# ENERGY STORAGE IN POWER GRIDS – APPLICATIONS AND OPPORTUNITIES

**C. Levillain, E. Serres, D. Chantelou, C. Bonety, A. Marquet**
**Electricité de France – R & D Division**
**1, Avenue du Général de Gaulle, F-92141 Clamart Cedex (France)**
**Tel : + 33 1 47 65 31 91 – Fax : + 33 1 47 65 59 28 – E-mail : Clotilde.Levillain@edfgdf.fr**

## *SUMMARY*

*Over the last several years, the energy sector has undergone major changes. Consumption growth has slowed considerably, electricity utilities face growing difficulties in developing their supply networks, and deregulation has significantly shifted established balances and practices. Driving greater flexibility in the electrical supply system and meeting the increasingly targeted and diversified needs of customers are the key focus of current strategies. This new context harbors potential opportunities for energy storage systems.*

*After a review of energy storage applications in the power grid, EDF has performed a more detailed evaluation of the most promising cases. This article provides an synthetic review of power grids and small supply networks, identifying production, network operation and end-customer requirements.*

## INTRODUCTION

The concept of storing energy in the power grid is not new. Electricity producers have long used pumped-hydro storage facilities to optimize the expected power demand on generator units and to better distribute their output over periods. But aside from this type of pumped-hydro energy storage solution, there are few previous examples of grid-tied energy storage systems.

Historically, in fact, the generation-transmission-distribution network was based on the highly legitimate hypothesis that there was no satisfactory solution, in economic terms, for storing electrical energy. During periods of high consumption growth, and with no particular obstacles to developing pre-existing supply networks, this hypothesis has been confirmed. However, in the present context of considerably slower growth and opposition to network extension, the previous assumption requires closer scrutiny. Moreover, over the last ten years, significant improvements have been made to storage technologies.

Lastly, these shifts have been confirmed by the emergence around the world of a number of projects and sizeable demonstration energy storage units.

This article provides a synthetic review of power grids and small supply networks, identifying generation, network operation and supplier requirements to meet the needs of the end-customer.

While not claiming to be exhaustive, this approach seeks to determine both the opportunities and the challenges regarding grid-tied energy storage systems today and in the future.

## ENERGY STORAGE AND GENERATION

The challenge facing energy storage applications is to improve unit management in both economic and technical (dynamic and static performance) terms, as well as to optimize overall security of the power grid.

### Deferring generation

Within an electrical power system, consumption fluctuates according to several time scales: daily, weekly and seasonally. Electricity producers endeavor to level out the corresponding load in order to optimize utilization of their production facilities, some of which, such as nuclear power plants, are not optimized to respond to major shifts in output. However, there is always a discrepancy between customers' requirements and production, resulting in peak periods, off-peak periods, high season, low season, etc. Consequently, the excess energy produced during off-peak periods is stored and released to meet the surge in demand during peak periods, thereby resulting in lower peak production costs -- provided that the electricity conversion process is efficient. The energy storage technologies involved make it possible to store large quantities of energy. The storage time constants are in the range of one hour.

These technologies involve the use of hydroelectric pumped storage facilities or compressed gas units. Current storage units are managed by large power utilities and involve centralized storage applications, in the range of 20MW-500MW, or, in some cases, up to 2000MW.

### Power generation using renewable energies

There are two main types of production units that use renewable energy sources (solar, wind): those connected to the main power grid and those that supply micro-networks. Implementing energy storage technologies is particularly adapted when the capacity of the network supplied is of the same order of magnitude as the power plant.

On the one hand, a storage unit ensures more independent power supply for the micro-network outside energy generation periods. In this case, it is necessary to store the expected peak-load power (from several tens of kW up to several MW, depending on the size of the network supplied) on average for a period ranging from several minutes to several days, depending on whether there is a backup generation unit (in most cases, a diesel gen-set).

On the other hand, a storage system acts as a buffer during the exchange of power between the power plant and the network. This ensures more efficient control of problems relating to stability, harmonics or flicker. In this case, the capacity of the storage system must be of the same order of magnitude as the plant. However, the run time of the storage system is limited to just several seconds or, at most, several minutes [1].

### Security of supply or system backup

In the case of a partial collapse of the network, it is necessary both to ensure continued power supply for remote alarms and remote controls, correct operation of the system protection devices, and restart of units that are either shutdown or in house-load operation mode.

In most cases, the first of these functions is ensured at the production unit or substation level by electrochemical lead acid or cadmium-nickel batteries. Run time of approximately 20 minutes to one hour is required. These cells can provide power ranging from several tens to several hundreds of kW.

The second application requires a capacity ranging from several kW to several hundred kW to ensure restart of the unit's auxiliaries.

In these cases, highly reliable equipment is required, with substantially high energy density. Regular surveillance checks of these systems, which are usually redundant, are carried out to ensure that they function correctly.

Having examined these cases, it is clear that high-energy density applications offer several major technical advantages. Their cost-efficiency, which is equally important, determines the scale of the potential market for these applications.

Today, the majority of hydroelectric plants capable of ensuring pumped storage are already equipped and employed for this purpose in Europe, the United States, Japan. There are significant hydro-electric capability not yet equipped in Asia, Africa.

The other storage technologies remain relatively rare due to either inappropriate infrastructure or quite simply for economic reasons.

Electrochemical cells (batteries) are used to ensure system protection. However, as the investment, maintenance and operating costs of these solutions remain high, and their reliability requires further improvement, electricity producers tend to employ other methods.

## ENERGY STORAGE AND NETWORK OPERATION

In the face of institutional changes currently underway, electricity producers are seeking solutions to sustain their competitiveness, while offering the services needed to ensure their development within the electrical supply system. So any methods that facilitate flexibility in the system and help eliminate technical constraints are highly sought after. The main aim today is to operate the system to its maximum capacity and to defer new investments.

### Network stability

Extensive networks equipped with long-distance lines, such as those of the North American grids, periodically come up against problems of dynamic or transient stability. Smaller-scale networks supplied by high rating generation units connected radially also face similar problems. In these cases, energy storage systems can be employed to control power fluctuations and to improve management of incidents occurring on power transmission structures. Rapid exchanges of active and reactive power can solve this problem. The power ratings in question range from several MW for high rating generation units connected radially to several tens of MW for controlling power exchanges along long-distance corridors. Storage system run time remains less than 30 seconds. The aim here is to employ storage systems with high specific energy and very good cyclability.

An example is the demonstration by the Bonneville Power Authority of a 30MJ and 10MW Superconducting Magnetic Energy Storage (SMES) system. Implemented in 1983, the system made it possible to damp 0.33 Hz power oscillations. Despite being technically efficient, the operating costs of this experimental (refrigeration) system were prohibitive. The economic cost of any storage system must be measured accurately.

However, energy storage solutions are not the only way to solve these phenomena. Installing a transmitted power controller, such as a DC link, can significantly alleviate these problems. Flexible AC Transmission Systems (FACTS) can also serve the same purpose with serious economical advantages [2].

Lastly, is it also possible to modulate the power exchanged between the network and the generators using variable-speed generators [3].

Deciding which of these solutions to adopt also involves enhancing pre-existing equipment and the present environment, and adapting the network by optimizing both technical and economic aspects [4].

### Frequency control

There are different levels of frequency control. The most commonly used one -- primary control -- is based on respecting the instantaneous balance between generation and consumption. Resources (secondary, tertiary or spinning reserves) are employed by the system operator in the case of shut down of a main generation units. To achieve this, primary frequency control utilizes a reserve that can be mobilized within 1 second. Secondary control then takes over, with the production reserve available within 2-3 minutes. Lastly, tertiary control steps in beyond the 5-minute mark.

The volume of primary and spinning reserves compared to the peak-load power depends on the size of the network. For example, for highly interconnected networks, such as the UCPTE, this ratio was recently revised downwards and re-sized to take into account the power of a major unit and the total startup power. For France, this corresponds to 1.5

to 2% of the startup power. For small networks (island types), shut down of a generation unit has a major impact on network stability. It is sometimes necessary to allow for much higher ratios in order to avoid massive load shedding in the event of damage, as shown in Table 1.

Table 1: Existing or projects for storage units used for spinning reserves.

| Plant | Technology | P (MW) | Run time | Pspinning /Peak |
|---|---|---|---|---|
| PREPA Puerto Rico | Battery | 20 | 40 mn | 300/2500 =12% |
| BEWAG Berlin | Battery | 17 | 20 mn | 54/2700 =2% |
| Anchorage MP&L | SMES | 30 | 1 mn | 30/600 =5% |
| Metlakatla Alaska | Battery | 1 | 1 h | 1/3.5 =30% |

Storage technologies that can be mobilized very rapidly and deliver high levels of power, such as SMES, inertial storage systems or even batteries, are considered for primary reserves. The required power is from 1 to 10MW for small networks [5,6].

Technologies with greater time constants, such as hydroelectric storage, pressurized gas and batteries, are better adapted to secondary and tertiary control. The energy-power pairs involved are in the region of 1 to 50MW over 0.5 to 1 hour for the spinning reserves used for small-scale networks, rising to several hundred MW over several hours for applications employed on much large-scale networks.

Comparative economic studies have shown that there are tangible opportunities for employing storage units to provide frequency control [4,7,8,9]. For example, the Puerto Rican electricity utility (PREPA) identified possible economic gains using lead acid batteries compared with conventional thermal generation. These conclusions are, of course, subject to the expected decrease in storage system costs.

By way of comparison, it is worth mentioning another technology that could ensure frequency control: adjustable speed hydroelectric generators. These make it possible to modulate the power absorbed from the network in pumping mode (energy storage) in order to release resources for the purposes of primary control. The Ohkawachi plant (managed by KEPCO) in Japan is an illustration of this principle [10]. In this case, the adjustable speed hydroelectric generators are used to replace the conventional fuel generators employed for this purpose during off-peak periods.

### Load leveling

Routing electrical power in the future during peak periods to the heart of densely populated Japanese cities raises a number of serious problems. Despite its recent sharp decline, Japanese consumption growth remains high. Producing electricity locally is difficult due to environmental constraints and the high population density. Any developments to the network must be systematically underground, which leads to very high costs.

An alternative power supply is currently being studied in Japan. This initiative is based, on the one hand, on encouraging consumers to conserve energy and to store energy in their homes (user-side storage), and, on the other, on leveling the load curve of customer. The power demand on the network upstream of the supply station is limited. The additional power required to meet consumption demand is supplied during peak periods by a battery-based energy storage system, which is recharged during off-peak periods [11]. The ultimate aim is defer any extension of the network, which would be both controversial and very costly. Table 2 details the demonstrations under way in Japan that are typical of Japanese consumption, which experiences a peak, with consumption over the 6 to 8 hours of a typical day varying only slightly (plateau). This results in quasi-constant discharge of power during 8 hours and recharging at night.

The power utility TEPCO is confident that this initiative will prove effective, and is actively engaged in developing the required technology. Current corresponding investment costs are approximately five times the profitability threshold that the manufacturer claims to be able to attain were the market to expand significantly. The production costs are comparable to those of an average extreme peak load.

Table 2 : Demonstrations or project in Japan – NaS Battery

| Plant | Power | Autonomy |
|---|---|---|
| Kawasaki | 0.5 MW | 8 h |
| Tsunashima | 6 MW | 8 h |
| Ohito | 6 MW | 8 h |

Similar evaluations conducted in several countries in the past have been updated recently [5]. Figure 1 shows the basic principle on the load curve of a French power supply unit.

As French consumption growth and population density patterns differ considerably to those of Japan, the conclusions of the study we conducted also differ significantly to the previous ones [12]. For example, the storage technologies examined in Japan (NaS battery technologies) were shown to be technically unsuitable for the French case, as it has to contend with much more irregular discharge. Maintenance-free lead acid batteries are more appropriate. However, the cost targets resulting from the study indicate that a minimum three-fold reduction is required in the best-case scenarios. In view of the currently estimated market size, this cost dynamic is unrealistic, unless there is a major change in technology that has not yet been foreseen.

Demonstration operations were conducted in different countries during the 1980s and early 1990s on this subject, but with lower power ratings [4,5]. Advances in these projects do not appear to invalidate the major trends outlined above.

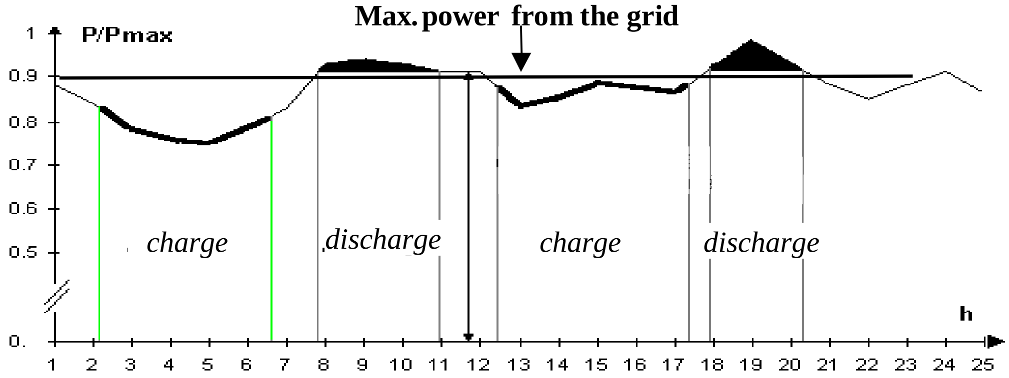

**Figure 1: Typical load curve for French nationwide consumption. Load leveling at power supply unit level.**

### Voltage support in the network

Networks in rural areas, serving extensive zones, often have very long outgoing feeders. Major voltage sags at the tip of an outgoing feeder are observed during peak consumption periods, sometimes resulting in equipment malfunctions or complaints from customers. EDF recently evaluated the performance of devices based on energy storage batteries installed in the low-voltage (LV) network to eliminate these problems. As shown in Figure 2, an active power injection at the tip of the outgoing feeder (point 3) effectively maintains the network voltage within the rated voltage defined by the applicable standard. By controlling voltage to limit the constraints, the aim is to significantly defer new investments in the LV network, which is largely considered to be the only solution to these problems.

This study was performed on three actual cases of low-voltage outgoing feeders that were considered to be representative of outgoing feeders subject to voltage sags. These sections are situated in rural or industrial zones.

The evaluation proves that, if the voltage sag remains moderate (e.g., approximately 2%, reducing the voltage sag from 10 to 8%), the use of storage batteries ensures compliance with the applicable standard of voltage variation and makes it possible to defer extension of the network by 5 to 10 years, assuming moderate growth levels (0 to 1% per year). Given the realistic hypotheses of the scenarios examined -- "network extension" and "battery storage" -- the average gains obtained by comparing the strategies remain moderate (in the region of 10% of the "network" solution cost). However, at the regional or country level, in which a sizeable proportion of the network is under stress, substantial aggregate gains are possible. In this case, the systems generate a unit capacity of several kW for 1 to 2 hours.

On the other hand, it is quite clear that the use of a storage battery system to more significantly reduce voltage sags is unrealistic. In this case, extending the network would systematically be the optimum economic solution.

In addition, these storage systems can be moved around to meet the needs of the network. It is possible, for example, to rapidly install this type of system on an outgoing feeder under stress. This makes it considerably easier to adapt the network to shifts in load and stress. At the regional level, it is thus possible to manage an installed base of such systems.

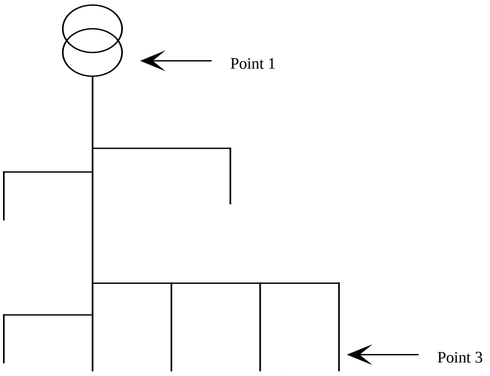

Figure 2: Low-voltage outgoing feeder

These conclusions are, of course, subject to the implementation of highly reliable, maintenance-free batteries that are endowed with good cyclability. These hypotheses appear realistic for the power ratings considered. However, this point remains to be confirmed by actual network demonstrations.

## ENERGY STORAGE AND MEETING CUSTOMER DEMAND

The challenge facing these applications is to fully meet customer needs in a satisfactory manner. Customer expectations include minimization of energy bills, outsourcing of utility operation and maintenance, and the supply of high-quality power to meet the needs of industrial processes and equipment.

### Load curve leveling for tariff optimization.

In most cases, customers bills are composed of the cost of the energy consumed, plus a demand charge. Over the past several years, there has been a tendency to reduce energy costs by rationalizing and optimizing management of the generating system. The demand charge is more directly

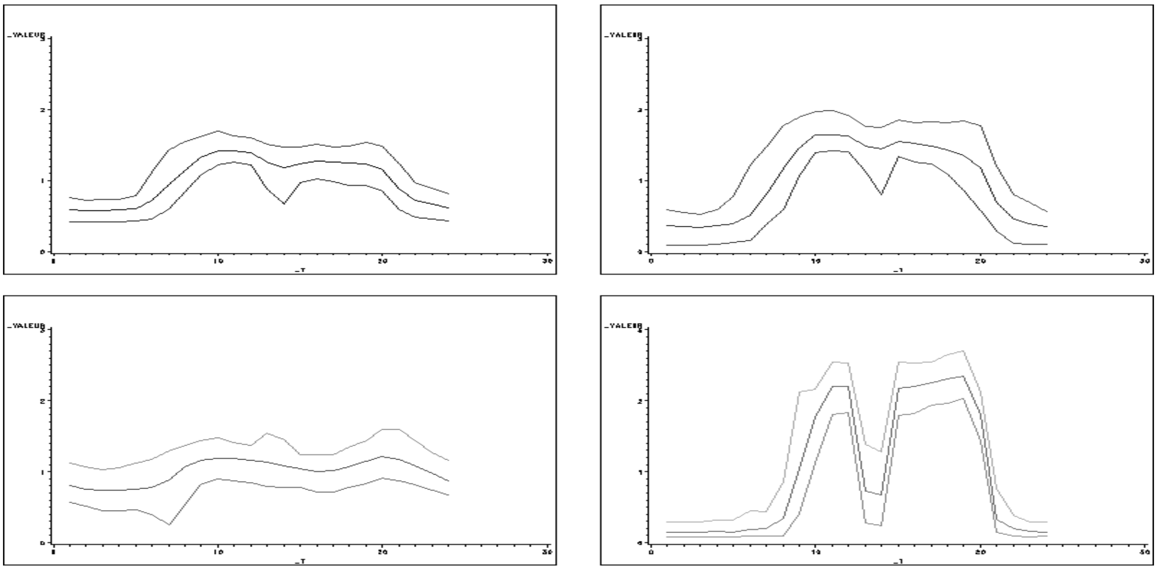

Figure 3: Typical profiles of customers daily load curves, read remotely during winter 97-98. Shown here are both range curves and average curves. Four categories were determined. Modulated profile: 52% of customers (top left); Highly modulated profile: 16% of customers (top right); Slightly modulated profile: 27% of customers (bottom left); Highly modulated profile with mid-way break: 3% of customers (bottom right).

linked to the development cost of the network that delivers the power to the end customer. These networks are designed to ride-through consumption peaks under satisfactory safety conditions. Deferring peak-period consumption to off-peak periods effectively helps alleviate network constraints. Efforts to spread consumption and make more rational use of electricity are undertaken jointly by the customer and the power utility. Leveling the customer load curve can perhaps also be pursued in a more proactive way, as shown in Figure 1. By limiting their power demand on the network, and by supplementing their consumption needs using an energy storage solution, and thereby establishing optimum conditions of storage efficiency and load curve regularity, customers can effectively reduce their demand charge and thus their overall energy bill.

From 1997 to 1998, EDF monitored the load curves of 200 industrial and service sector customers and evaluated the economic benefits of such an approach. Realistic technical parameters were considered for the maintenance-free batteries taken into account in this study.

Like the study carried out for the load leveling at HV/MV substation, generating profit margins through billing structures (user-side) appears to be difficult. The demand charge effectively measures the network development costs. Nevertheless, several niches were identified that could offer potential limited gains: customers with very regular, intensive use during peak periods. Once again, the cost of investing in the storage solution is high and does not generate substantial margins.

For this type of application, reliability has proved to be a decisive factor: a battery failure leads to excess of consumed power from the grid, the cost of which can easily cancel out any gains made elsewhere. The required levels of reliability (97-98%) are high, but seem accessible given the current state of the art and the range of suitable structures.

Lastly, it seems necessary to combine load leveling with other functions, such as quality of supply, which would allow additional gains to be made.

## Matching quality of supply to customer needs

Finally the last but maybe the most promising application of energy storage is dealing with Custom Power, in particular in the area of Power Quality. Prototype or commercial demonstration units can be found in the power range from a few hundreds of kW to about 10 MW. Run time for energy storage is required from a few seconds (SMES, flywheel, capacitor) to several tens of minutes (battery). Storage technologies able to deliver energy through pulses are specifically adapted for voltage sags, dips or outages mitigation.

Such systems are involved in services proposed to customers in order to customized power quality dedicated to their specific needs. Relocatable devices are particularly appreciated for a general optimization of the management of services and related equipment. The technical performances presently obtained with small scale supercapacitors make them very attractive for future if these properties are confirmed [13]. However, the systems available are small sized and also still very expensive.

The valorization of energy storage aimed to improve the Power Quality level is not an easy exercice at all. Some industrial process are facing significant losses directly or undirectly, hard to evaluate. In fact the cost estimation for not adapted level of Power Quality corresponds to a wide range. Equipment costs of storage system, of related services must be compared to several items: network reinforcements devoted to Power Quality improvement, cost spent by the customers to protect their facilities from voltage disturbances, the non-satisfaction of customers who can change the energy supplier…

The potential market for energy storage system devoted to customized Power Quality seems to be significant [5]. However commercial products presently available in the range from a few hundreds of kW to 10MVA are not yet numerous. The cost dynamic (especially decrease!) is a key element for the development of the market. Decentralized power generation can efficiently be added to this offer, provided the units are properly rated.

Table 3 : Demonstration units devoted to Power Quality

| Plants Manufacturer | Power MVA | Autonomy | Technology |
|---|---|---|---|
| Omnium-EPRI | 2 | 10 s | Battery |
| Vernon/GNB | 5 | 10 s | Battery |
| ASC/USA | 1.4 | 3 MJ | SMES |
| IGC/USA | 0.75 | 6 MJ | SMES |
| Piller/Germany | 1.6 | 10 s | Flywheel |

## OPPORTUNITIES AND PROSPECTS

Major changes in the energy sector faced since a few years lead on the one hand to requirements for enhanced flexibility for the power system operation and on the other hand to meet the increasingly targeted and diversified needs of customers. This new context provides exciting and real opportunities for energy storage.

High rating stationary applications requirements are today efficiently met with hydro-pumped plants. For power ranges from a few hundreds of kW to a few tens of MW during some hours, such as load leveling, frequency control or voltage drop mitigation, energy storage systems operating with power electronics interface can be valorized through the flexibility. However present costs lead to use energy storage system in highly constrained environment.

Besides energy storage applications close to the end user (customer) such as Power Quality, tariff optimization, storage of energetic fluids (gas, heat, compressed air, electricity, UPS) seems to be the most promising. In accordance with this conclusion, EDF is now significantly involved in the development of services for customers : Custom Power, tariff optimization through energetic consumption diagnostic on processes and widely tariff optimization.

The evolution of the technical and economical performances of these equipment will play a decisive role for the size of the market. The well known “Demand and Offer” law will leads to innovating functions and devices and related market.

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