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Lead–acid batteries in stationary applications: competitors and new markets for large penetration of renewable energies

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Abstract

With increasing deregulation of the European electricity market, the quality of supply is becoming an issue of growing importance. Grid-connected electricity storage systems (ESSs) can enhance the quality of supply by: (i) shortening black-out periods; (ii) shifting excess energy for use during periods of high demand; (iii) sustaining the grid for better power quality. These problems are being addressed by using technologies such as power electronics and ICT. But storage systems offer a cheap and efficient solution to such concerns. ESSs can also power high-value, ancillary services. This paper analyses the new potential markets for storage systems in the context of distributed energy resources with a high penetration of renewable energies in the electricity networks. While lead–acid batteries are the most used technology in all types of stationary applications, many different storage technologies are claimed to fulfil the technical requirements of the above applications, in particular the emerging ones. Therefore, a comparison is made of lead–acid technology and its competitors in terms of technical and economic considerations.

Keywords: Lead–acid battery; Distributed energy resources; Storage technologies; Stationary applications; Power quality; Renewable

1. Introduction

Deregulation of the European electricity market is highly favourable for an increased penetration of renewable energy sources (RESs). Wind energy and photovoltaic energy are, however, intermittent and unpredictable, but consumers require an electricity supply that is both highly reliable and of good quality. Therefore, in order to secure a grid with a high penetration of RESs and other distributed energy resources (DERs), 'quality of supply issues' need to be addressed such as:

(i) power quality concerns (flickers, voltage sags, harmonic distortion, reactive power consumption, etc.),
(ii) grid balance concerns (matching of energy consumption with total generated capacity), and
(iii) concerns relating to compliance with grid requirements (power flows limited by the thermal capacity of the lines, avoidance of over-voltage on the distribution line, etc.).

In many European countries, grid operators address these problems by setting stringent interconnection rules. These rules are designed to limit the penetration of RESs below a level that ensures that the above mentioned reliability concerns will not occur, and thus inhibit the development of RESs.

Most recent RES devices incorporate the latest advances in cutting-edge technologies such as power electronics and ICT to limit their grid impact. Indeed, modern wind turbines have rather small harmonic emissions, are controllable, and can even support the grid by providing reactive power when needed. Demonstrating the feasibility of grids with large penetration of RESs will, in turn, convince grid operators to allow larger access to small and distributed power producers.

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Energy storage systems (ESSs) have the potential to play a key role. Although they have been little studied for this application in Europe, ESSs appear to be complementary to ICT and power-electronic based solutions, since they can provide large capacity with a short response time and provide ancillary services such as uninterruptible power supply (UPS). It is therefore pertinent to consider more precisely the role of energy storage systems and evaluate their market potential. Since many different storage technologies are claimed to fulfil the technical requirements of the above applications, it is necessary to compare their performances and costs so as to identify the best candidates. The results presented here are taken mostly from work conducted by the INVESTIRE. Thematic Network [1,2].

2. RES integration in the grid and implemented solutions

Integrating renewable energy into electric networks causes some familiar power-quality problems, as well as some problems related to reliability of supply that are less common. These issues can be categorized as either interface (engineer) or operational/planning issues.

2.1. Interface issues

Interface issues are related to all the events that affect the power quality of the energy supplied to the end-users (harmonics, reactive power supply, voltage regulation, frequency control). Compared with conventional electricity-generating units, RES power plants have a larger impact on the quality of supply because their output power depends on external conditions such as wind speed or solar irradiation. Examples of the resulting phenomena that affect the grid are:

(i) transients of wind turbines (high consumption of reactive power for direct-connected turbines),
(ii) flickers emission due to the shadow effect of wind turbines (direct-connected turbines), and
(iii) harmonic injection of photovoltaic (PV) inverters using self-commutated converters, etc.

Interface problems are issues of growing concern for utilities because RES penetration tends to increase while the computer-based economy requires reliable electricity.

2.2. Operational/planning issues

Operational/planning issues essentially deal with the intermittent power output inherent to RES generation. This intermittence raises concerns over balancing of the grid. To ensure a constant grid balance, i.e., an energy production equal to the energy consumption, the grid operator has to address: operating reserve requirements, economic dispatch, consumption modelling, and RES output power prediction. When integrating RES into a utility system, reserve margins must account for the maximum probable decrease in wind or PV plant output over a given period. Whereas RES power quality issues are relatively well known, operational/planning issues remain the main barriers to the widespread penetration of renewables in present electricity markets.

2.3. Implemented solutions

So far, grid integration issues have mainly been addressed by improving RES technologies, by integrating latest advances in power electronics, and by developing new grid concepts. Experience has shown, however, that these solutions do not address all the grid-integration problems and that energy storage systems could provide a cheap and efficient response to the remaining technical issues.

2.3.1. Development of grid-friendly RES technologies

Wind turbines were once considered to be a major grid polluter. Indeed, the first Danish wind turbines consumed a considerable amount of reactive power during transients and injected a large level of harmonics in the grid. This was a source of concern when turbines were connected to weak grids. The latest wind turbine models are equipped with more sophisticated power electronics and/or more advanced generators (e.g., the doubly-fed induction generator, DFIG) than their predecessors. These newer systems have largely eliminated past problems associated with harmonics and reactive power.

Photovoltaic inverters now use leading-edge power electronics technologies that greatly improve the quality of current injected into the grid. The same trend exists for all RES technologies and improvement in performance, reliability, and controllability tends to limit the impact on the grid. Most recent wind turbines (advanced DFIG wind turbine) can even support the grid by consuming or producing reactive power when needed.

The extent to which grid integration of RES is a cause for concern today appears to be largely a function of the grid strength at the point of integration.

2.3.2. Development of innovative grid concept including ICT and power electronics

Recent advances in ICT technologies and microelectronics have enabled the development of a new concept of grid structure that can manage the fluctuating output power of RES power systems. This innovative structure is generally called a micro-grid or a mini-grid.

The micro-grid structure assumes an aggregation of loads and small generating sources (including RES) to be a single system that provides both heat and power. The majority of the generating systems are power electronics based to provide the required flexibility to insure controlled operation as a single aggregated system. Such systems are generally connected to the conventional grid through a single interconnection point. But, given that the energy drawn from the main grid can be very expensive, the micro-grid is designed to be operated in a way that minimizes energy exchanges with the mains. Therefore, when RES systems bring about imbalance in a small grid, the control system will require the operation of a load or a generating set to dispatch the surplus or shortage power.

Many studies have demonstrated that this new grid design operates well. Nevertheless, the main drawback of such a structure is the response time of the elements of the micro-grid. Indeed, in case of a large grid imbalance in shortage, the control unit will order the operation of a small driveable generating unit (micro-turbine or diesel-generating set), which has a longer response time than needed.

2.4. New opportunities for energy storage systems related to the development of RES

The increased share of RES in the energy mix and the integration of DER in electricity networks lead to problems with the 'quality of supply' of the interface and with the operational characteristics. The above-mentioned solutions are efficient but do not fully solve the integration concerns. Indeed, if the integration of power electronics in RES technology limits its grid impact, the use of energy storage systems for power quality and other grid-supporting applications can improve even more the quality of the energy supply and thus increase the possible penetration of renewable energy resources. In addition, up-to-date experiences with micro-grids show that storage systems are a crucial element of the systems. Indeed such micro-grids fast-response and a large source of energy. This role can only be played by storage systems that also provide numerous ancillary services.

3. New markets for stationary energy storage systems

3.1. Identification of applications

Considerable work has been undertaken in the USA to identify and evaluate the value of these new electricity markets [3–6]. In 1998, for example, SANDIA estimated the yearly national cost of poor power quality to customer to be in the range of US$150 billion [3].

The location of the ESS can be at different level in the networks, namely: at the production level (utility or private renewable energy power plant owner), at the transmission level, or at the end-user level. A comprehensive summary of the electric power applications of energy storage has been reported [4]. The applications are categorized in terms of integration level of the ESS, as presented in Table 1.

Table 1
Definitions and categories of electric power applications of energy storage [4]

Category	Application name and definition
Generation	*Rapid reserve* Generation capacity that a utility holds in reserve to meet North American Electric Reliability Council (NERC) Policy 10 requirements to prevent interruption of service to customers in the event of a failure of an operating generating station.[a] *Area control and frequency responsive reserve* The ability for grid-connected utilities to prevent unplanned transfer of power between themselves and neighbouring utilities (area control) and the ability of isolated utilities to instantaneously respond to frequency deviations (frequency responsive reserve). Both applications stem from NERC Policy 10 requirements. *Commodity storage* Storage of inexpensive off-peak power for dispatch during relatively expensive on-peak hours. In this report. commodity storage refers to applications that require less than four hours of storage.
Transmission and distribution	*Transmission system stability* Ability to keep all components on a transmission line. *Transmission voltage regulation* Ability to maintain the voltages at the generation and load ends of a transmission line within five percent of each other. *Transmission facility deferral* Ability of utility to postpone installation of new transmission lines and transformers by supplementing the existing facilities with another resources. *Distribution facility deferral* Ability of utility to postpone installation of new distribution lines and transformers by supplementing the existing facilities with another resources.
Customer service	*Customer energy management* Dispatching energy stored during off-peak or low cost times to manage demand on utility-sourced power. *Renewable energy management* Applications through which renewable power is available during peak utility demand (coincident peak) and available at a consistent level. *Power quality and reliability* Ability to prevent voltage spikes, voltage sages, and power outages that last for a few cycles (less than one second) to minutes from causing data and production loss for customers.

[a] Available for download at http://www.nerc.com/~oc/.

3.2. Long-term storage versus short-term storage

The power ranges for the required storage times of various applications at different integration levels are given in Fig. 1. The data shows that at all levels, wide ranges of both power and storage times are required. Two main applications are considered below, namely, short-term storage (discharge times of less than second to one minute), which corresponds to power quality and system stability applications, and the long-term storage (discharge times of minutes and over) for all other applications.

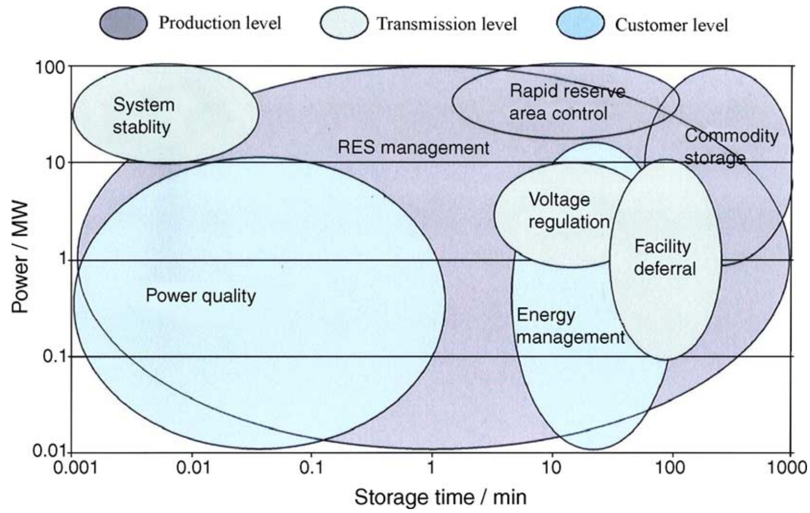

Fig. 1. Power vs. storage time required by different applications at different levels (production, transmission and end-user level).

4. Competitors for the new markets

Within the INVESTIRE network, nine storage technologies have been addressed and evaluated on a technical and economical basis for the above two applications. These technologies are:

- lead–acid batteries,
- lithium batteries,
- double-layer capacitors,
- nickel-based batteries,
- hydrogen-based energy storage,
- flywheels,
- redox-flow batteries,
- compressed air, and
- metal–air systems, e.g., $Zn–O_2$.

This list of technologies is of course non-exhaustive, e.g., hydro-pumping, superconducting magnetic energy storage and ‘heat and turbine’ storage have not been addressed. The selection of the storage technologies has been made on the basis of the expertise of the consortium members.

In order to obtain a fair comparison, typical sizing was performed for each application and the storage technolo-

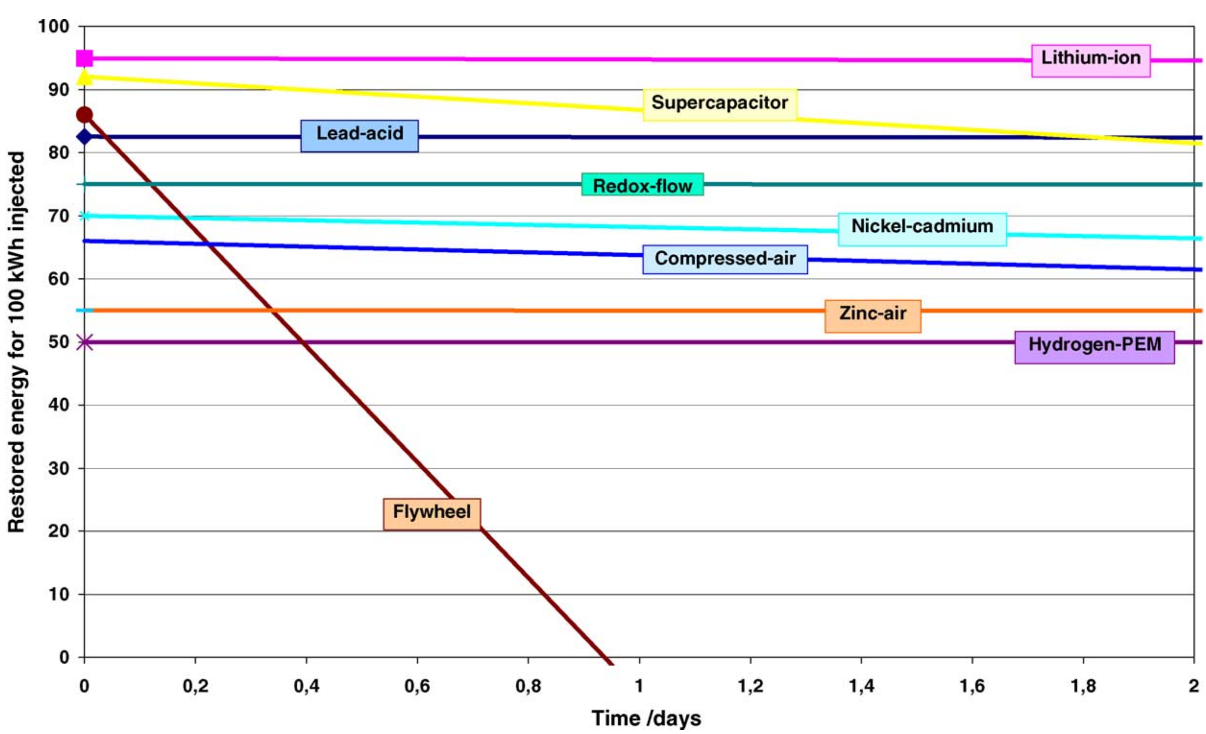

Fig. 2. Energy discharged depending on storage time for 100 kWh fed into the storage system.

gies were evaluated accordingly. To characterize a typical power-shifting application (long-term storage), a storage system with 2 h of autonomy and a size of 1000 kWh has been defined. The number of full cycles per year amounts to 1000, which results in 1 GWh per year of discharged electricity. For power-quality devices (short-term storage), an average of 5 MW is assumed, with a period of autonomy of 30 s and a storage capacity of 41.5 kWh. The typical number of equivalent full cycles is assumed 10,000, which results in a total amount of discharged electricity of 415 MWh per year.

4.1. Technical comparisons

The combination of the energy efficiency and the self-discharge, expressed as the charge retention, allows a determination of the amount of energy that can be taken out of a given storage system after a given storage time. This charge retention for the nine storage technologies is given in Fig. 2.

Since the storage systems are connected to the grid, the energy efficiency of the chosen storage technology will be a criterion of growing importance with increase in the cost of the electricity fed in the storage system for charging. The data in Fig. 2 shows that on a purely technical point of view, lithium-ion batteries are the best choice for high energy efficiency, followed by supercapacitors when they are discharged rapidly and the flywheels when discharged within a few seconds. The lead–acid battery is a satisfactory choice with respect to the energy efficiency, especially in applications with rest periods of some days.

The evaluation of the technical ad-equation of the storage technologies to the applications was performed within INVESTIRE [7] by weighting the different technical criteria and defining thresholds that the technologies must pass in order to be defined as ‘suitable’, (see Table 2). The results of the analysis are shown in Fig. 3. Metal–air failed for both applications, due to the short lifetime of this system. There may, however, be some opportunities to use this technology in hybrid storage systems where the requirement is greater reserve power. In the same way, due to its low energy efficiency, the electrolyser/hydrogen storage/fuel cell system failed for both applications.

Power shifting: long duration storage. Supercapacitors and compressed air show the highest performance in this application. Li-ion batteries also fulfil the minimum requirements, but have major disadvantages in terms of short lifetime under full depth-of-discharge cycling (5000 required) and low power density. Lead–acid batteries do not satisfy the minimum requirements, mainly due to their limited lifetime. If the lead–acid battery is oversized, the performance can be improved significantly.

Power quality: short duration storage. Only supercapacitors, flywheels and compressed air deliver the required high cycle life in combination with high specific power. The small advantage of supercapacitors over flywheels is caused by the smaller self-discharge. All other performance parameters are very similar. Looking at the developing trend, both systems will reach a performance index of around 90 within the next 5 years.

Table 2
Weighting factors and minimum requirements for evaluation of storage technologies

Parameter	Weighting factors	Minimum requirement
Energy efficiency	0.1	50
Self discharge	0.1	5
Gravitation energy density	0.03	0
Volume energy density	0.03	0
Specific power	0.15	10
Time to full power	0	0
Cycle life @ 100% DOD	0.18	20
Cycle life @ 10% DOD	0.18	20
Float life	0.03	0
Shelf life	0.03	0
Temperature impact on lifetime	0.03	0
Maximum charge temperature	0.03	50
Minimum discharge temperature	0.03	10
Temperature increase[a]	0.03	0
Health and safety	0	0
Maintenance	0.05	2
SOC and SOH monitoring	0	0
Electronic efforts	0	0

[a] For compressed air this is a reversible effect, therefore data for one cycle used.

From a purely technical point of view, the best matching storage technologies within the application categories defined above can be summarised as follows:

- long-duration storage: supercapacitor, compressed air, and
- short-duration storage: flywheel, supercapacitor.

Some storage technologies are characterized, however, by wide spans in performance parameters, which means that

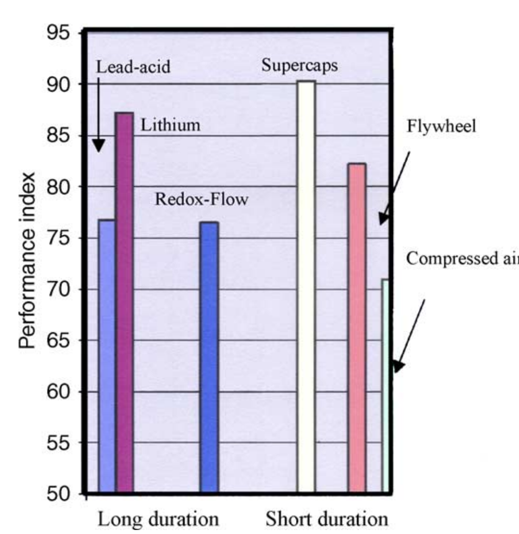

Fig. 3. Performance index of storage technologies for different categories of application.

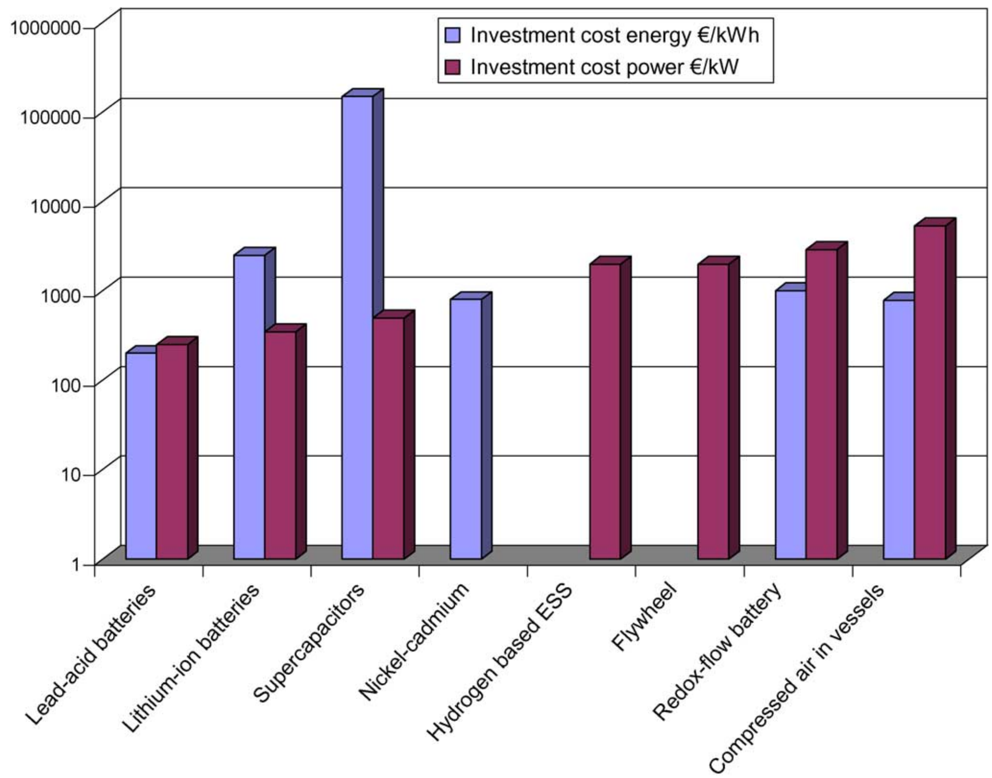

Fig. 4. Investment cost for power or energy of different storage technologies.

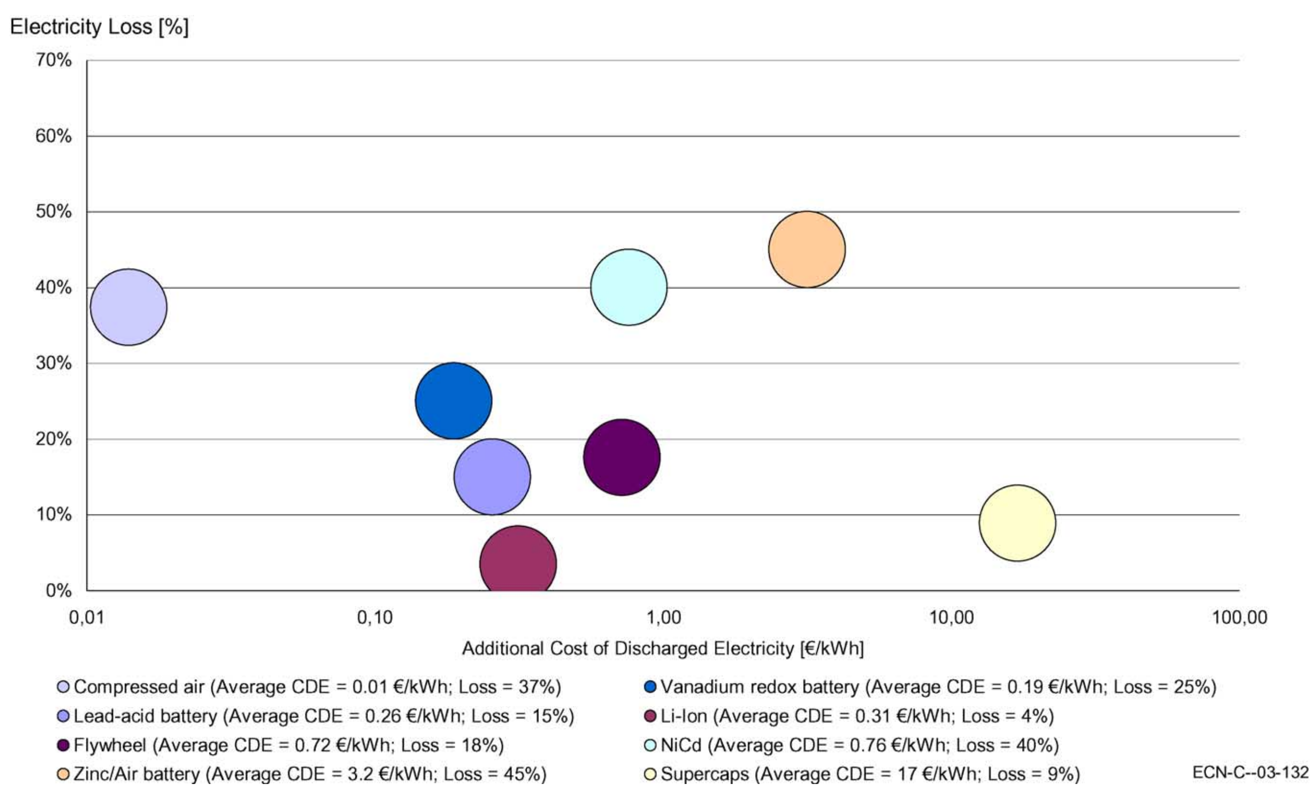

Fig. 5. Additional cost of discharged electricity and electricity loss for storage applications with storage times in the range 30 min to some hours.

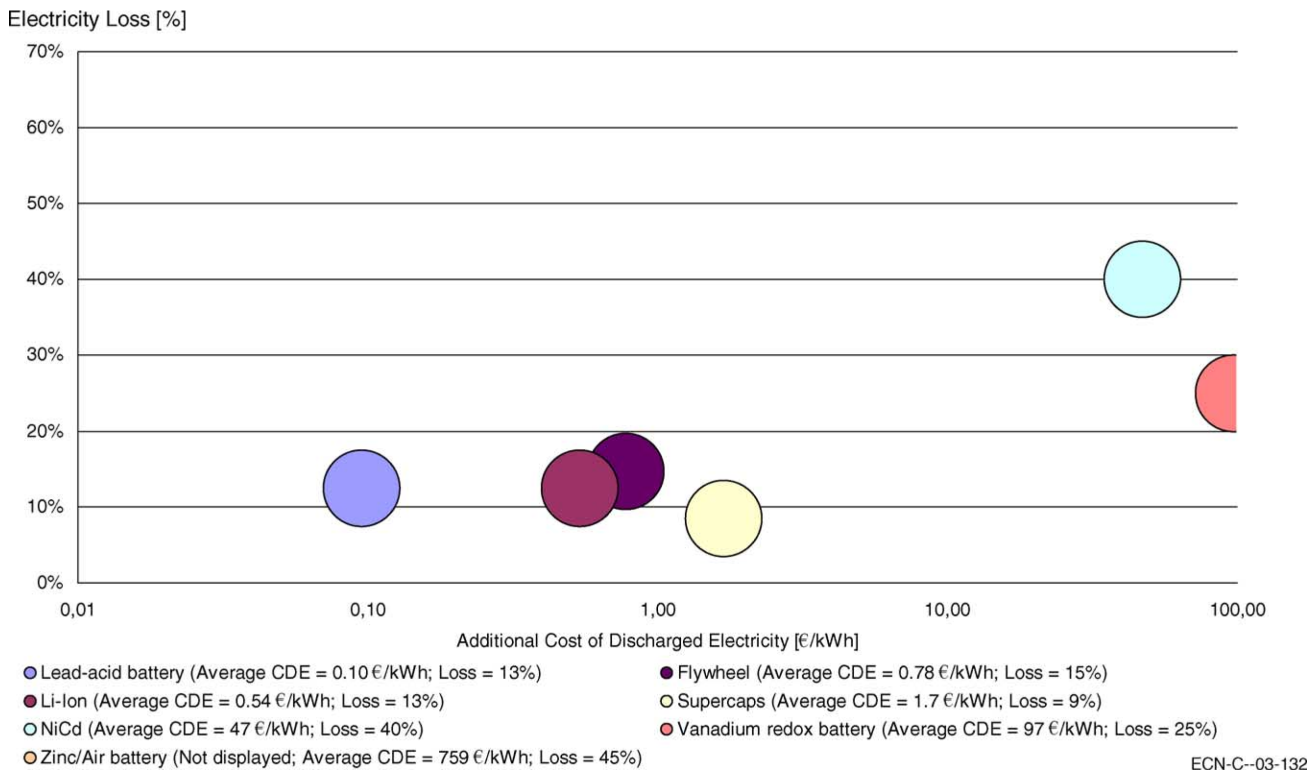

Fig. 6. Additional cost of discharged electricity and electricity loss for short-duration storage applications.

there exist different products for different applications. In these cases, a careful selection of the storage product is necessary.

Another degree of freedom exists in the possibility of oversizing the storage to improve matching for a special application category. This possibility has not been analysed in detail, to reduce the complexity of the analysis. Therefore, most calculations have been performed with storage systems that are sized in terms of energy.

4.2. Economical evaluation

The previous analysis was based on the purely technical characteristics of the different storage technologies. An evaluation of the associated investment costs that has been addressed within the INVESTIRE project is presented in Fig. 4 [8]. It is clear that lead–acid batteries are the cheapest option for both power and energy.

Rather than the investment cost, the cost of ownership is the determining criterion for the selection of one or another technology. The cost of ownership of a storage system (i.e., cost of 1 kWh transited through the system without taking into account the price of the input electricity) is shown in Figs. 5 and 6 for large and short-duration applications, respectively. It includes the costs of maintenance and replacement over system life. For this purpose, the losses associated with each storage technology are also included.

For the longer discharge application, pneumatic storage in vessels appears to be a very valuable solution, followed by the lead–acid battery and the promising vanadium redox battery. Of these three systems, only the lead–acid battery is commercially available.

The best candidates for short-discharge time applications are lead–acid batteries. Lithium-ion batteries, supercapacitors and flywheels are in the same cost range, viz., €1 kWh^{-1}, which is an order of magnitude higher than lead–acid batteries.

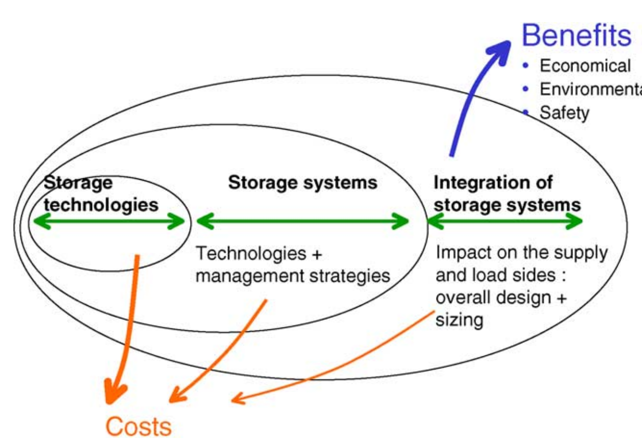

Fig. 7. Illustration of the partition of costs and the provenance of benefits for the integration of ESSs.

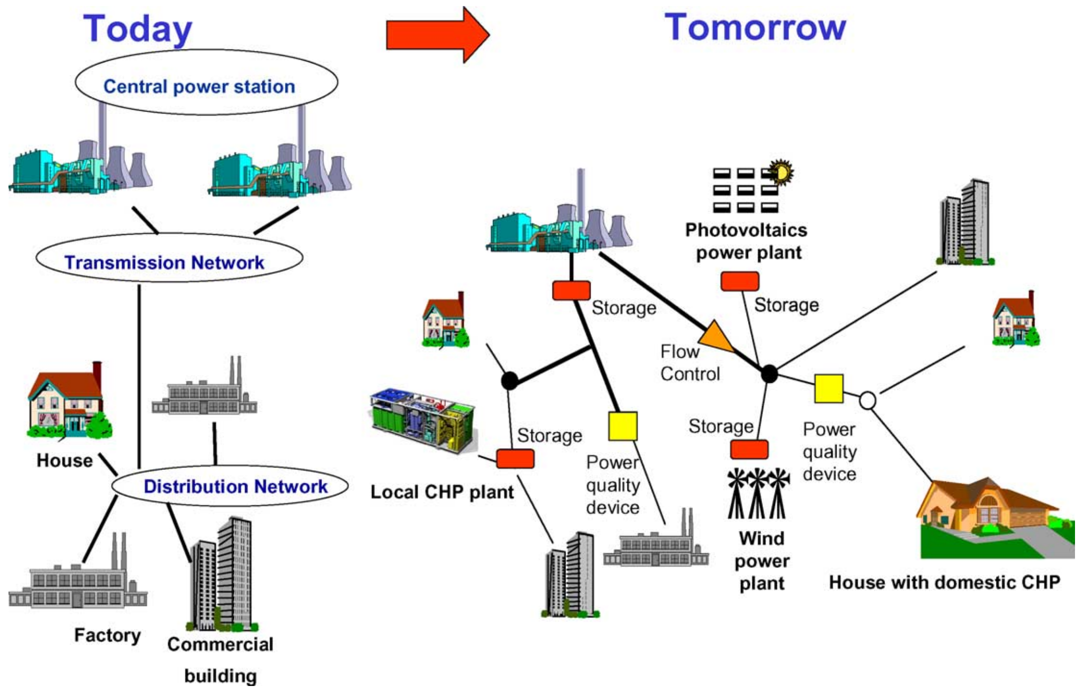

Fig. 8. Schematic representation of present and future electricity networks.

5. Further work

5.1. Technical and economical data

The INVESTIRE project together with more recent literature surveys have demonstrated that there is a critical lack of reliable technical and economical data for emerging storage technologies. Furthermore, if data are available, then very seldom do they include management system and peripherals such as inverters, control systems, etc. Only technical and economical evaluation of the system as a whole can provide a reliable comparision, as shown in Fig. 7. Harmonization of test profiles for the required applications would also assist comparative evoluations.

5.2. Benefits from integration of energy storage systems

A schematic of the potential new grid structure is presented in Fig. 8 and clearly shows the increased complexity of future electricity networks. While one provider had in the past the responsibility for production, transmission and distribution, there would now be a large number of providers. As a result, since electricity storage provides transversal services, the benefits and cost related to ESS integration is a critical issue.

So far, the benefits of storage systems have only been considered for the ESS owner. When a storage facility is connected to a grid, however, it will have a beneficial impact on the whole electricity chain from the producer to the transmission system operator, distribution system operator and the end-user. For example, a group of end-users can affect a deferal of distribution-line investment by installing an ESS. In such a case, the actual pricing system does not allow reallocation of the benefits made by the DSO to the ESS owner. Despite its complexity, this issue of the benefits allocation of storage systems needs to be addressed urgently in Europe in order to obtain optimized electricity networks in the future.

Finally, while it may sometimes be difficult to prove the economic benefits of the integration of storage systems in electricity networks, it has also to be noted that the operational/planning issues at the generation and transmissions levels remain the main barriers to a widespread penetration of renewable energies in the present electricity markets. For example, sites that are suitable for renewable resources are generally isolated or connected to the mains by a weak transmission line. In such situations, investment in a new transmission (or distribution) line is generally so expensive that the project has to be abandoned. On the other hand, ESSs allow large wind farms to be connected to the grid through a line, which would otherwise have a too small capacity, by smoothing out the peaks in power production. Therefore, evaluation of non-monetary criteria must be taken into account when assessing the value of grid-connected storage systems. As a result, it is essential for European research to ascertain and quantify the potential benefits of grid-connected storage systems that are not solely based on economic considerations. Regulation and market design have to provide the correct framework in order to evaluate all the services that storage facilities can efficiently provide.

6. Conclusions

In Europe, the present quality of the grids is fairly high with over 95% of the disturbances lasting for less than 12 s. Therefore, only critical processes and data safety can be impacted and concerns at end-user level are relatively limited. For these uses, while flywheels are mostly used nowadays, progress is being made with the integration of lithium-ion batteries. Supercapacitors were judged to be the most promising technology some years ago, but practical experience has shown them to have insufficient energy, and this drawback is largely solved by lithium batteries.

For fast response and high-power storage systems such as UPSs, the development of lithium-ion batteries is expected because of substantial improvement in reliability, cycle-life, and investment cost. In addition, it is likely that the advancement of lithium-ion batteries will hinder the larger deployment of nickel–metal–hydride batteries that are still expensive and more sensitive than nickel–cadmium counterparts. Systems with fast response, high-power capability and reasonable energy content will be of growing profitability as deregulation proceeds and the quality of main grids decreases.

Since power quality issues in main grids are presently not a major issue in Europe, storage can mainly be seen as bringing added economic or environmental value when allowing RES energy management or customer energy management. This is especially the case if real-time pricing is performed and if renewable energy system operators are allowed to inject electricity also from storage systems, whatever the size of their system. For large-scale storage (in the range of MWh) that will concern more the storage for some hours of wind energy, the potential candidates are lead–acid batteries, the redox-flow batteries, compressed-air systems, and, in certain special conditions of temperature, nickel–cadmium batteries.

Two redox-flow technologies were competing in the market for large grid-connected ESSs, namely, vanadium systems and Regenesys technology. The latter option, however, was abandoned at the end of 2003. The all-vanadium system is still quite expensive and appears to have difficulty in reaching very large power levels. It will possibly gain a share of the market for grid-connected electricity storage as soon as numerous industrial property issues are solved.

Finally, improvements need to be made in energy management and reliability to allow widespread deployments of lead–acid batteries in the large grid-connected ESS market. Besides life expectancy, the present limitation of lead–acid in grid-connected applications is its lack of predictability. Nevertheless, on costs grounds alone, lead–acid is expected to secure a large share of the future deployment of large grid-connected storage systems.

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