)

The transmission cost avoided refers to the grid that is not to be upgraded since the storage system is going to support it locally. It is essential to highlight that this application should be combined with another use of storage, so the benefit is multiple.

4.3 Load following

4.3.1 Application overview

Utilities need to match at any time energy supply and demand. This means adding additional generation to available energy supplies to meet moment-to-moment demand in the distribution system served by the utility, and/or keeping generating facilities informed of load requirements to insure that generators are producing neither too little nor too much energy to supply the utility's customers.

In load following operation the power output changes as frequently as several minutes in order to match demand with generation whilst remaining the system frequency within predetermined limits. Conventional units output *increases* to follow demand *up*, as system load increases. Conversely, units output *decreases* to follow demand *down*, as system load decreases. A simple description of load following is shown in Figure 4.3.

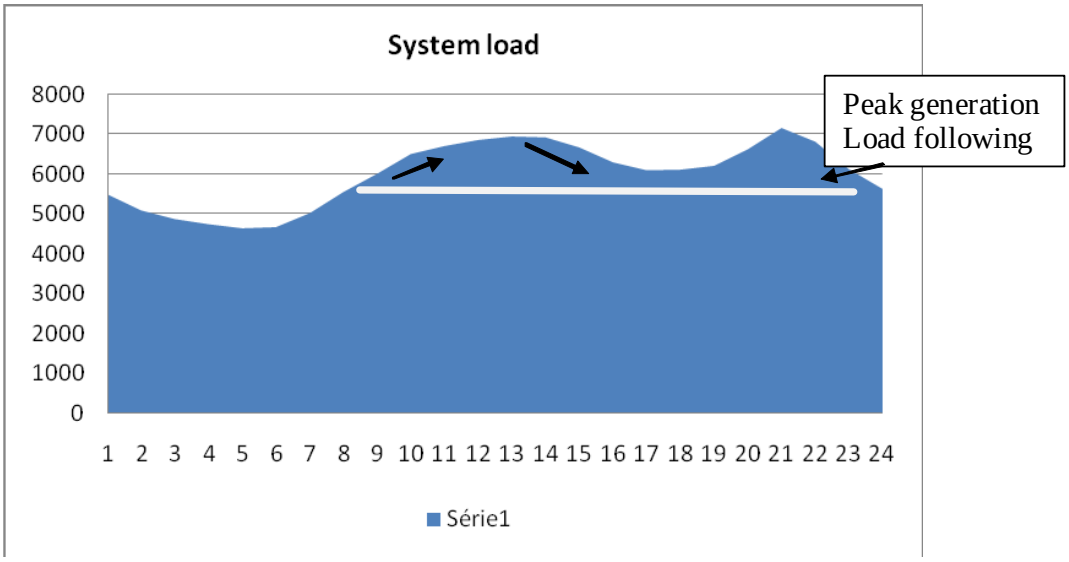


Figure 4.3: Electric supply for load following

For using the power station for the load following operation, the station's technical limits must be respected. Thus, the generator can operate in a power rate lower than the installed capacity to have a certain ability to increase the output, also leaving the potential to decrease the output but no more than the technical minimum of the generator.

This use of the generator unit may lead to more fuel consumption and increased air emissions since the unit will not work in steady state form. The variable maintenance cost can be also increased due to the unit stress.

Most of storage systems can be valued as suitable for this type of operation since they work at partial output level, and they can respond quickly to follow the demand. When the system need is to increase the load and requires more energy then storage can discharge, leaving charging to be used for load following down.

To integrate the storage system for this application, consideration upon the profit is essential. To charge the storage for load following, the energy stored must be purchased at the system wholesale price. In this case the storage with low efficiency might not be suitable for this application. Of course the profit from the service provider can be obtained if the service income is higher than the cost of charging. The income for the storage owner is the result of selling both energy when discharging as well as the provision of the load following service. These conditions are described below:

Value_of_service- Cost_of_charging > 0
Annual_benefit = Value_of_service + Value_of_energy(wholesale_market)-Maintenance cost

4.3.2 Technical considerations

Load following as all the system services are provided upon contractual obligations. Thus storage systems must be able to meet these obligations so that the participant can participate in the market according to bidding systems and will not suffer any penalties

For this application, storage could provide up to two service hours per hour of discharge duration.

4.3.3 **Application synergies**

If applications are coordinated to fit to the charging-discharging operation of the storage systems, then load following can be combined with other services such as renewable capacity firming, and electric energy time-shift.

4.3.4 **Benefit**

4.3.4.1 Description

The load following service in existing power systems is a service that can be characterized by the mix of generation or the time of the year or the topology. Generators that can provide the service during several hours of the year may not be able to provide it the whole year because of the congestion of transmission lines. Depending on the system throughout the year and the time of the year, the load following can be provided by hydro electric stations or gas turbines.

The load following is most of times provided by the generators that strongly affect the SMP (system marginal price). The cost of that service is consequently the variable cost of the generator that is affecting the SMP, that is mainly the fuel cost and the total emissions related cost.

4.3.4.2 Estimate

When the marginal price of the system is affected by the hydroelectric generation the service price for load following assumed is 20° €/MW per service hour. When the marginal price of the system is affected by the combined cycle generation the service price for load following assumed is 70° €/MW per service hour. The capacity benefit is estimated based on the generation capacity cost. Values in Table 4.2 show annual and cost calculations for load following including service-related costs and capacity-related costs. Service costs are assumed to reflect a low price of 20° €/MW per hour, a midrange price of 50° €/MW per hour of service, and a high price of 70° €/MW per hour. Annual capacity costs include a low value of 60° €/kW-year and a high value of 120° €/kW-year. Three scenarios shown include 500, 1,000, and 2,000 hours per year of load following service.

Table 4.2: Assumptions for the load following calculations

		500 (h/year)	1000 (h/year)	2000 (h/year)
		Annual (€/kW-year)	Annual (€/kW-year)	Annual (€/kW-year)
Service	20 €/MW-hour	10	20	40
	50 €/MW-hour	25	50	100
	70 €/MW-hour	35	70	140
		Annual (€/kW-year)		
Capacity	60 €/kW-hour	60		
	120 €/kW-hour	120		

Assuming 2,000 service hours per year and an average unit price of 40° €/MW per hour of service, the value of the service is about 80° €/kW. Assuming that at least some capacity cost will also be incurred over the year, a generic load following benefit value of 120° €/kW is used in this guide.

4.4 Spinning reserves (electric supply reserve capacity)

4.4.1 Application overview

In power system scheduling reserve margins are kept in order to maintain the security of the system if an unforeseen event occurs. This security is maintained by re-dispatch of the generators in the system. The maximum increase of the generation during this time when excess energy is required is called the spinning reserve. The energy storage provides a dual remedy of providing immediate backup for the shortfall in the power supply as well as the retention of excess power that was generated but left unutilized. This guide addresses the impact of such energy storage on the spinning reserve in an electric system. The discussion is based on the load curve of a typical power utility and clearly indicates that the introduction of storage energy in the system reduces the need for excessive generation to meet peak load demand. Generally, reserve capacity is equivalent to 15% to 20% of the normal electric supply capacity.

The three generic types of reserve capacity are:

- Primary reserve – On second/minute timescales, rapid variations in the total power capacity output occur randomly, such as existing load variations. Furthermore, the amount of primary reserve allocated in the power systems is dominated by potential outages of large thermal generation plants, meaning it can easily cope with these rapid variations.

- Secondary reserve – It is up-regulation that is activated manually and has to be available within 15 minutes. It can be delivered by both production and consumption. The secondary reserve is activated manually (or automatically using Automatic Generation Control, AGC) by the TSOs. Activation of the secondary reserves relieves the primary reserves, which enables it to handle new deviations.
- Tertiary reserve – It is up-regulation reserve activated manually, with a warning time varying from one to several hours. This type of reserve compensates for deviations from planned exchanges between control areas and assists secondary reserve. This service is given to the system from plants with high variable costs. Generation units used for tertiary reserve should be online and operational (at part load). Unlike generation, in almost all circumstances, storage used for reserve capacity does not discharge at all; it just has to be ready and available to discharge if needed.

4.4.2 **Technical considerations**

This service demands storage units that are able to discharge for the required duration (usually at least one hour). Reliability of the storage system is essential as well as the response to control signals.

4.4.3 **Application synergies**

This service is compatible with other applications since:

- Most times when storage is used for reserves, it does not discharge.
- When charging, storage can provide twice its capacity as reserve capacity.
- During the time when the storage is used for the service, it cannot be used for other applications. Yet when the storage unit is not supplying the grid with the reserve capacity, it can be used for energy time shift or any other applications quoted here.

4.4.4 **Benefit**

4.4.4.1 Description

The value of the service can be calculated taking into account that the reserve capacity is given to the grid by conventional power stations so the profit for the storage systems is the same as for the conventional units. Depending on the system and the type of generator that is taking part in the reserve market the value can change significantly. The added value of the storage is that while charging, storage can provide twice its capacity as reserves.

4.4.4.2 Estimate

As in the previous calculations the value of storage is based on the hours of service delivery and the price of reserves. Benefits are estimated assuming a low price of 10° €/MW per service hour and a high of 20° €/MW per service hour. Storage is assumed to provide 2500 service hours per year or 5000 service hours per year. The resulting annual benefit for those two scenarios is shown in Table 4.3.

Table 4.3: Electric supply reserve capacity annual benefit

	Low	High
Capacity factor	0.3	0.6
Annual service hours	2.500	5.000
Charge (€/MW per service hour)	10	20
Annual value (€/kW-year)	25	100

Where:

Annual_benefit = Value_of_service x Annual_service_hours

In the calculations, maintenance costs are not taken into account, just the net benefit of the service provider.

4.5 Integration of non predictable sources/renewable capacity firming

4.5.1 Application overview

Energy storage systems complement the deployment of renewable generation. Renewable resources are both difficult to forecast and have intermittent output, resulting in the production of low value electricity, lack of firm capacity needed to bid into energy markets and an increasing reliance on ancillary services necessary to maintain system-wide reliability. Energy storage systems add value to renewable generation and provide improved ancillary service efficiency necessary to support the integration of intermittent power sources.

Renewable resources often produce energy during off-peak times when energy is both lower in demand and price. These occurrences create inefficiency for both the generation owner and energy markets. Energy storage systems mitigate this problem by allowing renewable generation to bid stored off-peak energy into peak energy markets. This prevents waste of off-peak production, provides increased value for renewable generation by increasing capacity bids in peak markets, and also improves wholesale market efficiency by increasing the amount of lower cost energy bids.

The intermittent output of renewable resources may prevent resource owners from bidding into energy markets. In many cases, energy providers must guarantee to supply the amount of capacity bid into energy markets or they will be subject to financial penalties. Many renewable generation resources cannot meet the guarantee (firm) requirements because of the systems intermittent power output. However, renewable generation can use the capacity of an energy storage system to meet firm output requirements. The capability of an energy storage system to provide renewable generation with the ability to meet firm requirements and bid into energy markets adds economic value to renewable generation.

The intermittent output of renewable resources increases the occurrence of disturbances that threaten system-wide reliability. For example, photovoltaic cells cannot control the occurrence of clouds and wind turbines cannot control the occurrence, duration or strength of wind gusts. The rapid response and discharge times of storage systems provide the necessary improvements in ancillary services needed to mitigate the added stress that such disturbances place upon transmission systems.

In principle, storage combined with renewable sources can play an important role, filling the intermittency that may last from some minutes to some hours (short or long duration). Critical factor is that the storage device can respond rapidly and sufficiently, and that the charging or discharging durations may occur in peak or off-peak hours.

PV capacity firming

PV static systems are supposed to have an output curve that is gradually increasing up to the midday hours (which coincide with the peak demand hours) and then decreasing in the evening hours. PV tracking systems have increased efficiency producing more energy during the day, and also in off-peak hours.

Wind generation firming

The capacity firming generation is much more valuable for wind generation since its output is not forecasted with high accuracy. The smallest the application (integrated in distributed systems), the more difficult to be predicted. The storage systems should in this case be selected in a careful way, since the installed capacity should be greater for wind parks than for small wind generators. The difference is also significant between wind farms and PV systems.

4.5.2 **Short-duration intermittency**

Solar generation short-duration intermittency — The event that can cause this type of intermittency on the PV systems is the clouds passing over the PV panels, having the effect of voltage decrease and the MPPT trying to find the new point of operation. The rate of change of the solar system output can be quite rapid. The result, if the PV system is combined with storage, is that it should have the ability to “fill the energy gap” with fast response.

Wind generation intermittency — Short-duration intermittency from wind generation is caused because of the wind velocity that is changing rapidly; the event becomes even more critical when peak demand for electricity coincides with windy conditions.

In Figure 4.4, the one minute average renewable energy output (for a 1-kW renewable energy plant) is plotted [10]. As shown in Figure 4.4, the power needed from storage to offset the short-duration intermittency is determined based on the maximum difference between the renewable energy output and the reduced output due to short-duration intermittency. In the example, the largest short-duration drop-off of power from the renewable energy generation is about 34% of the plant rating. Consequently, the storage plant would need to have a power rating of at least 0.34 kW per kW of renewable energy generation output.

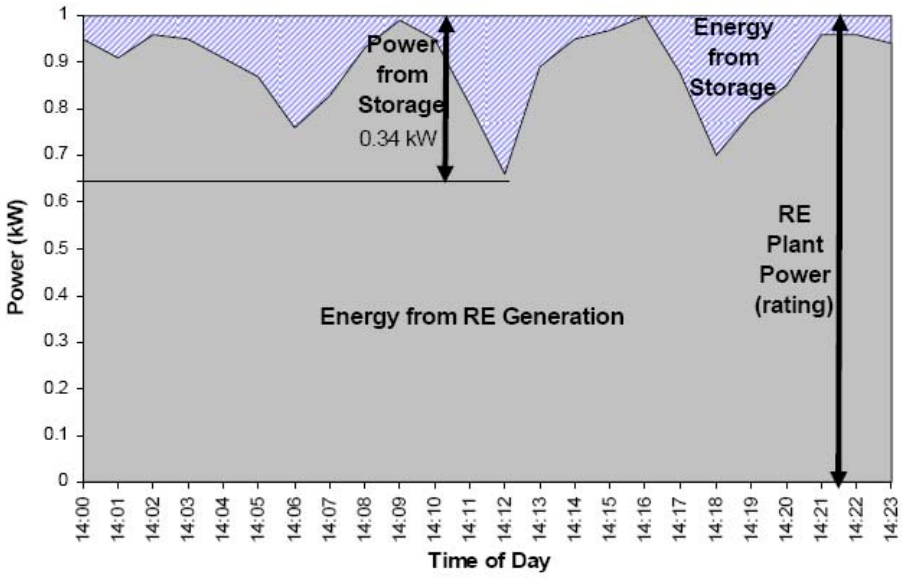


Figure 4.4: Renewable generation, short-duration intermittency (example) [10]

4.5.3 **Long-duration intermittency**

Solar generation intermittency — Long-duration intermittency of solar systems is the outcome of certain phenomena such as the insolation change throughout the day, the shading when lasting for many hours, and the climate changes that can affect the PV system operation like the temperature.

The storage in this service can be used in order to give energy when the PV output is less than the expected during certain hours, or to produce a steady output compared to the system installed capacity. Firming of the PV output requires storage whose capacity (power) is equivalent to:

Storage_capacity = (RES_output – Min_output) x Hours_of_delivery

As it becomes obvious, it is upon the decision of the storage owner to commit upon the firming level of the renewable generation (power, energy, hours).

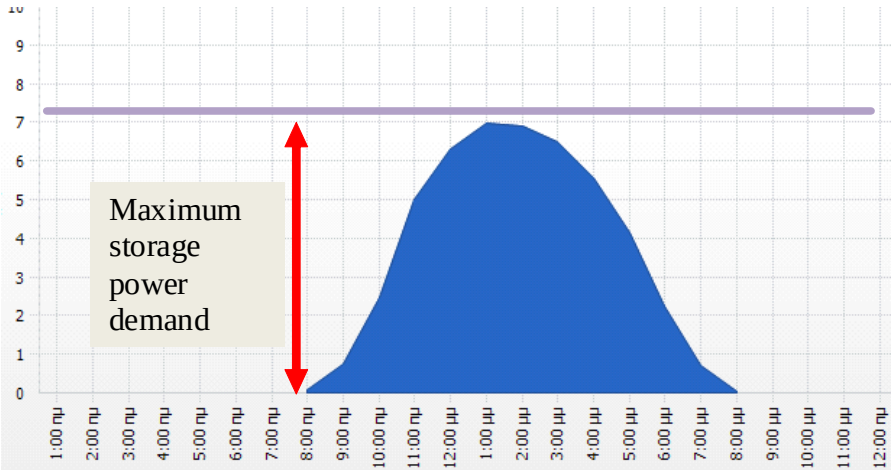


Figure 4.5: PV generation output variability during peak demand hours (example)

Wind generation intermittency — When the duration of wind variations is significant, the storage fills in the wind generation output since it is less than the wind turbine rated output. Such scenario is depicted in Figure 4.6.

In Figure 4.6, the storage must provide capacity (power) equal to about 65% of the wind turbine rating. The storage must be able to deliver 2.36 kWh per kW of wind capacity for firming, for the 5 hours from 12 to 17 pm.

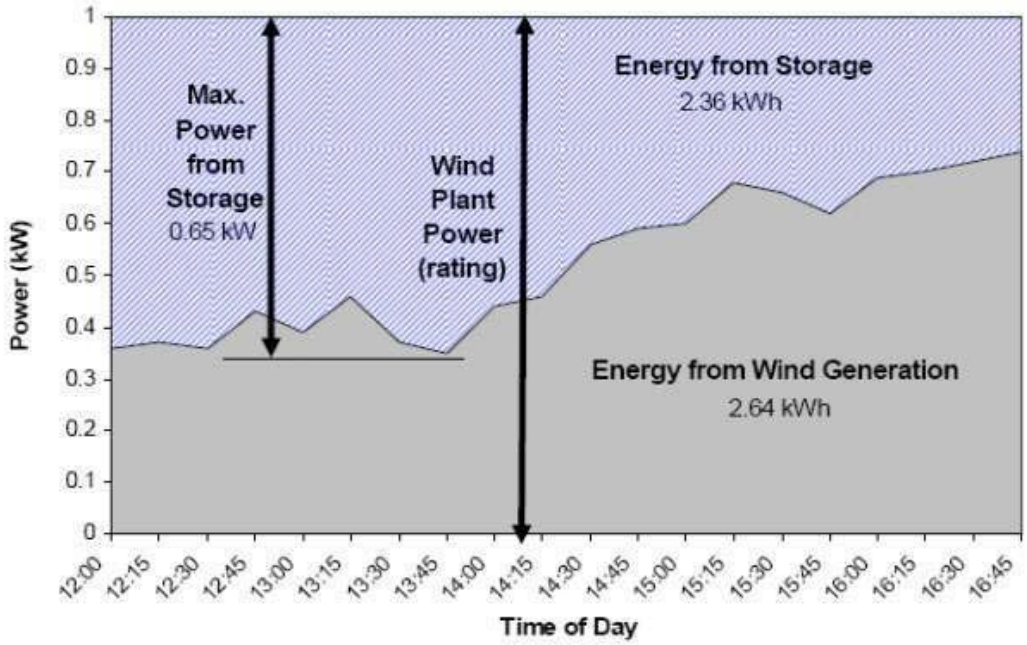


Figure 4.6: Wind generation intermittency during peak demand hours [10]

4.5.4 **Technical considerations**

It is upon the storage owner to decide the discharge duration that can be guaranteed, since it is not the same for all the storage types. What is critical here is the reliability of the storage device, since the primary reason for capacity firming is to provide constant power. Also, the price paid for constant power (i.e. market price for capacity for the wholesale part of the market) is usually accompanied by a significant financial penalty if power is not firm.

4.5.5 **Application synergies**

The service provider can operate in multiple ways, offering different services and obtaining the best profit, therefore, it is very important that the design of the storage system is such that gives multiple possibilities. In the case of renewable capacity firming, the charging-discharging capacity and velocity for long periods must be obtained and may also coincide with the energy time shift or other services.

4.5.6 **Benefit**

4.5.6.1 Description

The benefit of firming renewable generation is calculated by the avoided conventional generation that would be used for the service. So the capacity credit is linked to the reliability to serve the system load, more important to be the peak demand periods.

It is important to mention that storage, in case of renewable firming, has two options. Within the first, it cannot be charged from the grid if the energy is not linked to the renewable generation. Some part of the installed capacity of renewable generation should be dedicated to the storage charging (and the system revenue for selling energy in respectively charging durations). In this case the storage owner is buying energy to charge from the renewable energy plants and sells the capacity credit to the renewable station so that it trades the credits with the system. Otherwise the storage owner is buying energy from the grid in off peak hours and sells to the grid the capacity firming service.

4.5.6.2 Estimate

The renewable firming revenue is based on the logic that there is avoided cost for conventional generation that would serve the system, and the criteria to be the degree to which the renewable energy generation output is firmed (capacity).

Capacity_firming_benefit = (Avoided_cost_for_generation_per_year) x Difference_on_Capacity

The calculations are depicted in Table 4.4. The total revenue for the storage owner would be the energy-related benefit (for the energy discharged from storage) added to the capacity-related benefit.

Table 4.4: Total renewable capacity firming benefit

	Storage energy (hours/day)	*Renewables effective capacity*[1]		*Storage incremental value (€/MW-day)*		
	Discharge Duration	Without Firimg	Firmed	Capacity[2]	Energy	Total
PV	2.5	0.40	1.00	60.0	50	110
Wind	3.5	0.25	1.00	75.0	50	125

Note 1: During peak demand periods.

Note 2: Assuming 100€ per MW-day for combustion turbine based generation.

4.6 Control/Power regulation

4.6.1 Application overview

Power regulation ("regulation") is one of the ancillary services through which the balance between supply and demand variations is obtained, and for which storage can be used. With power regulation the power flow from and to a part of the system is controlled. This type of service also helps in maintaining the grid frequency and recovering from any disturbance in the system. In Figure 4.7 the thin plot with numerous fluctuations depicts total system demand without regulation. The thicker (blue) plot shows system load after damping of the short-duration fluctuations with regulation.

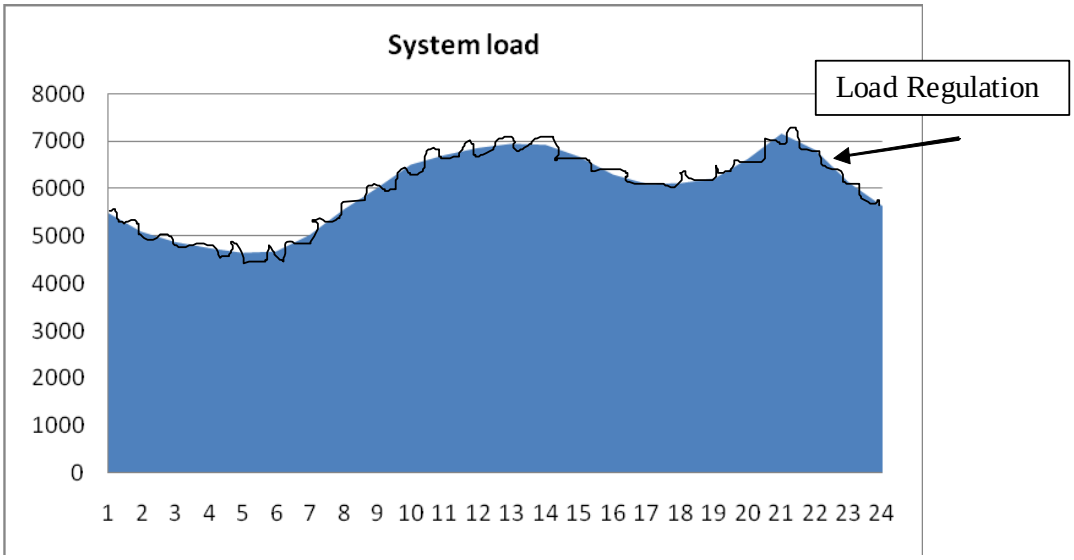


Figure 4.7: System load without and with area regulation

Most types of thermal/baseload generation are not designed for operation at part load or to provide variable output, since they work more efficiently at constant power output. Yet the power regulation has the prerequisite for the plant that is providing the service, to have the availability to increase/decrease the output as required within a short notice. So, storage may be an attractive alternative to load following because in general, storage has superior part-load efficiency, and storage output can be varied rapidly.

The storage can be used for regulation in multiple ways. Increased storage discharge can be used to provide up regulation and reduced discharge is used to provide down regulation. Alternatively, the charging can be used for down and the discharging for up system regulation. When storage provides down regulation by charging, it absorbs energy from the grid, and the storage operator must pay for that energy. Storage with lower efficiency would not be suitable for the service since the cost for the charged energy may exceed the value of the load following service.

4.6.2 **Technical considerations**

Storage used for regulation should be able to respond to a signal which may require a response time of less than five seconds. This service may be provided by storage with a fast ramp rate (e.g, flywheels, capacitors, and some battery types). Resources used to provide regulation should be reliable, and they must have high quality, and stable (power) output characteristics.

4.6.3 **Application synergies**

In most cases, storage used to provide area regulation cannot be used simultaneously for another application. However, at any given time, storage could be used for another more beneficial application instead of using it for regulation (e.g, electric energy time-shift, electric supply capacity, electric supply reserve capacity, or upgrade deferral).

4.6.4 **Benefit**

4.6.4.1 Description

The system price for the power regulation service would be the same in case the service is provided by conventional power or by storage systems. The reasons of the suitability of storage for the service

provision are the fast response capability of some type of technologies, and the capacity of providing the service while charging as well as discharging.

4.6.4.2 Estimate

Revenue for providing up and down regulation services can be estimated taking into consideration the regulation price, i.e. the prices in €/MW per hour of service for up and for down regulation.

The value for the price assumed is an hourly average of 70 €/MW per service hour. In this sense the calculations are as follows:

Power_Balancing_benefit = Annual_Service_Hours x Regulation_Price

Table 4.5: Power regulation annual benefit

	Typical values
Capacity factor	0.60
Annual service hours	3500
Regulation price* (€/MW per service hour)	70
Annual benefit (€/kW)	245

*For up regulation plus down regulation.

4.7 Power quality

4.7.1 Application overview

Power quality is the set of limits of electrical properties that allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load, and the load ability to function properly with that electric power. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power. Power quality may not be delivered for at least the following ways:

- variations in the peak or RMS voltage,
- variations in the frequency,
- variations in the waveform (usually due to harmonic distortion),
- random or repetitive variations in the RMS voltage between 90 and 110% of nominal can produce a phenomenon known as "flicker" in lighting equipment,
- when the RMS voltage exceeds the nominal voltage by 10 to 80% for 0.5 cycles to 1 minute, the event is called a "swell",
- a "dip" or a "sag" is the opposite situation: the RMS voltage is below the nominal voltage by 10 to 90% for 0.5 cycle to 1 minute.

4.7.2 Technical considerations

Storage used for power quality should produce high-quality power output and should not adversely affect the grid. Typically, the time required for the power quality application ranges from a few seconds to about one minute.

4.7.3 Application synergies

Storage that is used for this service is considered to provide it supplementary with other applications. The reason is that storage systems should not be used solely for the power quality application for few hours per year, since combining energy management for example can offer better revenues for the owner.

4.7.4 Benefit

4.7.4.1 Description

Power quality benefit is dealing with the customers that are mainly affected by disturbances (like industries) and as such, it is difficult to generalize. Power quality anomalies cause damages in the electrical equipment, so storage becomes valuable to avoid such events. Thus power quality benefit cannot be considered to exceed the cost to replace the damaged equipment.

4.7.4.2 Estimate

Power quality events considered are those whose effects can be avoided if storage is used. A generic value per event for each kW of end user load is the assumption used in this document. If the annual number of events is 25, the result is that storage used in such a way that the electricity end user can avoid 25 power quality events per year. An assumption made is that the power quality benefit is the same for each disturbance. To this end the value for this service would be:

Power_Quality_Benefit = Cost_of_disturbance x Disturbances_per_year

5 STANDARDS

As it has been mentioned in this White Book, grid-connected storage systems are defined as bidirectional devices, connected to the grid (permanently or temporarily), controllable and able to communicate and exchange information with the grid operator.

After a literature search for existing standards dedicated to energy storage systems interconnected to electric power systems, it was revealed that the most relevant existing standard is IEEE 1547. This standard does not have to do only with grid-connected storage but it deals also with general guidelines for interconnection of distributed generators (DGs) to the grid and DG interconnection testing. It is divided into different parts, namely:

- IEEE 1547: interconnection system & interconnection test requirements for interconnecting DER with electric power systems (EPS),
- P1547.1: standard for interconnection test procedures,
- P1547.2: guide to 1547 standard,
- P1547.3: guide for monitoring, information exchange and control of distributed resources interconnected with electric power systems,
- P1547.4: guide for DER island systems,

- P1547.5: technical guidelines for interconnection of electric power sources greater than 10 MVA to the power transmission grid,
- P1547.6: recommended practice for interconnecting distributed resources with Electric Power Systems distribution secondary networks.

From the above standards, 1547.3 is the one which is most correlated to grid-connected storage systems. More specifically, this document facilitates the interoperability of one or more distributed resources interconnected with electric power systems. It describes functionality, parameters and methodologies for monitoring, information exchange and control for the interconnected distributed resources with, or associated with, electric power systems. Distributed resources include systems in the areas of fuel cells, photovoltaics, wind turbines, microturbines, other distributed generators, and, distributed energy storage systems.

In March 2009, IEC 61850-7-420 standard was passed and it is now publicly available as IEC 61850-7-420 Ed.1: “Communication networks and systems for power utility automation - Part 7-420: Basic communication structure - Distributed energy resources logical nodes”. The logical nodes in this document are intended for use with DER, but may also be applicable to central-station generation installations that are comprised of multiple units of the same types of energy conversion systems, which are represented by the DER logical nodes. Communications for DER plants involve not only local communications between DER units and the plant management system, but also between the DER plant and the operators or aggregators who manage the DER plant as a virtual source of energy and/or ancillary services.

Apart from the above, it should be mentioned that the IEC-Technical Committee 8X (IEC/TC8X) is currently working on the development of standards which among others deal with planning and interconnection of DGs to medium voltage/low voltage (MV/LV) grids. More specifically, some of the tasks of the Working Group 3 (WG3) focus on:

- connection of dispersed generation on MV/LV grids,
- discussion and accumulation of experiences in order to develop a guide of practical rules,
- planning and design of MV/LV grids, etc.

Some of the above mentioned tasks are not covered by IEEE 1547.

In the IEC/TC8X WG3, the maximum voltage and power limits for distributed generators connected to the distribution network are set to 35 kV and 10 MVA correspondingly. In the IEEE 1547, regarding the size limits of Distributed Energy Resources connected to the distribution grid, a maximum power limitation of 10 MVA is mentioned.

Another point to be mentioned here is that EVs and PHEVs need to be considered as being specific cases of grid-connected storage. These small-scale storage devices could be connected to the grid for charging, and thus increase the network load. The influence on the grid can be considerable if they are in large numbers. Without a suitable management strategy, operational problems may appear, increasing congestion in already heavily loaded grids. However, bidirectional use of the storage capacity of a large number of vehicles offers a great potential for improving the network management.

The whole system from the road through the plug and the household to the distribution network has to be considered and related test procedures must be developed. To really finalise this approach, it is necessary to go up to the standardisation step. Standards for the use of EVs as bidirectional storage units are crucial to enable the real deployment of EVs on a large scale. As the large integration of EV battery capacity will be in the LV grid, the impact of these distributed resources to the networks has to be considered and standardised in terms of voltage and frequency regulation. So far, the distributed resources in the LV and MV network were not considered as significant.

GENERAL CONCLUSIONS

In this paper, the fundamental functions and duties of energy storage systems are examined from the macro viewpoint. The evaluation uses both the technical and the economic perspective. This approach analyses different applications especially **electric energy time shift, investment deferral, load following, spinning reserves, integration of non predictable sources/renewable capacity firming, and power quality**.

Technically, the outcomes of this analysis show that the very large number of different applications which are commonly identified, can be clustered in only three categories, which are very similar from the **storage solicitation viewpoint**:

- Time shift applications
- Power balancing
- Power quality support

For each of these three categories, important storage parameters are then extracted and discussed, in particular in terms of measurement methods.

The economical analysis clearly shows that the present arrangements and mechanisms for pricing of distribution services do not treat DG and storage adequately and systematically. Issues related to charges of losses, connection and the use of network along with the use of storage are subject of negotiations between stakeholders, where many different arguments are used. Network operation and practices, together with adopted pricing policies, define the level of access available to participants in the electricity marketplace and therefore make a considerable impact on the amount of storage generation that may be accommodated.

Such a comprehensive description of storage systems will help an optimized integration of storage systems into the grid, by enabling:

- easier specifications,
- easier comparisons,
- easier measurement and monitoring,
- easier cost of ownership calculation and comparison.

Finally, innovation will be easier by allowing comparison between different manufacturers or different product generations.

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