ELEKTROTEHNIŠKI VESTNIK 83(5): 243-250, 2016
ORIGINAL SCIENTIFIC PAPER

# Economic evaluation of energy-storage systems for grid-scale applications. Part 1: methodological approach and selection of candidate technologies

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**Abstract.** This work performs a preliminary comparative economic analysis of various energy-storage systems (ESSs) for MW-scale applications in medium-voltage (MV) distribution systems. Two specific applications are analyzed, depending on the amount of the total local photovoltaic (PV) generation. In case of a low PV generation, the ESS is used to improve the power quality (PQ). In case of a high PV generation, the ESS is used to allow a full local consumption of the PV generation as well as to improve the PQ. The two cases imply different power/energy specifications for the ESS and, thus, different candidate storage technologies. In this Part 1 we: 1) illustrate the methodology used; 2) select the ESS power/energy specifications in both cases and 3) define, for each case, a set of candidate storage technologies. For each of these candidate solutions, detailed calculations and results are reported in the following Part 2, where the current ESSs sustainability for MW-scale power and energy applications is finally discussed.

**Keywords:** Electric energy storage, Battery storage systems, Microgrids, Power quality, PV generation

**Ekonomsko ovrednotenje sistemov za shranjevanje električne energije v srednjenapetostnem distribucijskem omrežju. 1. del: Metodologija in tehnične rešitve**

V članku so predstavljene predhodne primerjalne ekonomske analize različnih sistemov za shranjevanje električne energije v srednjenapetostnem distribucijskem omrežju. Glede na količino energije, pridobljene iz fotovoltaičnih sistemov, sta predstavljeni dve rešitvi. Pri manjši količini proizvedene električne energije uporabimo sistem za izboljšanje kakovosti električne energije. Pri večji količini proizvedene električne energije uporabimo sistem za shranjevanje energije in za izboljšanje kakovosti električne energije. Oba primera narekujeta različne zahteve za sistem za shranjevanje električne energije in posledično različne uporabljene tehnološke rešitve. V prvem članku predstavljamo uporabljeno metodologijo, zahteve in primerne tehnološke rešitve.

## 1 INTRODUCTION

The idea that the energy-storage technologies will play a fundamental role in power systems, bringing economic, technical and environmental benefits, gains today a wide consensus. The European Commission's 2012 Communication "Renewable Energy: a Major Player in the European Energy Market" stated that "electricity storage is a clear key technology priority for the development of the European power system of 2020 and beyond, in the light of the increasing market share of renewable and distributed generation (DG) and the growing limitations of the energy grid".

The energy-storage systems (ESSs) support the use of the renewable generation, because they can ensure that the wind and PV power are available when needed. Accordingly, in several recent installations, ESSs are used side by side with renewable power plants to improve their integration in the grid. Furthermore, ESSs can provide a large spectrum of performances to support operation of electrical grids. These include peak shaving, PQ improvement, frequency and voltage control, and others [1-4].

Some applications are power intensive, when the ESS exchanges a large power in short time intervals, up to some minutes. Other applications are energy intensive, when the ESS steadily exchanges the rated power in a time range of hours. A basic parameter is then the ESS energy/power ratio (E/P), between the ESS capacity and power rating. The E/P gives the ESS autonomy at the rated power. For power applications (low E/P), the energy can be stored in capacitors, supercapacitors (SCs), or flywheels (also SMES systems are potentially suitable for power applications. However, since SMES is not yet a mature technology, it is not analyzed in this study). For energy applications (high E/P), in addition to the pumped hydro-power storage used at power transmission level, smaller-scale and more flexible storage technologies are required at all grid levels as penetration of the renewable energy sources increases. Electrochemical storage systems (or

*Received 20 July 2016*
*Accepted 9 November 2016*

battery energy-storage systems – BESSs) are adequate for applications with E/P in the range from several minutes to several hours, and are gaining acceptance in MW-scale storage applications, often in conjunction with renewable sources. Today, a strong R&D activity concerns BESSs, whose penetration in power systems – both in transmission and distribution grids – is expected to increase rapidly.

ESSs are also a building block of a microgrid, defined as "a local group of electricity generation, energy storage, and loads". A microgrid normally operates connected to a main grid, but the (single) point of common coupling can also be disconnected (isolated microgrid). Usually, generators and loads are interconnected at low voltage (LV), but a similar structure can be realized also at a higher scale, within a MV distribution system.

The aim of this study is to evaluate the economic sustainability of the storage technologies for MW-scale applications at MV level. Several recent works deal with the ESSs economics. In this field, however, many variables lead to a variegated landscape characterized by different approaches, methodologies and scopes. For example, the study [5] focuses on a specific approach, as it analyzes operation of a generic BESS, rated 2 MW and 4 MWh, used for the primary frequency control. The work [6] performs an economic evaluation and optimal scheduling of a generic BESS in power systems with a large PV generation (a typical energy application). A wider approach is adopted in [7], where different technologies to accommodate the wind-energy expansion in a specific power system are compared. Even more general approaches are used in [3, 8], where various storage technologies and applications are considered.

It is also worth mentioning a specific tool (the Energy Storage Valuation Tool) developed by EPRI for quantifying the value of grid energy-storage opportunities [9]. The tool – a software developed to support the methodology – enables a preliminary economic analysis prior to more resource-intensive analytical efforts.

In this study, two applications of ESSs are considered: one is power intensive, the other energy intensive. Due to the considerable amount of material involved, the work is divided in Part 1 and Part 2. In this Part 1, we first define the reference system, set the basic hypotheses for the study and illustrate the methodological approach. Second, we select the basic power/energy specifications of ESSs for the two applications. Finally, for each application, we individuate a set of candidate storage technologies. Detailed calculations and final results are reported and discussed in Part 2 [10].

## 2 REFERENCE ARRANGEMENT AND ESS APPLICATIONS

The study applies to the reference arrangement depicted in Fig. 1. This arrangement matches a principle scheme originally proposed by Certs (Consortium for Electric Reliability Technology Solutions) to improve reliability in distribution systems, and later investigated in [11-12] in the frame of premium power parks. We assume that:

- DG includes PV and, in addition, possible "traditional" generators, dotted in Fig. 1
- one ESS is installed downstream of the normally closed separation breaker (SB).

The system downstream of the SB can be regarded as a microgrid. Although some approximations are required, this arrangement allows investigation of two different ESS applications – a typical power and a typical energy application – changing only the size of the local PV.

Case 1. Consider a limited PV generation, smaller than the local load demand. The PV generation integrates production of traditional generator(s) and reduces the power supply from the main grid. We assume that the ESS is designed to improve PQ downstream of the SB. This means that, upon detection of a PQ event, the SB opens (see the closing discussion) and the ESS delivers the energy to the local load.

Case 2. If, on the contrary, the installed PV power exceeds the local load demand, we assume the ESS is used to store the energy when the PV power (more generally, the local DG generation) exceeds the local load power, and to deliver the energy during a low PV generation. This way, the ESS allows a full exploitation of the PV generation and matches the microgrid paradigm to feed the local loads with a local generation, using as far as possible the main distribution grid as a backup power source. In fact, there are good reasons to avoid a reverse power flow on the SB: a better voltage control in the distribution system, lower power losses (efficient use of generation), and possible benefits deriving from self-consumption of the local generation. In addition, the ESS is used also to improve PQ in the microgrid, as in Case 1.

These two different case-studies imply different ESS power/energy specifications and, accordingly, the candidate storage technologies are different, too.

Throughout this work, we assume a 1 MW load level downstream of the SB. In order to simplify computation, this load is supposed to be constant.

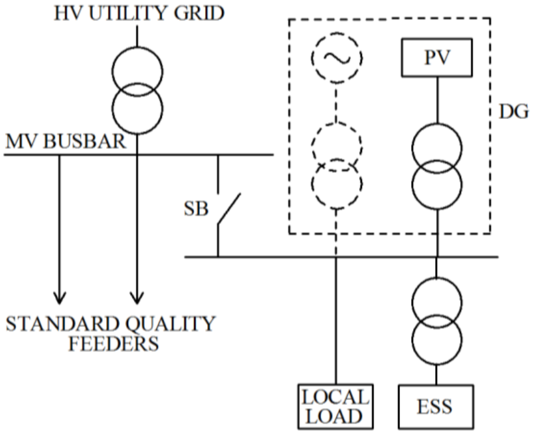

Figure 1. Reference arrangement.

## 3 STATISTICAL PQ DATA

To improve PQ, the ESS should compensate for harmful PQ events. Resorting to the approach used in [11-12], we assume these are accidental interruptions and voltage dips, which are the main origins of the equipment damage or malfunction and ‘production process halts’ (PPHs), with related financial losses for customers. In what follows, we call these losses the PQ direct costs (PQC). In agreement with the 50160 European Standard, interruptions are classified in long (>3 minutes) and short (<3 minutes). Less than 1 s long interruptions are termed transient interruptions and can be regarded as severe voltage dips with a zero residual voltage on all phases.

A basic variable is the load sensitivity to the PQ events. To this regard, we assume that the whole local load is affected by all interruptions (i.e., each long, short and transient interruption causes a PPH). As to the voltage dips, we consider four different (average) sensitivity levels to characterize the load. In order of increasing immunity, they are: Class 2 sensitivity, R-DFI sensitivity[1], Class 3 sensitivity, and “Class ∞” sensitivity [12, 13]. Class ∞ represents the loads not affected by the voltage dips (but affected by all types of interruptions, as already stated).

For calculations, we use statistical data of the Italian MV public supply provided by AEEGSI, the Italian National Regulatory Authority, and by Queen [11, 12], the Italian MV PQ monitoring system, relevant to the period 2009-2013. As to accidental interruptions, we assume the following average figures, which characterize a “normal-quality” MV supply: two long, six short, and seven transient interruptions per year. As to the voltage dips, we assume the dip distribution reported in Tab. 1, consistent with the voltage dip classification of the 50160 European Standard [13]. In Tab. 1, the Class 2 and Class 3 immunity areas are chromatically evidenced (Class 2 area = light grey, Class 3 area = light and dark grey).

Using these interruption and voltage dip data, for each load sensitivity level it is easy to obtain the expected number of PPHs/year reported in Tab. 2.

Table 1. Annual voltage dips for a normal-quality MV supply.

| Residual voltage | Duration | | | | |
|---|---|---|---|---|---|
| | 10 – 200 [ms] | 200 – 500 [ms] | 0.5 – 1 [s] | 1 – 5 [s] | 5 – 60 [s] |
| 80 – 90 [%] | 33.5 | 7.1 | 1.5 | 0.7 | 0.2 |
| 70 – 80 [%] | 14.9 | 4.1 | 0.5 | 0.1 | 0.0 |
| 40 – 70 [%] | 20.4 | 5.1 | 0.4 | 0.1 | 0.0 |
| 5 – 40 [%] | 7.2 | 1.6 | 0.2 | 0.0 | 0.0 |
| 0 – 5 [%] | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |

Table 2. Expected PPHs/year for a normal-quality MV supply.

| | Voltage dips | Transient interrupt. | Short interrupt. | Long interrupt. | Total |
|---|---|---|---|---|---|
| Class 2 | 38.1 | 7 | 6 | 2 | 53.1 |
| R-DFI | 26.8 | 7 | 6 | 2 | 41.8 |
| Class 3 | 15.5 | 7 | 6 | 2 | 30.5 |
| Class ∞ | 0 | 7 | 6 | 2 | 15 |

## 4 BENEFIT EVALUATION

Computation of the economic benefit provided by the ESS requires evaluation of:
- PQ improvement (for both Case 1 and Case 2)
- PV-generated energy increase (for Case 2 only).

### 4.1 *Benefit connected with the PQ improvement*

This benefit is computed as the annual PQC avoided owing to the compensation of harmful PQ events. In order to evaluate PQC, we link a cost figure with each type of PQ event that causes a PPH. We use here the methodology and cost figures adopted in [12]. Thus, the unitary costs of long and short interruptions, referred to a 1 MW load, are 12,500 € for each long interruption, and 4,375 € for each short interruption.

As to the transient events, we group together the transient interruptions and voltage dips, and call them micro-interruptions. For them, we adopt the unitary cost of 2 k€ per event. Notice that all the four load sensitivity levels considered in this study are more or less affected by microinterruptions, since also the least sensitive one (Class ∞) is affected by transient interruptions.

Multiplying the PPHs/year reported in Tab. 2 by the unitary costs of the PQ events, we obtain the expected PQC/year with no compensation reported in Tab. 3. The PPHs/year avoided are the difference between the PPHs/year without ESS (Tab. 2) and the residual PPHs/year with ESS, which can be easily calculated assuming that: 1) all the PQ events shorter than the ESS autonomy are effectively compensated, and 2) all the PQ events longer than the ESS autonomy cause a PPH.

Finally, the annual benefit is the product, for each

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[1] The R-DFI - *regulated dip frequency index* - is a middle course between the Class 2 and Class 3 immunity levels. It is got weighting 1 each voltage dip below the Class 3 curve, 0 each voltage dip over the Class 2 curve and 0.5 each voltage dip between the two curves.

type of PQ event, of the expected PPHs avoided and the corresponding unitary direct cost.

Table 3. PQC/year without EES (for a 1 MW load) [k€]

| | Micro-interrupt. | Short interrupt. | Long interrupt. | Total |
|---|---|---|---|---|
| Class 2 | 90.2 | 26.3 | 25 | 141.5 |
| R-DFI | 67.6 | 26.3 | 25 | 118.9 |
| Class 3 | 45 | 26.3 | 25 | 96.3 |
| Class ∞ | 14 | 26.3 | 25 | 65.3 |

### 4.2 Benefit connected with the full exploitation of PV

In Case 2 we assume a 2 MW PV rated power. At the latitudes of Northern Italy, the corresponding production is ~2,500 MWh/year, i.e. ~2/7 of the energy consumed by the 1 MW constant local load (8,760 MWh/year).

In order to assess the PV production increase, $\Delta E_{PV}$, we simulated the PV generation with a specific software (PVGIS – solar photovoltaic energy calculator). Taking into account the realistic availability of the ESS (for the BESSs availability data, see for instance [14]), $\Delta E_{PV}$ can be predicted in the range of 300÷375 MWh (i.e., 12÷15% of the annual PV production) if no traditional DG is installed downstream of the SB. Conversely, if the local DG includes also traditional generators, $\Delta E_{PV}$ increases, increasing also the required storage capacity and the relevant investment costs, finally making the ESS less convenient (see [10]). Therefore, looking for the most favorable cost/benefit evaluation, in the analysis of Case 2 we will assume $\Delta E_{PV}$ in the range above reported.

For simplicity, we compute the benefit connected to $\Delta E_{PV}$ as the value of the same production from traditional generators (for example, gas-fired generators). This way, we overestimate the benefit since we neglect the value of the PV energy delivered to the grid. On the other hand, we neglect further benefits resulting from the energy time-shift aimed at increasing the value of the PV production. The benefit connected to $\Delta E_{PV}$ is, thus, computed as the value of the energy supplied by the main grid and produced by traditional generators, $B_1$, plus the value of the $CO_2$ emissions avoided, $B_2$. They are proportional to $\Delta E_{PV}$ according to:

$$B_1 = E_P \Delta E_{PV} \tag{1}$$

$$B_2 = K_1 K_2 \Delta E_{PV} \tag{2}$$

where $E_P$ is the (average) energy price at the MV level, $K_1$ is the ratio between the $CO_2$ emissions and the energy produced, and $K_2$ is the cost assigned to the $CO_2$ emissions.

The average reference values for these parameters are $E_P$=125 €/MWh, $K_1$=0.4 ton$CO_2$/MWh (adequate for the current energy mix of the Italian power plants), and $K_2$=10 €/ton$CO_2$[2]. Accordingly, $B_2$ turns out in the order of 1 k€, much less than $B_1$. Finally, taking $\Delta E_{PV}$=350 MWh, the annual benefit is about 45 k€. This value is used in Part 2, in the analysis of Case 2 [10].

## 5 CASE 1

### 5.1 ESS power/energy specifications

The PQ improvement involves a small annual energy, mainly required to compensate long interruptions, whereas the shorter PQ events contribute less even though they are many more. On average, long interruptions are very few. Assuming for them an average duration of 1 hour[3], the energy required for compensation of the PQ events can be a few MWh/year. The relevant cost, in the order of some hundred euros, is negligible compared with the ESS costs.

The ESS autonomy should be sufficient to compensate long interruptions. However, a backup generator (BG) allows reducing the ESS autonomy to the generator start-up time or little more, say about 20 s.

In conclusion, the ESS main specifications are P=1 MW rated power (i.e., the load demand in the worst case of zero local DG power), whereas the capacity E can be less than 10 kWh for a 30 s autonomy, or 50 kWh for a 3 minute autonomy (i.e., the maximum duration of short interruptions). For a comparison, the typical capacity of a battery for electric vehicles is 10÷15 kWh. In practice, however, the ESS rated capacity E strongly depends on the storage technology (see the next section).

Anyway, the PQ improvement is a power application, and requires low E/P (for example, E/P=0.01÷0.1 h) and a low number of charge/discharge cycles for the ESS.

### 5.2 Candidate technologies

The above ESS specifications match the traditional electrolytic capacitors, SCs, and flywheels performances. All these technologies have a fast response time, consistent with the compensation of the transient PQ events.

Capacitors have a very low energy density (about 0.05 Wh/kg), autonomy and charge/discharge times.

SCs locate halfway between the traditional capacitors and BESSs [1, 4, 8]. They can store much more energy per unit mass than capacitors (1÷10 Wh/kg) and store and deliver the energy faster than batteries but slower than capacitors (typical charge/discharge times are tens of seconds). SCs have a life of about one million cycles (extremely high compared to the thousands typical of BESSs), have a high efficiency and can operate in a wide temperature range, between -40°C and +65°C. Compared with batteries, SCs have a higher specific

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[2] In line with the mean peer reviewed value of the social cost of carbon and with the carbon tax currently adopted in some countries.

[3] Italian 2010-12 PQ data show that 50% of long interruptions at MV level last less than 30 minutes, 42.6% less than 15 minutes.

power (0.3÷10 kW/kg) but a remarkably lower specific energy, thus being about ten times larger than batteries for a given charge capacity.

The flywheels energy storage systems (FESSs) [1, 8, 15] have a specific power similar to SCs, specific energy in the range 70÷200 Wh/kg, comparable to many BESSs, long life (more than 100,000 cycles), and high efficiency (up to 90%). The FESSs defining feature is the instantaneous response time, which makes them technically suitable for the UPS and PQ applications. However, FESSs are not yet mature. There are still few FESSs installations in support of power systems worldwide, most being demonstration projects made up by several small size units connected in parallel [10]. In this work, we refer to commercially available solutions with a virtually unlimited autonomy, based on an FESS+BG combination. Their typical applications are in data centers, where an extremely high supply availability and PQ are required. These solutions are expensive but can provide further services (voltage control, harmonic rejection). We do not consider ESSs based on flywheels only, as there are no reliable cost data for them available.

Also BESSs can be considered in Case 1, as most technologies feature a short response time (about 20 ms), adequate for compensation of the transient voltage events [1]. Compared with capacitors, SCs and FESSs, the longer BESSs autonomy can allow compensation of long interruptions without resorting to a BG. Among several technologies, the most interesting (either most promising or technically and commercially mature) include the lead-acid, sodium sulfur (NaS), NaNiCl, Lithium Ion (Li-ion), and Redox Vanadium (VRB) batteries, reported in Tab. 4 [1, 2, 4, 7, 8, 14, 16].

Table 4. Main BESS technologies: indicative data.

| BESS technology | Energy density[a] [Wh/kg] | Power density [W/kg] | Life cycles at 75% DoD | ac/ac roundtrip efficiency |
|---|---|---|---|---|
| VRLA | 20÷40 | 70÷80 | 1000÷2000 | 75÷85% |
| Li-Ion | 40÷220 | 200÷1500 | 3000÷6000 | ~85% |
| NiCd | 50÷60 | 500÷800 | 1500 | ~70% |
| NaS | 240 | 210 | 4500 | ~80% |
| NaNiCl | 150 | 160 | 4500 | ~80% |
| VRB | 25 | 100 | 10,000 | ~70% |

The Li-ion family includes several cell technologies with different performances. This explains the wide ranges reported in Tab. 4. Versatility is a major advantage of the Li-ion batteries: they are highly scalable and adaptable to different power/energy requirements. In particular, the high specific power of some Li-ion batteries makes them well suited for power applications. However, at a high power normally corresponds a low energy, and vice versa. Among the Li-ion technologies, best used for the power applications are LMO, LFP, and LTO, whereas for the energy applications NMC and NCA are used. On the other hand, the Li-ion technology is not yet mature, and its main drawback is given by still high costs.

Also NiCd is a natural candidate technology for power applications, however, the NiCd batteries are not considered here because of the cadmium toxicity.

No recent grid-scale installation concerns the traditional valve-regulated lead-acid (VRLA) batteries[4]. However, this is the most mature BESS technology, characterized by a low cost, good versatility, stable connection of cells and availability of raw materials. The main cons are the limited energy and power density and, most of all, service life. However, the low frequency of discharge required in Case 1 can allow the conventional VRLA batteries reaching ten years of life before replacement. Viable alternatives are the advanced lead-acid batteries, having a much longer cycle life, better performances but a much higher cost [1, 14, 16]. Different types of advanced lead-acid batteries have been used since 2011 in many grid-scale demonstration projects [17]. In short, these batteries derive from the conventional VRLA technology, with the main difference of the electrode plates enhanced with carbon. A further type of advanced lead-acid battery is the UltraBattery, that is basically a lead-acid battery coupled with an asymmetric SC [16]. At present, the UltraBattery is more versatile but has a higher manufacture cost.

Tab. 5 reports the energy-storage technologies selected for Case 1: capacitors, SCs, FESS+BG, and three BESS technologies: standard VRLA, advanced lead-acid and Li-ion batteries. The analysis also includes the capacitors+BG and SC+BG combinations [10].

Table 5. Candidate ESS technologies for Case 1.

| Technology | Rated power P | Rated capacity E[a] | Autonomy at rated power |
|---|---|---|---|
| Capacitors | 1 MW | 0.28 kWh | 1 s |
| Cap. +1 MW BG | 1 MW | 0.28 kWh | 1 s[b] |
| SC | 1 MW | 8.33 kWh | 30 s |
| SC + 1 MW BG | 1 MW | 8.33 kWh | unlimited |
| FESS + BG | 1 MW | 5 kWh | unlimited |
| Convent. VRLA | 1 MW | 1 MWh | 45 min at 75% DoD |
| Adv. lead-acid batt. | 1 MW | 0.25 MWh | ~11 min at 75% DoD |
| Li-ion batteries | 1 MW | 0.25 MWh | ~11 min at 75% DoD |

[a] E is given by the rated power times the autonomy (or discharge time).

[b] Since the ESS autonomy is lower than the BG startup time, a total continuity system cannot be obtained. In this case, the BG allows transforming long interruptions in short interruptions.

The BESSs capacity must be optimized: it is useful to oversize the battery reducing the DoD well below 100%. This way, the battery life markedly increases, improving the BESS economic evaluation [7]. In Tab. 5, for BESSs we assume 75% DoD. Thus, the battery

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[4] The Li-ion and advanced lead-acid batteries are currently the most used technologies for grid-scale BESS applications (both for power and energy applications, see [10]), together with the NaS batteries, which are used, however, only for energy applications [17].

useful energy is 0.75*E and the autonomy at the rated power is 0.75(E/P).

Notice that, in Case 1, the ESS roundtrip efficiency has a scarce importance because of the limited number of cycles required by the application.

## 6 CASE 2

### 6.1 ESS power/energy specifications

In Case 2, the ESS goals are full exploitation of the local PV plant(s) and PQ improvement. Since a sufficient energy for compensation of random PQ events must be always available, the ESS must be controlled to avoid reaching an insufficient state of charge (SoC). However, the PQ improvement requires a low energy storage, as already pointed out. Conversely, exploitation of the PV generation requires a much greater capacity and some/several hours autonomy. In the case of an ESS+BG combination, in order to improve the PQ the ESS capacity can be, according to the numerical values assumed above, as low as ~10 kWh, whereas a capacity of some MWh is required by the other task. Therefore, the ESS must be controlled to keep available for the PQ improvement a very low capacity percentage (~1%). Conversely, if no BG is connected, more energy must be available to compensate supply interruptions. This leads to a certain superposition of the two tasks and, thus, to a reduced ESS effectiveness in reaching the goals, unless the ESS capacity is increased.

With the input data PV=2 MW and 1 MW constant load, we assume that a minimum useful energy of 3 MWh is required for the ESS. This minimum value privileges a “light” ESS sizing rather than a 100% exploitation of PV plant(s). In other words, in agreement with the economic analysis performed in [10], it is preferable to give up a (small) part of the PV production potentiality in a limited number of sunny days, if this allows reducing the (high) ESS capital cost.

The resulting power/energy specifications are typical of BESS. Taking 75% DoD, the BESS main requirements are P=1 MW and E=4 MWh. Clearly, capacitors, SCs and FESSs are not suitable for the Case 2 application.

### 6.2 Candidate technologies

BESSs listed in Tab. 6 are among the most mature or promising technologies for the Case 2 application.

The candidate solutions include the transversal Li-ion and lead-acid batteries. As to the lead-acid technology, the operation required and the higher number of cycles make the usual VRLA batteries inadequate for Case 2 (at present, such batteries are not used in any grid-scale energy application [17]). Accordingly, only the advanced batteries are included in the Case 2 analysis.

The NaS batteries have reached a good maturity (notice that the small-scale NaS technology is well developed, but the grid-scale NaS batteries are still in early commercialization). They are used for energy applications and are commercially available with typical ratio E/P=6÷7.2 h. Accordingly, for the NaS batteries we assume E=6 MWh.

The NaNiCl batteries have a structure similar to the NaS batteries. The main difference is given by one electrode, made of nickel instead of sulfur. Having a high specific energy (up to 150 Wh/kg, about five times higher than the VRLA batteries) and good safety, also the NaNiCl batteries are an interesting candidate for Case 2.

The VRBs are flow batteries. P and E are largely independent, as the power depends on the quantity of electrolyte involved in the chemical reactions and thus on the pumps flow rate, whereas the capacity depends on the storage-tank volume. Possible large capacities make the VRBs suitable for an autonomy of 2÷8 hours, matching well the present application. The advantages of VRBs are a very long service life and no ill effects if they remain completely discharged for long periods. The main cons are the higher system complexity compared with other BESSs, and an about twice-space requirement compared to other BESSs.

Possible BESS+BG combinations are investigated, too (see [10]). On the contrary, possible hybrid solutions consisting of two different ESSs, i.e. a power intensive ESS for the PQ improvement and an energy intensive BESS for a full exploitation of PV plants, will not be investigated since it would involve excessive costs.

Notice that the connection of a BG maximizes the PQ improvement, but does not modify $\Delta E_{PV}$. Also, $\Delta E_{PV}$ is independent from the specific BESS technology except for the NaS batteries, whose higher capacity allows a small $\Delta E_{PV}$ increase (and makes more independent the two ESS goals). Therefore, in Part 2 the benefit connected with $\Delta E_{PV}$ is assumed 50 k€ for the NaS batteries, instead of the value 45 k€ used in the other cases.

Table 6. Candidate BESS technologies for Case 2

| BESS technology | Rated power | Rated capacity | Autonomy at rated power |
|---|---|---|---|
| Adv. lead-acid | P=1 MW | E=4 MWh | 3 h at DoD=75% |
| Li-ion | P=1 MW | E=4 MWh | 3 h at DoD=75% |
| NaS | P=1 MW | E=6 MWh | 4.5 h at DoD=75% |
| NaNiCl | P=1 MW | E=4 MWh | 3 h at DoD=75% |
| VRB | P=1 MW | E=4 MWh | 3 h at DoD=75% |

## 7 ECONOMIC EVALUATION

The ESS costs, both capital (capex) and operative (opex), are evaluated for Case 1 (P=1 MW, E variable according to the storage technology) and Case 2 (P=1 MW, E=4÷6 MWh) resorting to the cost data reported in technical literature and/or provided by manufacturers and specialists. Finally, we perform a preliminary economic evaluation of each ESS solution by calculating two widespread economic indices: pay-back time (PBT) and net present value (NPV). PBT is defined as:

$$PBT\ [years] = capex/annual\ saving \tag{3}$$

Clearly, PBT merely involves the annual cash flows without actualizing them. It can be used for a preliminary evaluation of different solutions over a given time period. Conversely, NPV actualizes the cash flows during the time period considered, making them comparable with the capex. Actualization is made using the weighted average cost of capital (WACC). NPV is defined as:

$$NPV\ [monetary\ unit] = \Sigma_{k=1}^{n} \frac{C_k}{(1+c)^k} \tag{4}$$

In (4), $k$ are the cash flow times (year 1, year 2, and so on), $n$ is the time horizon, $C_k$ is the financial cash flow at year k, and $c$ is WACC. For calculations, we assume WACC=7% (c=0.07) and n=10 years (base-case).

## 8 DISCUSSION

In this section we shortly discuss some aspects relevant to the methodology adopted.

1) R*eference arrangement and SB state*. The specific arrangement of Fig. 1 is related to the microgrid and premium power park concepts [11, 12]. In both cases, a high PQ level is a technical goal. Assuming that the SB is normally closed, the average PQ data of the MV public distribution systems can be used. These data are available and reliable. Vice versa, a normally open SB state (not a common situation in real distribution systems) would make uncertain both the ESS capability to improve PQ and the PQ data that should be assumed for the analysis.

2) *SB opening time.* If the local load is sensitive to voltage dips (Class 3 or higher sensitivity), according to the 50160 European Standard the SB should open in less than one cycle. This can be obtained through a static circuit breaker [11, 12]. Conversely, if the load is less sensitive, a less sophisticated (and expensive) circuit breaker can be used. However, without getting involved in these considerations, in Part 2 we assume that the SB is adequate to allow an effective compensation of the PQ events.

3) *PQC calculation*. In Section 4, we compute the PQC avoided using the unitary costs of the PQ events derived in [12] with reference to a 1 MW load, the same power of the local load in this study. Doing so, we consider the local load as a unique system, neglecting the individual characteristics of the various devices that compose it. This approach is acceptable for interruptions, as they affect most individual loads, but it seems not in case of voltage dips, since they affect only some devices. Applying the unitary costs of microinterruptions to the whole local load, PQC can be overestimated. Taking this in mind, we can interpret the four sensitivity levels described above as the average sensitivity levels of the local load. Accordingly, the highest sensitivity (Class 2) appears excessive to represent the load, whereas the Class 3 and Class ∞ levels appear more realistic.

4) *PQ events originated downstream of the SB*. The approach adopted for computation of the PQC avoided by the ESS assumes that all PQ events originate upstream of the SB. Concerning this, it looks acceptable to assume that, owing to an accurate construction and a limited extension of the microgrid, faults downstream of the SB are very unlikely and can be neglected.

5) *Residual PPHs*. Computation of the residual PPHs assumes that each PQ event shorter than the ESS autonomy can be compensated. This assumption does not take into account the real availability of the ESS and of the relevant power-conversion system [14].

## 9 CONCLUSION

This Part 1 defines and discusses a methodology for the economic evaluation of different ESSs and different grid-scale applications in MV distribution systems. The study applies to a specific network arrangement that allows the investigation of both power and energy applications, depending on the size of the local PV generation. In such frame, in case of a low PV generation (Case 1), the ESS is used to improve the PQ. In case of a high PV generation (Case 2), in addition to the PQ improvement, the ESS is used to allow a full local exploitation of the PV generation (in agreement with the microgrid concept).

We individuate the ESS power/energy specifications, different in the two cases, and the candidate storage technologies. The candidate technologies selected are, in Case 1, capacitors, SCs, flywheels, conventional VRLA, advanced lead-acid and Li-ion batteries, and in Case 2 advanced lead-acid, Li-ion, NaS, NaNiCl, and VRB batteries. In both cases, the ESS may be coupled with a BG to extend the compensation capability of the PQ events.

We base the cost/benefit evaluation on PBT and NPV. The costs include the ESS (and the BG, if the case) capex and opex. The benefits are the PQC avoided (in both cases), and the energy and environmental costs avoided because of the PV production increase (in Case 2). Resorting to an already tested procedure, we assume that PQC are caused by interruptions and voltage dips. Four different load sensitivity levels and original cost models for the supply voltage events are used in the analysis. Detailed calculations are reported in the following Part 2.

## ACKNOWLEDGEMENT

This work was financed by the Research Fund for the Italian Electrical System under the Contract Agreement between RSE S.p.A. and the Ministry of Economic Development – General Directorate for Nuclear Energy, Renewable Energy and Energy Efficiency in

compliance with the Decree of March 8, 2006.

The author thanks Mr. Massimo Ceraolo, Università di Pisa, and Mr. Davide Falabretti, Politecnico di Milano, for their valuable suggestions on BESS technologies.

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