Екологично инженерство и опазване на околната среда, No 1, 2009, с. 40-48

A REVIEW OF SOME TECHNICAL AND ECONOMIC FEATURES OF ENERGY STORAGE TECHNOLOGIES FOR DISTRIBUTION SYSTEM INTEGRATION

Gauthier Delille, Bruno Francois

Abstract: This paper deals with the results of a study aiming to assess the suitability of various energy storage technologies for medium-term (2015) integration into distribution systems. Based on a review of many scientific and industrial materials, and by taking into account a few hypotheses, a shortlist of some properties to consider was first identified and defined. More than twenty storage techniques were then studied and nine of them were found to be particularly suited. An up-to-date overview of their performances is given at the end of the article.

Keywords: energy storage technologies, distribution grids, distributed energy resources, smartgrids

INTRODUCTION

In the future, distribution grids and power systems will carry on facing many challenges. On the one hand, increasing peak loads and the appearance of plug-in electric or hybrid vehicles will result in the need for grid reinforcements, which will probably come up against a growing public opposition. On the other hand, the continued development of renewable generation will bring variability that will have to be addressed when significant penetration levels are reached.

Besides, oil prices have fetched unprecedented levels lately and the International Energy Agency anticipates continued market tightness to 2013 [1]. Raw materials are now quite expensive too, as well as new grid equipment.

Such a context calls standard practices into question and might bring new market opportunities for technical options that were previously unable to compete with conventional solutions for utility distribution systems. That is a reason why Distributed Energy Storage Systems (DESS) have received considerable attention over the past few years. New products have recently found their way to the market and some stationary applications have been successfully demonstrated (e.g. peak shaving for capital deferral), while others are still under investigation (as output fluctuation mitigation of wind farms).

This paper deals with Energy Storage Technologies (EST) and their medium-term (around 2015) integration into distribution grids. With this aim in view, it handles the characterization of EST and provides an up-to-date overview of the properties of selected storage techniques.

PRELIMINARY CONSIDERATIONS

The present review of EST is an intermediate step to an ongoing analysis of the potential of DESS to contribute to the advanced management of distribution grids, allowing for example a better integration of renewable energy sources, asset utilization improvements or power quality and reliability enhancements. In France, distribution systems are radial and consist of medium-voltage (MV, mainly 20kV) and low-voltage (LV, exclusively 400V) underground and overhead lines. They are operated either by ERDF, the national distribution network subsidiary of EDF or by non state-owned, local electric distribution utilities.

METHODOLOGY

An extensive literature review on EST was first conducted, including both very broad studies (such as [2]-[10]) and technology-specific resources ([11]-[20]). Specification sheets of various existing energy storage products were also collected and, whenever necessary, manufacturers were contacted for further information.

It soon appeared that there are multiple ways of characterizing EST: depending on the application requirements, some pieces of information can be more or less critical, leading to potentially different approaches of the problem. For example, among the technical features of EST, peak power density (W/kg) and specific energy (Wh/kg) are often considered to be key parameters for vehicle applications whereas they appear to be relatively secondary for stationary systems. That is why an analysis of the characteristics to prioritize from a system-level perspective was conducted in order to maximize the pertinence of the review. The main result of this preliminary study was a characterization table adapted to the specific needs of this project.

The data gathered from the literature and manufacturers was then crosschecked to complete the characterization table of some fifteen EST. This comprehensive analysis was used to draw conclusions about the potential of each considered technology for medium-term distribution grid integration.

WHAT IS A DESS?

Based on the definition of distributed generation provided by [21], DESS might be seen as energy storage within distribution grids or on the customer side of the network. Fig.1 shows the generic structure of an ESS.

The first remarkable part is, of course, the Energy Storage Device (ESD) itself, i.e. the component in which the energy is stored to be released later, after deduction of some losses. Electricity is a physical phenomenon realizing an instantaneous energy transfer and therefore cannot be stored as it is. Another form of energy is thus used as intermediary storage medium, such as chemical potential energy for batteries, gravitational potential energy for pumped hydro or kinetic energy for flywheels.

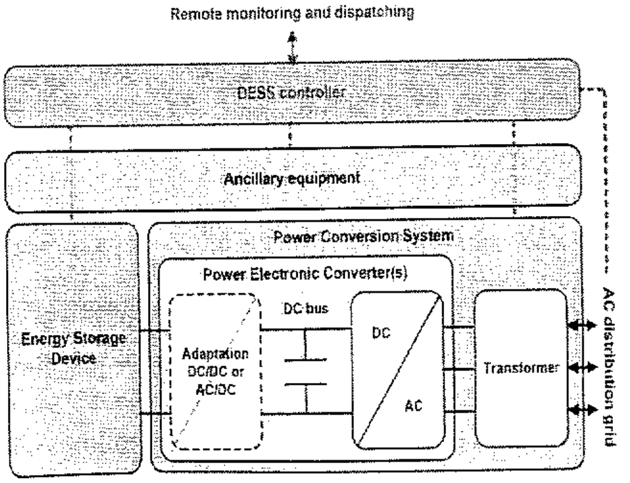

Fig.1. Typical layout of (battery) energy storage systems

With the exception of CAES and pumped hydro, all the EST addressed herein have DC power output or variable-frequency AC output (flywheels). A Power Conversion System (PCS) is thus used to interface the ESD to the 50-Hz or 60-Hz AC voltage of the grid. It usually includes a power electronic bidirectional inverter, monitoring/control systems, protective devices, a step-up transformer and harmonic filters [2][12]. Additional converter(s) are sometimes required to match the output voltage level and/or waveform of the ESD to the DC bus, or to control power flows in parallel multi-string or multi-storage configurations.

Finally, some ancillary equipment is often needed to perform functions such as ESD and PCS cooling/heating or environmental control (e.g. ventilation).

SOME PARAMETERS FOR EST CHARACTERIZATION

Storage capacity and power range

The energy storage capacity is the amount of charge or energy that can be delivered by an ESD during a single discharge. For electrochemical devices, it depends on various factors, such as the final limiting voltage, the condition of the battery, its age, the temperature and the discharge rate. The influence of the latter is particularly substantial and appears clearly on a Ragone chart, which plots specific energy versus specific power. It is a widespread tool that can be helpful for sizing purposes, but which is also extensively used to compare the performances of EST (an example is given in [9]).

Fig.2 shows the Ragone chart of a commercial nickel-cadmium battery. The rated capacity is the energy recovered during a 5-hour discharge (C_5). At higher rate, increasing losses and the diffusion processes of reactants reduce the actual amount of energy retrieved during a single discharge or vice versa at lower rate. Therefore, it is customary to distinguish the rated capacity W_{rd} and the retrievable capacity under specific conditions W_{ut} [8].

The charge/discharge power an ESS can exchange with the grid depends on the power rating of its electromecanical or power electronic converter (P_{max}). This one can be sized allowing for pulse discharges, provided their impacts on the lifetime, energy efficiency and retrievable capacity of the ESD are suitably taken into account. From the point of view of the grid operator, two properties seem quite useful to assess the adequacy of EST for distribution system applications:

- The medium-term feasible system power range. The lower bound is linked to the smallest single ESD (module) of the considered technology whereas the maximum can derive from various factors such as technical limits, complexity or costs.
- The discharge duration at rated power (T_c).

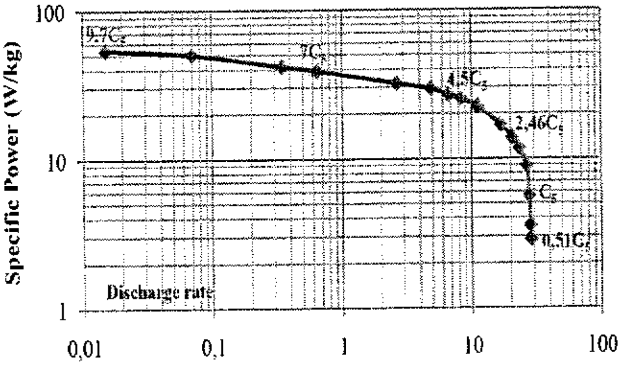

Fig.2. Ragone chart of a commercial nickel-cadmium battery

Lifetime

At some point, ESD cease working or their performances have decreased an extent that they cannot fulfil their object, or be economically justified anymore. For example, an electrochemical device is usually considered failing when its capacity reaches a given fraction (typically 60% or 80% [2][7]) of its initial value. At least two ways to assess the expected lifetime of EST are commonly defined [2][5][8]:

- The first is the so-called intrinsic or calendar lifetime. It is the statistical maximum service life (D_T, in years) of a given EST independently of its use, no matter whether it is appealed to or not.
- The second integrates the progressive defacement of the device due to its utilization. This expected cycle life (N_{max}, in cycles) is usually quoted under certain hypotheses: Depth of Discharge (DoD), mean State of Charge (SoC), charge/discharge rates, etc. Knowing the duty cycles and the frequency of use of an ESS allows deducing from N_{max} the order of magnitude of its cycle life in years.

The actual service life can therefore be much lower than D_T as the working conditions of an ESS harden.

Energy efficiency

The energy efficiency of EST can be defined different ways, depending on the storage technique, the subsystems of the DESS taken into account to make the computation and the time horizon. For example, various instantaneous, round-trip or long-term efficiencies are more or less frequently encountered.

The literature of ESS usually quotes round-trip efficiencies based on one or more realistic cycles for a given application. Since the energy efficiency depends strongly on the duty cycle, these figures should be regarded as indications. Within the context of the present study, it was chosen to focus on:

- The DC round-trip efficiency of the EST ($з_{DC}$). This is the ratio between the released energy and the stored energy, quoted for the ESD alone or including a possible adaptation converter (e.g. a rectifier for flywheels). The AC round-trip efficiency ($з_{AC}$) is obtained by multiplying $з_{DC}$ by a factor between 0.8 and 0.9 to allow for PCS losses.
- The self-discharge rate of the device, expressed in percent of the stored energy lost per day or month. It is a key parameter to assess the potential of EST for applications requiring long-term charge retention. It is noteworthy that the self-discharge usually depends very much on the temperature. The energy consumption of ancillary equipment, when significant, is sometimes considered as additional self-discharge by the literature of EST.

Specific energy and footprint

The dimensions of EST are much less critical for stationary than for vehicle applications. Within the framework of the present project, the output specific energy (E_M in Wh/kg) and output energy density (E_V in Wh/m^3) or footprint (E_S in m^2/MWh) were recorded. They may notably be useful for niche applications with space constraints, like underground power substations.

Costs

Following the example of energy efficiency, the cost of ESD must be considered vigilantly. The profitability of a DESS and comparisons should be based on a life cycle cost analysis including the initial, O&M and disposal cost of ESD, PCS and ancillary equipment, as well as balance of plant (engineering, construction management, land, etc.) [2][8]. Some data about PCS economics and the O&M costs of ESS is provided by [2] but these cost scales were very difficult to crosscheck with other sources, as they are seldom mentioned.

Initial capital cost of ESD, on which we focus herein, can be integrally expressed per kW (C_P) or per kWh (C_E), depending on the sizing factor: power or energy. For some EST, these two dimensions are relatively independent and can therefore be included separately using partial costs per kW (C_{PP}) and per kWh (C_{PE}). In that case, the capital cost of the considered ESD can be computed using the equation (1) [8].

$$(1) \qquad Capital\ Cost = C_{PP} P_{\max} + C_{PE} W_{ut} .$$

Some other useful characteristics

To assess EST adequacy for various applications, the system response time is also a critical piece of information.

Finally, three qualitative criterions have been taken into consideration: the industrial maturity of EST (technical/commercial), the environmental impact and public acceptability (including various factors such as toxicity of materials, safety, recyclability, etc.) and the operating constraints (maximal DoD, charge/ discharge powers, operational conditions, etc.). For comparison purposes, a grading system ranging from 1 (worst case) to 5 (best case) was used for these parameters.

SCOPE AND RESULTS OF THE STUDY

Various storage techniques have been used so far for stationary applications and many others are still at a pre-commercial stage or undergoing research with an eye for the future. Among them, about twenty EST were considered within the framework of the present analysis. History and operational principles are not tackled herein, but are described in detail by [2], [3] and [8]. Table 1 shows the EST that were investigated.

Table 1. A list of the reviewed EST

General Classification		Technology	Notation
Chemical	"Standard"	Lead-acid	PbA
		Nickel-cadmium	NiCd
		Nickel-metal hydride	NiMH
		Nickel-zinc	NiZn
		Lithium(-ion)	Li
		Metal-air	Metal-air
	High-temperature	Sodium-sulphur	NAS
		Sodium-nickel-chloride	ZEBRA
	Redox-flow	Polysulfide bromide (Regenesys)	PSB
		Vanadium-vanadium	VRB
		Zinc-bromine	ZnBr
		Cerium-zinc	CeZn
	-	Hydrogen/fuel cell	H_2/PAC
Mechanical		Pumped hydro	PH
		Compressed-air energy storage	CAES
		Small-Scale (Subsurface) CAES	SS-CAES
		Advanced-adiabatic CAES	AA-CAES
		Hydro-pneumatic	HyP
		Flywheel energy storage	FES
Magnetic		Superconducting magnetic ES	SMES
Electrostatic		Ultracapacitors	UC
Thermal		Thermal energy storage	TES

Confronting EST to some requirements

In the light of the literature review, it became obvious that some EST does not meet all the minimum requirements for a short to medium-term integration into distribution grids.

The most discriminating criterion was indisputably maturity. Indeed, the hypothesis of an industrial deployment in 2015 requires that a stabilized product range already exists for stationary applications and is currently being tested in the field, or very close to be. CeZn, SS-CAES, AA-CAES, HyP and TES (all at the R&D stage) were thus ruled out, as well as NiZn (developed so far for cordless products and vehicle applications) and H_2/PAC (still evolving, in conjunction with technical and economic competitiveness issues).

Two more EST should be turned down because of technical considerations, even if commercial products have been available for years. On the one hand, in spite of their impressive features (high specific energy of 150 to more than 300Wh/kg, environmental friendliness and moderated costs), metal-air batteries have a very difficult and inefficient electrical recharging (3_{DC}=40-50%). On the other hand, SMES systems need cryogenic cooling that requires energy-intensive equipment and specific O&M know-how [2], thus limiting their competitiveness and commercial expansion.

Then, since a licence on its intellectual property was sold by RWE in 2004, the development activities of the PSB redox-flow technology have come to a standstill and the two large-scale (12MW/10h) demonstration plants under construction at the time were never completed, with subsequent financial consequences (e.g. $20m net project loss for Tennessee Valley Authority [22]). Even if a new effort was made to drive it to the market, it would probably take years to regain investors' confidence.

Although NiCd technology has been successfully demonstrated in the 27MW/15min ESS in Fairbanks, Alaska, NiCd is uncertain because of the current regulatory banishment of cadmium within the European Union, which is now effective for portable batteries [23].

Finally, PH and CAES, in addition to be site-specific, are to be left-out because their power range (usually more than 100MW per unit) does not fit at the distribution level. For example, in France, current regulations set the maximum rated power of generating units at 250kVA and 17MW for connection at LV and MV respectively [24].

What technologies for near-future DESS?

In the end, nine technologies became distinguishable by their apparent better adequacy and relative readiness for integration into distribution grids. They are briefly introduced in the following paragraphs and an overview of their characteristics is provided in Table 2, as well as those of PH and CAES for information.

PbA is widespread, indisputably mature and has a quite long history of use for grid-connected stationary applications from the middle 1980s, as shown in [3]. Its main advantages are its low cost, pretty good efficiency and very high availability in various application-specific products [2]. However, it has quite low specific energy, moderate lifetime, includes toxic materials and is temperature-sensitive and globally outperformed by newer techniques [2][5]. It can be considered as a very good reference for comparison purposes.

NiMH batteries made their way to the market in the early 90s and were developed very quickly for electronic devices such as mobile phones and laptops. Their specific energy is about twice as high as PbA, with a competitive lifetime, low maintenance and lower temperature sensitivity, but quite high self-discharge (about 20% a month) [5][11]. Vehicle applications are now offering them good perspectives, with expected price reductions.

Li batteries started challenging NiMH for portable applications in the 1990s and are now emerging on the vehicle market segment. They are known for their high power and energy densities as well as for their good efficiency and lifetime, but are still expensive and subject to safety concerns for large-scale systems [5][10].

NAS batteries were first demonstrated for stationary applications in the 1990s and found their way to the market in 2002 (50kW/7.2h modules). Thanks to their high efficiency, above-average energy density and good lifetime, they have been strongly developed for MW-scale, grid-connected applications, such as peak shaving (see [12]), power quality and fluctuation mitigation in wind farms. Their main drawback is the need for thermal management to keep the internal temperature of the module at about 300°C during non-use time, thus reducing the overall efficiency of NAS systems (~20% of W_{rd} is thus lost each day during standstill) [2][7].

ZEBRA batteries are also high-temperature devices presenting more or less the same features as NAS, excepted their lifetime, which appears to be lower (1000-1500 cycles at 80% DoD as against 5000). They were originally designed for vehicle applications and their potential for stationary ESS was demonstrated later through a few experiments. Their industrial development is still relatively limited at the moment [7][13].

VRB is a redox-flow technology that has been commercialised over the past few years for stationary systems ranging from a few kW to bespoke installations of several MW. Its main advantages are its modularity, the independence of power and discharge time, environmentally friendliness of the materials and good lifetime. Nevertheless, VRB devices need energy-consuming ancillary equipment for electrolyte circulation and have quite low specific energy. Demonstrations for a few grid-connected applications are in progress [2][7].

ZnBr, redox-flow batteries as well, have quite similar advantages/drawbacks as VRB apart from a lower lifetime and a fixed discharge time at maximal power of about 2h-2h30 for intrinsic, technical reasons. Moreover, a zinc deposit on the anode of the battery should be removed all the 5-10 cycles, requiring a complete discharge (stripping) [2]. Modules (50kWh) and complete units are commercially available at present and a list of recent demonstration projects is provided by [3].

FES products are currently available under various constructions, ranging from conventional steel rotors to advanced composite structures, which are still being developed. The large majority of flywheels are designed for power applications, presenting a very high cycle-life and outstanding efficiency. Their self-discharge is however quite high, usually leading to the loss of full capacity in no more than a few hours [2]. FES is currently being demonstrated for frequency regulation.

UC is another technology for high power applications available since the early 2000s and showing very good cycle life and efficiency, at the cost of low energy density and environmental concerns for some products comprising acetonitrile. Current applications of UC include notably electric vehicles and regenerative braking for urban transportation.

DISCUSSION

The characterisation of various EST using such a common set of properties raised some difficulties in terms of compatibility and comparability of the data. A significant dispersal in the collected information was noticed. It can be explained, on the one hand, by the fact that many application-specific constructions are usually available for a same EST (for example high-power and high-energy batteries) and, on the other hand, because DESS are highly non-linear devices: the performances of a given ESD vary in accordance with its duty cycle.

Moreover, the definitions of the characteristics quoted by the literature of EST usually may change from one source to another, making crosschecking quite arduous.

That is why the proposed figures should be considered as guidelines. An analysis throughout a complete life cycle is indispensable for comparing DESS to other solutions within a decision making process, both on the economical and environmental levels. Such a characterisation could also be prepared for a given application as an intermediate step: by selecting only dedicated products for some EST, the dispersal would presumably be much lower.

Besides, the suggested set of properties could be generously completed with additional factors such as transportability, cell voltage, maintenance frequency, etc.

CONCLUSION

This article deals with the suitability of EST for medium-term (2015) integration into distribution systems. More than twenty EST were characterised within the framework of the present review and nine of them rose through the ranks: seven "standard", high-temperature or redox-flow batteries (PbA, NiMH, Li, NAS, ZEBRA, VRB, ZnBr), plus FES and UC.

Planned further work includes the study of the current opportunities of multi-service DESS in liberalized power systems and the modelling of the more promising types.

Table 2. Some characteristics of EST for DESS, compared with two mature bulk-storage techniques ([2]-[20])

Technology	Medium-term, feasible system power range	Typical discharge duration at rated power	Shortest feasible response time	DC round-trip efficiency (%)	Self-discharge rate (% per unit of time)	Specific energy (Wh/kg)	Energy density (Wh/liter) and/or *footprint (m^2/MWh)*	Maximum service (calendar) lifetime (years)	Expected cycle-life at 80% DoD (number of cycles)	Cost per kW of the ESD alone (€/kW)	Cost per kWh of the ESD alone (€/kWh)	Medium-term maturity for stationary applications (/5)	Operating constraints (/5)	Environmental impact and acceptability (/5)
PbA	f.kW-f.10MW	2-8h	f.1ms	70-85	1-5% month	25-35	60-130	3-12	200-1500	Not relevant	25-250	5	2	3
NiMH	f.kW-f.MW	f.10min-f.hours	f.1ms	65-75	15-25% month	50-100	80-300	10-15	1500-2000	Not relevant	400-2000*	3	4	4
Li	f.kW-1MW	f.hours	f.1ms	85-90	2-10% month	60-180	150-400	10-15	f.1000	Not relevant	300-1500*	2	4	3
NAS	50kW - f.10MW	7-9h	f.1ms^a	85-90	Low^b 14-24%	100-120	120-150	15	~5000	1000-2500	115-350	4	4	3-4
ZEBRA	5kW-500kW	2-10h	f.1ms^a	85-90	Low^b 7-17%	95-120	130-190	11	1000-1500	200-400*	500	2	3	3-4
VRB	f.kW-10MW^3	f.hours^c	f.1ms^a	80-85	Low^b f.%	12-15^d	11-17^d *20-120*	10-15	~10000	C_{PP}= ~3500 *	C_{PE}= ~400*	3	4	3-4
ZnBr	25kW-f.MW	2h30	f.1ms^a	75-80	1% hour	30-40	10-15 *~30*	~10	1000 - 2000 *	700	300	3	3	3-4
FES	f.kW-f.10MW	10s-f.hours^e	f.1ms	85-95	20-10^3% hour	1-10	5-20	20	10000-10^7	150-3000	Not available	3	3-4	3-4
UC	f.kW-f.MW	1s-f.10s	f.1ms	85-98	f.%-50% day	2-15	3-10	~10	10000-1000000	100-500	5.10^4 - 1,5.10^5	3	3-4	3
PH	100MW-f.GW	20-40h	Minutes	65-80 AC/AC	Very low	2 (water, 1000m)	2 (water, 1000m)	40-60	50000-200000*	C_{PP}=500-1500	C_{PE}= 5-30	5	1	1-2
CAES	100MW-f.GW	4-30h	Minutes	40-55 AC/AC	Very low	Not available	1-18 (air only)	30-40	10000-25000*	C_{PP}=450-550	C_{PE}= 5-30	4-5	1	1-2

f.-a few, ^{a}-under conditions: for example, NAS and ZEBRA must be kept at operating temperature, ^{b}-the energy consumption of ancillary equipment (given in percent of the nominal capacity per day) must be taken into account during non-use time, ^{c}-Discharge time and power are independent in VRB systems, ^{d}-electrolyte only, ^{e}-just a very few products have T_C>f.minutes, *-insufficient data for crosschecking, confirmation required.

Acknowledgements: *This work was funded by EDF and ADEME (French Agency for the Environment and Energy Management).*

The authors kindly acknowledge Stephane BISCAGLIA (ADEME), Eric PEIRANO (ADEME), Gilles MALARANGE (EDF R&D) and Mehana CHAMI (EDF R&D) for their involvement in the management of the present PhD research project. Besides, a considerable technical support was received from Regine CLAVREUL, Alain COMTE, Lionel JAMY and Stephane LASCAUD from EDF R&D.

REFERENCES

[1] IEA press release (08)14, Despite Slowing Oil Demand, IEA Sees Continued Market Tightness Over the Medium Term, 2008, available: http://www.iea.org.

[2] EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, Palo Alto, CA, and the US Department of Energy, Washington, DC: 2003. 1001834.

[3] EA Technology for the British Department of Trade and Industry, Review of Electrical Energy Storage Technologies and Systems and their Potential for the UK, contract n°DG/DTI/00050/00/00, URN n°04/1876, 2004, available: http://www.berr.gov.uk/files/file15185.pdf.

[4] British Department of Trade and Industry, Regenesys Utility Scale Energy Storage – Overview report of combined energy storage and renewable generation, contract n°K/EL/00246/00/00, URN n°04/1047, 2004, available: http://www.berr.gov.uk/files/file15180.pdf.

[5] INVESTIRE Network, Final Publishable Technical Report (and nine other reports on various energy storage technologies), contract n°ENK5-CT-200-20336, 5th Framework Programme, 2004, available: http://ired.iset.uni-kassel.de/investire/index.html.

[6] The Australian Greenhouse Office, Department of the Environment and Heritage, advanced electricity storage technology programme – Energy Storage Technologies: a review paper, ISBN 1 921120 37 1, 2005.

[7] KONSTANTINOS E., DESPOINA D., 1.5a – Report on Use of Energy Storage Units, DISPOWER, in D1.5 deliverable, del_2005_0058, 2005.

[8] IBRAHIM H. et al., Energy storage systems – Characteristics and comparisons, Renewable and Sustainable Energy Reviews, doi:10.1016/j.rser.2007.01.023, 2007.

[9] VAN DEN BOSSCHE P., VERGELS F., VAN MIERLO J., MATHEYS J., VAN AUTENBOER W., SUBAT: An assessment of sustainable battery technology, Journal of Power Sources, Volume 162, Issue 2, 2006, pages 913-919.

[10] MARIYAPPAN J., BLACK M., STRBAC G., HEMMI K., Cost and Technical Opportunities for Electricity Storage Technologies, GreenNet, Work Package 3, 2004.

[11] KOPERA J., Considerations for the utilization of NiMH battery technology in stationary applications, The Battcon 2005 Proceedings, Florida, 2005, available: http://www.battcon.com.

[12] NOURAI A., Installation of the First Distributed Energy Storage System (DESS) at American Electric Power (AEP) – A Study for the DOE Energy Storage Program, Sandia National Laboratories, SAND2007-3580, 2007, available: http://www.osti.gov/bridge/.

[13] DUSTMANN C., Advances in ZEBRA batteries, Journal of Power Sources 127, pp. 85-92, 2004.

[14] British Department of Trade and Industry, Regenesys Utility Scale Energy Storage – Project summary, contract n°K/EL/00246/00/00, URN n°04/1048, 2004, available: http://www.berr.gov.uk/files/file16056.pdf.

[15] JONSHAGEN B., The zinc bromine battery for Renewable Energy Storage, presentation, Proceedings of the first International Renewable Energy Storage Conference (IRES-I), Gelsenkirchen (Germany), October 30-31 2006.

[16] JOSSEN A., UWE SAUER D., Advances in Redox-Flow batteries, presentation, Proceedings of the first International Renewable Energy Storage Conference (IRES-I), Gelsenkirchen (Germany), October 30-31 2006.

[17] ENSMP/CENERG, 1.5b – Fuel cell/Electrolyser combinations for long-term storage, NNES-2001-00075, DISPOWER, in D1.5 deliverable, del_2005_0058, 2005.

[18] LEMOFOUET S., Investigation and optimization of hybrid electricity storage systems based on compressed air and supercapacitors, thesis EPFL n°3628, defended on 10/20/2006, available: http://library.epfl.ch/theses/?nr=3628.

[19] RIZOUG N., Modйlisation йlectrique et йnergйtique des supercondensateurs et mйthodes de caractйrisation : Application au cyclage d'un module de supercondensateurs basse tension en grande puissance, thesis Ecole Centrale de Lille n°20, defended in Lille on 02/28/2006, available: http://hal.archives-ouvertes.fr/docs/00/06/65/36/PDF/These_Nassim_RIZOUG_L2EP_LILLE.pdf.

[20] SARRE G., Advanced PV Energy Storage System with Lithium-Ion Batteries, Proceedings of the first International Renewable Energy Storage Conference (IRES-I), Gelsenkirchen (Germany), October 30-31 2006.

[21] ACKERMANN T., ANDERSSON G., SODER L., Distributed generation: a definition, Electric Power Systems Research n°57, 2001, pp. 195-204.

[22] Tennessee Valley Authority, 2004 Information Statement, available: http://www.tva.gov/finance/reports/pdf/tva2004info s tatement.pdf.

[23] Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006, on batteries and accumulators and [...] repealing Directive 91/157/EEC, available: http://eur-lex.europa.eu.

[24] Departmental order NOR: DEVE0808815A of 23 April 2008 issued by the French Ministry of energy, technical requirements for distribution grid connection of generation units. Available: http://www.legifrance.gouv.fr.

Gauthier Delille, PhD student

Laboratory of Electrical Engineering (L2EP)
Ecole Centrale de Lille, Cité Scientifique, BP 48, 59651 Villeneuve d'Ascq Cedex, France
E-mail: gauthier.delille@centraliens-lille.org

Assoc. Prof. Bruno Fransois, PhD

Laboratory of Electrical Engineering (L2EP)
Department of Electrical Engineering of Ecole Centrale de Lille, Cité Scientifique, BP 48, 59651 Villeneuve d'Ascq Cedex, France
E-mail: bruno.francois@ec-lille.fr).

ОБЗОР НА НЯКОИ ТЕХИЧЕСКИ И ИКОНОМИЧЕСКИ ХАРАКТЕРИСТИКИ НА ТЕХНОЛОГИИ ЗА АКУМУЛИРАНЕ НА ЕНЕРГИЯ ПРЕДНАЗНАЧЕНИ ЗА ВГРАЖДАНЕ В РАЗПРЕДЕЛИТЕЛНИ СИСТЕМИ

Готие Делил, Бруно Франсоа

Резюме. Статията представя резултатите от изследване целящо оценката на годността за интеграция в разпределителните системи в средносрочен план (2015) на различни акумулиращи технологии. Изследването е базирано върху проучването на много научни и индустриални документи с отчитането на няколко хипотези. По този начин е определен и съставен списък от някои свойства и параметри. Проучени са повече от двадесет технологии, като девет от тях са определени като особено подходящи. Осъвременен преглед на техните характеристики е показан накрая на работата.