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Economic evaluation of energy-storage systems for grid-scale applications. Part 2: analysis and results

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Abstract. In this Part 2 we perform an economic evaluation of the candidate energy-storage systems (ESSs) selected in the previous Part 1 for two different applications in medium-voltage (MV) distribution systems: power quality (PQ) improvement, and full local exploitation of the photovoltaic (PV) generation. The first application is power intensive, the second energy intensive. Accordingly, the ESS power/energy specifications are different. Starting from the two sets of candidate technologies and their specifications, and using the methodology outlined in Part 1, in this Part 2 we calculate, for each case and each candidate technology, the annual benefits and two economic indices: the pay-back time (PBT) and the net present value (NPV). The results, compared and commented, provide information on the current sustainability of different storage technologies in the frame of different grid-scale applications – either power or energy intensive – in MV distribution systems.

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

Ekonomsko ovrednotenje sistemov za shranjevanje električne energije v srednjenapetostnem distribucijskem omrežju. 2. del: Analiza in rezultati

V članku predstavljamo ekonomsko ovrednotenje sistemov za shranjevanje električne energije za izboljšanje kakovosti električne energije in za shranjevanje električne energije, ki jo proizvedemo s fotovoltaičnimi sistemi. Prvi primer uporabe je intenziven glede električne moči, drugi glede električne energije. Za oba primera uporabe podajamo ključne ekonomske kazalce. Dobljeni rezultati podajajo informacijo o ekonomski upravičenosti različnih tehnoloških rešitev za shranjevanje električne energije v srednjenapetostnem distribucijskem omrežju.

1 INTRODUCTION

This Part 2 performs a cost/benefit evaluation of MW-scale energy-storage technologies for two different applications in MV distribution systems. The analysis is based on the methodology outlined in Part 1 [1].

For the reader's convenience, we briefly recall here the main assumptions, data and results obtained in Part 1. We refer to the arrangement described in [1], with a 1 MW (constant) load downstream of the separation breaker (SB). As to PQ, we assume that both the supply interruptions and voltage dips cause equipment damage or malfunction and lead to 'production process halts' (PPH), with a related financial loss (the so-called PQ direct costs - PQC) for the users. According to the Italian average PQ data relevant to the MV public supply, we assume the local load experiences two long, six short, and seven transient interruptions of supply per year. We also assume that all of them affect the load, causing in all 15 PPHs/year. In addition, comparing the voltage dips distribution reported in [1] and the four load sensitivity levels considered (Class 2, R-DFI, Class 3, and Class ∞), we obtain the further PPHs reported in Tab. 1.

Table 1. PPHs/year for a "normal-quality" MV supply.

	Class 2	R-DFI	Class 3	Class ∞
Interruptions	15	15	15	15
Voltage dips	38.1	26.8	15.5	0
Total	53.1	41.8	30.5	15

For the PQC calculation, we use the same unitary costs evaluated in [2]: 12.5 k€ for each long interruption, 4.375 k€ for each short interruption and 2 k€ for each microinterruption (i.e., transient interruption or voltage dip). Accordingly, with no ESS compensation the annual PQC amount to 25 k€ due to long interruptions, 26.3 k€ due to short interruptions, and 90.2/67.6/45/14 k€ due to microinterruptions, respectively for Class 2/R-DFI/Class 3/Class ∞ sensitivity levels (see [1], Tab. 3).

We consider the two ESS applications illustrated in [1]. With a moderate local PV generation (total $P_{PV} < 1$ MW = load power), the ESS is used only to improve PQ downstream of the SB (Case 1). This is a typical power application. If the local PV generation exceeds the load demand (we assume P_{PV}=2 MW), in addition to the PQ improvement the ESS is used, in agreement with the microgrid concept, to allow a full exploitation and local

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consumption of the PV generation (Case 2). This is a typical energy application.

The ESS economic evaluation is made computing the two widespread indices PBT and NPV. The ESS costs include the investment costs (capex) and O&M costs (opex). For the NPV calculation, we assume a ten year ESS lifetime, and a 7% weighted average cost of capital.

Case 1. Tab. 2, where BG stands for back-up generator and FESS for flywheel-ESS, reports the power/energy specifications of the candidate storage technologies selected in [1]. For each solution, PBT and NPV are computed resorting to a simple cost/benefit evaluation, in which the annual benefits are the PQC avoided. Accordingly, the annual saving is given by:

$$\textit{Annual Saving} = \textit{PQC avoided} - \textit{ESS opex} \qquad (1)$$

Table 2. Candidate ESS technologies for Case 1.

Technology	Rated power P	Rated capacity E	Autonomy at rated power
Capacitors	1 MW	0.28 kWh	1 s
Cap. +1 MW BG	1 MW	0.28 kWh	1 s
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
Advan. lead-acid	1 MW	0.25 MWh	~11 min at 75% DoD
Li-ion batteries	1 MW	0.25 MWh	~11 min at 75% DoD

Tab. 3 reports the indicative capex and opex of the candidate solutions [3-10]. These rounded costs derive from different sources: technical literature, specialists and manufacturers[1]. Capex includes the power-conversion system (PCS) and battery-management system[2] (BMS), whose capex depends on the rated power and is usually expressed in €/kW [3, 6]. Overall, the capex assumed for the advanced lead-acid and Li-ion batteries may be optimistic, and takes into account the expected cost reduction trend. For FESSs, the cost data refer to a specific solution available on the market [1].

Table 3. Capex and opex for Case 1 (indicative values, in k€).

Energy storage technology	Capex	Opex
a) capacitors (E=0.28 kWh)	250	15
b) capacitors + BG	380	25
c) supercapacitors (E=8.33 kWh)	550	20
d) supercapacitors + BG	680	30
e) FESS + BG (E=5kWh)	1000	50[a]
f) conventional VRLA batt. (E=1 MWh)	450	30
g) advanced lead-acid batt. (E=0.25 MWh)	550	25
h) Li-ion batteries (E=0.25 MWh)	600	25

[a] For specialized maintenance provided by the manufacturer.

For battery-storage (BESS), a more detailed opex is reported in [3-6], split into fixed and variable O&M costs. Fixed O&M costs include plant operating and maintenance staff, component/equipment replacement, insurances, and property taxes. Variable O&M costs include corrective maintenance and other costs (diagnosing, investigation and testing of components) proportional to unit output [5]. For simplicity, here opex is assigned one overall value for each candidate ESS.

For a 1 MW genset (BG), a capex of 130 k€ is used (LV/MV transformer included). Opex reduces practically to the maintenance costs, that we assume equal to 10 k€/year. Since the BG is used for an occasional operation, its lifetime can exceed ten years.

Case 2. ESS specifications are P=1 MW and a useful energy of 3 MWh, with E/P in a range typical of BESSs. Tab. 4 reports the candidate BESSs selected and their main specifications (for the NaS batteries, consistently with the commercial E/P ratios, we set E=6 MWh) [1].

Table 4. Candidate BESS technologies for Case 2.

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

Table 5. Capex and opex for Case 2 (indicative values, in k€).

BESS Technology	Capex	Opex
a) advanced lead-acid batteries	2600	60
b) Li-ion batteries	3600	60
c) NaS batteries	2500	60
d) NaNiCl batteries	2800	60
e) VRB	3000	78

All the selected BESSs can guarantee at least ten year lifetime. Notice that in Case 2 the limited cycle life leads to discard the conventional VRLA batteries.

For most technologies, a wide spread exists among the manufacturing costs reported by different sources [3-11]. In this paper, we use the indicative capex and opex (inclusive of PCS and BMS) reported in Tab. 5. Notice than the PCS and BMS capex are similar in Case 1 and Case 2, because the ESS power is the same.

As to the opex, in most cases the available data are not directly comparable. Anyway, the detailed model reported in [6] is identical for the Li-ion and NaS batteries, and [8] reports almost an identical opex for the lead-acid, Li-ion, NaS and NaNiCl batteries. Accordingly, we assume an equal opex for the lead-acid, Li-ion, NaS and NaNiCl batteries, and a higher opex for the VRBs because of their higher complexity [5, 7, 8]. These assumptions appear realistic and have the advantage to simplify and speed up the analysis (see Section 4).

In Case 2, the annual benefit equals the PQC avoided plus the value of the PV production increase, ΔE_{PV}. Therefore, the annual saving (AS) is computed as:

[1] Often the costs reported by various sources are rather different and not easily comparable. In these cases, we adopt average values.

[2] BMS is any electronic system that manages the battery, such as protecting it from operating outside its safe operating area, monitoring its state and so on. Each BESS technology requires a specific BMS.

$$AS = PQC\ avoided + value\ of\ \Delta E_{PV} - ESS\ opex \quad (2)$$

The value of ΔE_{PV} is 50 k€ for the NaS batteries and 45 k€ for all the other BESSs [1].

2 CASE 1 ANALYSIS

According to the methodology outlined in [1], this section analyzes the benefits provided by each candidate ESS. The economic PBT and NPV indices are reported in Tabs. 12-13 in Section 3. For each candidate ESS, we also report the main data of some existing installations, which look interesting for the present study.

a) Capacitors

The very short autonomy makes capacitors adequate to compensate only the transient events. A typical application of capacitors is in Dynamic Voltage Restorers (DVRs) for voltage dip compensation. Examples of installations are in the premium power parks of Delaware, Ohio, USA, and Sendai, Japan, (see [2] for more details).

The 1 s autonomy assumed here allows compensating microinterruptions, but not short and long interruptions. Accordingly, the expected PPHs/year reduce to eight (due to the two long and six short interruptions), regardless of the sensitivity level of the load. Multiplying the PPHs/year by the unitary costs of the different events, we obtain the PQC. The PQC avoided (i.e., the annual benefit) are the difference between the PQC expected without and with ESS (Tab. 6). Obviously, the annual benefit increases with the load sensitivity to the voltage dips.

Table 6. PQ direct costs avoided in Case 1a [k€].

	Class 2	R-DFI	Class 3	Class ∞
Microinterruptions	90.2	67.6	45	14
Short interruptions	0	0	0	0
Long interruptions	0	0	0	0
Total	90.2	67.6	45	14

b) Capacitors + BG

Using a BG (rated 1 MW) in combination with the capacitor-based ESS, PQC can be further reduced. Since the ESS autonomy is less than the BG startup time (usually ~15 s), this combination cannot provide a total continuity of supply. However, interruptions longer than the BG startup time can be partially compensated, becoming short interruptions. Using the above unitary costs of the PQ events, the relevant (small) annual benefit is 2x(12,500-4,375)=16,250 €. Accordingly, Tab. 7 reports the PQC avoided.

Table 7. PQ direct costs avoided in Case 1b [k€].

	Class 2	R-DFI	Class 3	Class ∞
Microinterruptions	90.2	67.6	45	14
Short interruptions	0	0	0	0
Long interruptions	16.3	16.3	16.3	16.3
Total	106.5	83.9	61.3	30.3

c) Supercapacitors (SCs)

SCs bridge the gap between the electrolytic capacitors and the rechargeable batteries. They are suitable for applications requiring many rapid charge/discharge cycles: within cars, buses, trains, and so on. A recent installation (2015) is at New York, USA, and involves SCs rated 1 MW to perform voltage support and regenerative braking, with charging and discharging in 20 s [12].

Another installation is the test project of La Palma, Canary Islands, Spain, where a 4 MW, 5.5 kWh (5 s autonomy) SC bank is used for frequency control in a small isolated 30 kV power grid [13-14].

For calculation, we assume that the ESS can compensate all microinterruptions and part of short interruptions, whereas the interruptions longer than 30 s still cause PPHs. Assuming that these are the two long interruptions plus 75% of the six short ones, we obtain 2 + 0.75x6 = 6.5 residual PPHs/year. Following the usual methodology, we obtain the annual benefit reported in Tab. 8. Clearly, the advantage respect Case 1a is small.

Table 8. PQ direct costs avoided in Case 1c [k€].

	Class 2	R-DFI	Class 3	Class ∞
Microinterruptions	90.2	67.6	45	14
Short interruptions	6.6	6.6	6.6	6.6
Long interruptions	0	0	0	0
Total	96.8	74.2	51.6	20.6

d) Supercapacitors + BG

We assume that this combination can compensate all PQ events, leading to zero PPHs/year. The benefit (Tab. 9) equals the expected PQC without compensation.

Table 9. PQ direct costs avoided in Case 1d [k€].

	Class 2	R-DFI	Class 3	Class ∞
Microinterruptions	90.2	67.6	45	14
Short interruptions	26.3	26.3	26.3	26.3
Long interruptions	25	25	25	25
Total	141.5	118.9	96.3	65.3

e) Flywheel + BG

A few FESSs are used worldwide in support of power systems, most of them in demonstration projects. Some examples are the 20 MWs, 500 kW (40 s autonomy) FESS installed in La Gomera, Canary Islands, Spain, for frequency control in an isolated MV power system [14], and the two similar 5 MWh, 20 MW each (15 min. autonomy) FESSs deployed in USA (at Stephentown, New York and Hazle, Pennsylvania) [5, 12, 15]. The latter consist of 200 individual spinning masses of 100 kW and one-ton each, and are used for frequency control. Equipment is designed for a 20 year life.

For calculation, we assume that the FESS+BG can compensate all interruptions and microinterruptions, reducing to zero the number of PPHs as in Case 1d. Thus, the benefits are those reported in Tab. 9.

f): Conventional VRLA batteries

The conventional VRLA batteries are used in the old BESS (E=1.4 MWh, P=1 MW (E/P=1.4 h)) of Metlakatla, Annette Islands, Alaska, USA, in operation since 1997 for voltage control [12, 16]. This is the only one grid-scale ESS with conventional VRLA batteries reported in the literature. The original cells have been substituted after more than 11 years of operation.

We assume that the BESS response time is short enough to allow compensation of voltage dips. Thus, all the PQ events can be compensated, except interruptions longer than 45 minutes (whose duration on the load, however, is reduced). Assuming that these are 20% of the long interruptions, the residual PPHs/year are 0.2x2=0.4. Finally, in the assumption that these 0.4 partially compensated events remain long interruptions (i.e.: longer than 3 minutes), the PQC avoided are those reported in Tab.10.

One can easily check that the BESS+BG combination does not improve the economic evaluation, because the further benefit that can be achieved through the BG is very low (5 k€) and cannot offset the BG costs.

Table 10. PQ direct costs avoided in Case 1f [k€].

	Class 2	R-DFI	Class 3	Class ∞
Microinterruptions	90.2	67.6	45	14
Short interruptions	26.3	26.3	26.3	26.3
Long interruptions	20	20	20	20
Total	136.5	113.9	91.3	60.3

g): Advanced lead-acid batteries

Several recent grid-scale ESSs use advanced lead-acid batteries. Some examples are the BESSs installed at Oahu, Hawaii, USA (3.75 MWh, 15 MW (E/P=0.25 h), 2011) [8, 12], at Albuquerque, New Mexico, USA (350 kWh, 0.5 MW (E/P=0.7 h), 2011) [15], and at Lyons Station, Pennsylvania, USA (750 kWh, 3 MW (E/P=0.25 h), 2012) [12, 15].

Assuming that the ~11 minute autonomy at 75% DoD allows compensation of 1/3 of long interruptions, i.e. 0.33x2=0.66 events/year, the residual PPHs/year are 1.34 and the PQC avoided are those reported in Tab. 11.

Again, the BESS+BG combination is not convenient, even though the further benefit achievable with the BG is greater (16.7 k€) than in Case 1f.

Table 11. PQ direct costs avoided in Case 1g [k€].

	Class 2	R-DFI	Class 3	Class ∞
Microinterruptions	90.2	67.6	45	14
Short interruptions	26.3	26.3	26.3	26.3
Long interruptions	8.3	8.3	8.3	8.3
Total	124.8	102.2	79.6	48.6

h) Li-ion batteries

Several worldwide installations demonstrate the high interest in the Li-ion technologies and their versatility. Installations cover a relatively wide E/P range. Among those characterized by low E/P, there are:

- the 8 MWh, 32 MW (E/P=0.25 h) BESS installed in 2011 at Elkins, West Virginia, USA [4, 12]. The battery is based on the nanostructured LFP cell technology
- the 4 MWh, 12 MW (E/P=0.33 h) BESS installed in 2009 at Gener's Los Andes, Chile, for frequency control (LFP cell technology) [12]
- the 0.5 MWh, 2 MW (E/P=0.25 h) BESS installed in 2006 at Anderson, Indiana, USA, for frequency control. The battery is based on nanostructured LTO cell technology and the expected lifetime is 15 years
- the 0.5 MWh, 0.7 MW (E/P=0.7 h) BESS installed in 2012 at Isernia, Italy, based on the NCA technology [13].

Since the BESS autonomy is the same as Case 1g, also the residual PPHs/year are the same, and the PQC avoided are equal to those reported in Tab. 11 above.

Once more, the BESS+BG combination is not convenient.

3 CASE 1: RESULTS AND DISCUSSION

Tables 12-13 show that, for a realistic load sensitivity of Class 3 or lower, all ESSs have negative NPV and high PBT. This means that, currently, an ESS for the PQ improvement can be convenient only if the load is very sensitive to voltage dips. This result improves in case of a less-than-average quality power supply (i.e., more PQ events), higher PQ unitary costs, and longer ESS life (a longer life improves NPVs, whereas PBTs remain unchanged).

Table 12. PBT [years] for the Case 1 candidate ESSs and different load sensitivity levels.

Storage technology	Class 2	R-DFI	Class 3	Class ∞
a) capacitors	3.3	4.8	8.3	-
b) capacitors + BG	4.7	6.5	10.5	71.7
c) supercapacitors	7.2	10.1	17.4	>100
d) supercapacitors+BG	6.1	7.6	10.3	19.3
e) FESS + BG	10.9	14.5	21.6	65.4
f) conventional VRLA	4.2	5.4	7.3	14.9
g) advanced lead-acid	5.5	7.1	10.1	23.3
h) Li-ion batteries	6.0	7.8	11.0	25.4

Table 13. NPV [k€] for the Case 1 candidate ESSs and different load sensitivity levels.

Storage technology	Class 2	R-DFI	Class 3	Class ∞
a) capacitors	278	119	-39	-257
b) capacitors + BG	192	34	-125	-343
c) supercapacitors	-11	-169	-328	-546
d) supercapacitors+BG	103	-56	-214	-432
e) FESS + BG	-357	-516	-675	-893
f) conventional VRLA	298	139	-19	-237
g) advanced lead-acid	151	-8	-167	-384
h) Li-ion batteries	101	-58	-217	-434

In consideration of the small number of cycles required in Case 1, as a new evaluation hypothesis we extend the ESS life to 15 years. This is critical only for the conventional VRLA batteries, but looks acceptable for all the other ESSs. The results, limited to capacitors, SCs+BG, advanced lead-acid and Li-ion batteries, are reported in Tab. 14. Even though the NPVs moderately improve, the economic evaluation of the different solutions remains, in essence, unchanged.

Table 14. NPV [k€] for Case 1, computed over 15 years.

Storage technology	Class 2	R-DFI	Class 3	Class ∞
a) capacitors	435	229	23	-259
d) supercapacitors+BG	336	130	-76	-358
g) advanced lead-acid	359	153	-53	-335
h) Li-ion batteries	309	103	-103	-385

As to the individual technologies, the best results are still got through the most traditional and less expensive ones: the VRLA batteries and capacitors. The convenience of capacitors, however, quickly reduces with the load sensitivity to voltage dips; capacitors are almost useless for Class ∞ or lower sensitivity. As to the conventional VRLA, their interesting results sharply worsen if cells substitution is required. Notice that their evaluation further improves reducing the ESS capacity. However, this technology currently is not used for grid-scale applications, nor will be in the future, when advanced and more performing technologies should dominate.

SCs get much worse results, penalized by a high capex. To become competitive, SCs need a sharp capex reduction. However, the economic evaluation considerably improves for the SCs+BG combination.

Also advanced lead-acid and Li-ion BESSs (E=0.25 MWh) have unfavorable results, because of their high capex. The analysis shows that, reducing the E/P ratio, the advantage due to a lower battery cost overtakes the lower annual benefit due to the lower autonomy. If the expected cost reductions will be fulfilled, the advanced lead-acid and Li-ion BESSs with a low E/P can become attractive for the PQ improvement and, more generally, for power applications.

FESS+BG gets the worst results. This solution can become attractive for specific applications requiring an extremely high supply availability. Simpler and cheaper FESS, however, may result more convenient for the application considered.

Finally, it is interesting to compare the previous ESS solutions with a BG alone. The BG allows transforming long into short interruptions. Thus, the avoided costs are those already computed in Case 1b, i.e.: 16.25 k€ for all equipment sensitivity levels. Using the BG capex and opex above reported, NPVs are negative (-86 k€ in the base-case, and -73 k€ over 15 years of operation) and the PBT is very high (about 20 years).

4 CASE 2 ANALYSIS

In Case 2, the annual benefit, equal to the PQC avoided plus the value of ΔE_{PV}, is the same for all BESSs except the NaS batteries.

For computation of the PQC avoided, as in Case 1 we assume that all BESSs have a response time short enough to compensate for voltage dips. But we cannot assume, as in Case 1, that a BESS can compensate all the PQ events shorter than its autonomy, because at the occurrence of a PQ event the battery SoC (which depends on the daytime, season, discharge strategy of the energy stored, and so on) can be insufficient. However, this problem concerns mainly long interruptions because the energy required to compensate the other PQ events is very small. Since the long interruptions last, on average, far less than one hour, we hypothesize that the BESS can compensate, on average, up to 80% of the long interruptions (90% with the NaS batteries). Accordingly, for each candidate BESS, the PQ direct costs avoided are those reported in Tab. 15.

Table 15. PQC avoided [k€]; in parenthesis: NaS batteries.

	Class 2	R-DFI	Class 3	Class ∞
Microinterr.	90.2	67.6	45	14
Short interr.	26.3	26.3	26.3	26.3
Long interr.	20 (22.5)	20 (22.5)	20 (22.5)	20 (22.5)
Total	136.5 (139)	113.9 (116.4)	91.3 (93.8)	60.3 (62.8)

Conversely, for any possible BESS+BG combination, we can assume that all PQ events can be compensated. This leads, however, to a small benefit increase of 5 k€/year (and only 2.5 k€/year with the NaS batteries), lower than the BG opex (10 k€/year). Overall, the annual saving reduces, making these solutions inconvenient. Therefore, in what follows, the BESS+BG combinations are not examined in more detail.

According to (2) and to Tab. 5 costs, the annual saving is the same for the lead-acid, Li-ion and NaNiCl batteries (thus, the economic indices of these solutions differ only because of their capex), whereas it is higher for the NaS batteries and lower for VRBs. The economic indices are reported in Tabs. 16-17 in Section 5.

In the following, for each technology we report the main data of some installations, interesting for the size, application or analogy with the present application.

a) Advanced lead-acid batteries

The advanced lead-acid batteries can guarantee more than a 10 year life for the Case 2 application. Two installations with E/P=4 h, like in the present case, are at South Burlington, Vermont, USA (1 MWh, 250 kW, installed in 2013) [12] and at Albuquerque, New Mexico, USA (1 MWh, 250 kW, installed in 2011) [15].

Several other grid-scale advanced lead-acid BESSs with E/P in the range of 2.67÷5.6 h have been installed in the last years for energy applications worldwide [12].

b) Li-ion batteries

More than 4000 cycles projected at 75% DoD for some Li-ion technologies, make the expected life longer than ten years for the application in study. Two grid-scale installations with E/P=4 h are at Tehachapi, California, USA (32 MWh, 8 MW, demonstration project deployed in 2013) [4, 15] and at Zhangbei, China (16 MWh, 4

MW, in operation since 2011 for the wind- and solar-energy integration, frequency control and voltage support within a large demonstration project) [12].

c) NaS batteries

The NaS batteries projected life is about 4500 cycles at 75% DoD, leading to more than ten years of operation for the Case 2 application. Some NaS grid-scale installations are:
- the 244.8 MWh, 34 MW (E/P=7.2 h) BESS installed in 2008 at Rokkasho, Japan, one of the first large-scale wind-battery integrated projects [17]
- the 7.2 MWh, 1.2 MW (E/P=6 h) ESS installed in 2006 at Charleston, West Virginia, USA [11]
- the two identical 14.4 MWh, 2 MW (E/P=7.2 h) BESSs installed in 2008 in USA, at Milton, West Virginia and Churubusco, Indiana [4, 12]
- the 24 MWh, 4 MW (E/P=6 h) ESS installed at East San Josè, California, USA [12].

d) NaNiCl batteries

Until today, the NaNiCl batteries have had more than a ten year successful experience in electric motion but their application in support of power systems is more recent. The first example is the 235 kWh, 230 kW (E/P=1 h) BESS in operation since 2010 at Almisano, Italy [7, 8]. Other NaNiCl BESS installations are at Mount Holly, North Carolina, USA (280 kWh, 402 kW (E/P=0.7 h), installed in 2011) and at Prince Edward Island, Canada (20 MWh, 10 MW (E/P=2 h), installed in 2013) [12].

The data-sheets of a world leading manufacturer show that the E/P=4h assumed here is acceptable. A 4500 cycle projected life at 75% DoD guarantees more than ten years of operation for the present application.

e) Vanadium redox batteries (VRB)

The VRBs life is very long, around 10,000 cycles expected at 75% DoD [1]. VRB are generally targeted towards grid-scale energy storage. Some installations are:
- the 6 MWh, 4 MW BESS installed at Hokkaido, Japan, in operation in the period 2005-2008 and coupled with a 30.6 MW wind farm [18]
- the 10 MWh, 5 MW world largest VRB installation so far, operating since 2013 coupled with a 50 MW wind farm at Shenyang, Liaoning province, China [19]
- the 8.8 MWh, 1.1 MW BESS installed in 2013 at Painesville, Ohio, USA; the long-term goal is to scale the BESS in stages, up to 80 MWh, 10 MW [12, 15].

5 CASE 2: RESULTS AND DISCUSSION

Since the annual saving is almost equal for all the BESSs analyzed, the differences among the PBTs and the NPVs are mainly due to the different capex and opex. Therefore, the results reported in Tabs. 16-17 are easily explained: the NaS batteries have the lowest capex and, thus, the best economic evaluation. The second ranked are the advanced lead-acid batteries. The not yet economically competitive Li-ion batteries come last. Nevertheless, according to the energy-storage projects worldwide [12], for grid-scale energy applications currently emerges a prevailing orientation towards the Li-ion technologies, followed by the advanced lead-acid and NaS batteries. In 2014, the NaS batteries had the highest installed capacity but the Li-ion were 90% of all proposed grid storage projects, accounting for 419 MW and 1555 MWh [15]. However, the existing installations are often demonstration projects partly funded by public or private institutions, where economics may not dictate the best choice.

Table 16. PBT [years] for the Case 2 candidate BESSs and different load sensitivity levels.

BESS technology	Class 2	R-DFI	Class 3	Class ∞
a) lead-acid batteries	21.4	26.3	34.1	57.4
b) Li-ion batteries	29.6	36.4	47.2	79.5
c) NaS batteries	19.4	23.5	29.8	47.3
d) NaNiCl batteries	23.0	28.3	39.3	61.8
e) VRB	29.0	37.1	51.5	>100

Table 17. NPV [k€] for the Case 2 candidate BESSs and different load sensitivity levels.

BESS technology	Class 2	R-DFI	Class 3	Class ∞
a) lead-acid batteries	-1747	-1905	-2064	-2282
b) Li-ion batteries	-2747	-2905	-3064	-3282
c) NaS batteries	-1594	-1753	-1911	-2129
d) NaNiCl batteries	-1947	-2105	-2264	-2482
e) VRB	-2273	-2432	-2591	-2808

Anyway, despite the favorable evaluation hypotheses here adopted, in all cases PBTs are far higher than the projected BESS lifetime, whereas NPVs are largely negative for all battery types and all sensitivity levels. These results show that the investments required are not yet sustainable for the application considered (this conclusion justifies the approximations made in Case 2 to simplify the analysis). These results are first due to the high capex compared to the annual benefits. The annual benefits increase with the ΔE_{PV} value, the number of the PQ events, the relevant unitary costs, and the BESS lifetime, but the large imbalance between the costs and benefits cannot be offset.

These results are in line with the conclusions of other recent studies. For example, studying the sustainability of ESSs used to optimize renewable resources in power systems, the work [7] concludes: “The gap between the profitability of investments in ESSs and a reasonable threshold value is still large, irrespective of the specific technology used”. In [20], simulation of a 2 MW, 4 MWh BESS used for the primary frequency control provides a benefit of about 20 k€/year in the Italian context, comparable with the ΔE_{PV} value computed here. The conclusion is, again, that adoption of BESSs for grid-scale applications requires a sharp cost reduction of the technologies involved.

6 Conclusion

This study aims at evaluating the current sustainability of ESSs for MW-scale applications in MV distribution systems. Two specific applications are considered: PQ improvement (a typical power application) and full local exploitation of the PV generation (an energy application) in addition to the PQ improvement. In both cases and for each candidate ESS, PBT and NPV are computed using the methodology outlined in Part 1.

For the PQ improvement alone, the analysis shows possible scopes of convenience of some ESSs in very favorable conditions, given by the combination of a high load sensitivity to PQ, high PQC, and low quality of supply. Anyway, currently the best results are achieved through traditional storage technologies like capacitors (for loads sensitive to the transient PQ events) and conventional VRLA batteries. Less favorable results are obtained for the emerging technologies like SCs, advanced lead-acid and Li-ion batteries, and flywheels. All of them need significant cost reductions, but sustainability is not too far away. More generally, similar conclusions can be extended to other power applications.

The second application leads to power/energy specifications typical of BESS but, despite the great interest in them and several demonstration projects and installations worldwide, the results show that they are still far from being sustainable for the application analyzed. More generally, a similar conclusion can be extended to other energy applications, with the only possible exception of the wind-energy integration: due to the higher profit obtainable from time-shift of the wind energy compared to the PV energy, it looks at present the most convenient grid-scale BESS energy application. However, wind farms are usually connected to the grid at the HV level, so that they cannot be directly compared with the MV applications studied here.

Of course, a given ESS can be used also to provide further services to the grid (for example, frequency or voltage control). In general, however, the overall benefit cannot improve very much, because the ESS assigned power and capacity are both limited and any further service penalizes the others.

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