# Electrical energy storage technologies and the built environment

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## Abstract

It is acknowledged that innovative electricity storage solutions are a prerequisite for achieving high renewable energy penetration in the built environment. This paper provides an overview of state-of-the-art electrical energy storage technologies, focusing on their distinct characteristics and areas of application. With growing concerns about the environmental impacts of the electricity sector, the electrical energy storage market is developing quite rapidly and the performance characteristics of these technologies are constantly improving. Therefore, the analysis provides an up-to-date evaluation of different storage options with regard to their overall efficiency, energy and power density, response time, lifetime, environmental impact, scale, maintenance requirements, reliability and spatial implications among others. It is concluded that Li-ion and Zinc-air batteries are promising technologies due to their exceptionally high gravimetric and volumetric energy density and are expected to play an important role in reliable, economical and energy efficient building design in the future. Along with these technologies, NaNiCl batteries are also considered an important technology with regard to the integration of storage systems in buildings, because of their high cycle lifetime and their high peak power capability.

## Introduction

Considering the large introduction of renewable energy sources in the built environment in the following years, electricity storage will play a double role. On one hand, it will enable renewable energy to be captured and stored for later use, without wasting extra amounts of resources for electricity generation. On the other hand, it can also serve as a valuable tool that will provide the needed flexibility in energy supply, by blurring the gap between supply and demand [1]. Electrical energy storage (EES) systems can therefore contribute to the increase of the power systems' efficiency, the improvement of the grid stability and reliability as well as to the increase of energy security, ensuring continuity of supply [2-4]. Given the attempts currently being made towards the reduction of $CO_2$ emissions around the globe, advanced EES technologies, along with renewable energy technologies, are expected to be a necessary element of the built environment in the future [1, 3, 5-9].

With growing concerns about the environmental impacts of the electricity sector, the EES market is developing quite rapidly and the performance characteristics of the technologies are constantly improving. Hence, the aim of this study is to gather the most recent findings in the field and analyse their relation to the integration of EES systems in the built environment.

The EES technologies considered in this review are the following: superconducting magnetic energy storage (SMES), supercapacitors/electrochemical double layer capacitors (EDLC), pumped hydroelectric storage, flywheels, compressed air energy storage (CAES), Lead-acid batteries, Lithium-ion (Li-ion) batteries, Nickel/Cadmium (NiCd) batteries, Nickel-metal-hydride (NiMH) batteries, high temperature Sodium/Sulphur (NaS) batteries, high temperature Sodium Nickel Chloride (NaNiCl) batteries, Zinc/Bromine (ZnBr) batteries, Redox-flow batteries, metal-air (Zn-Air) batteries and hydrogen storage used with either a fuel cell or a gas turbine.

### Characteristics of EES technologies

The currently available types of EES technologies exhibit a large spectrum of performances and capacities to match different application environments and electricity storage scales. The requirements concerning power, energy and discharge times are very different and are presented in Figure 1, taken from the International Electrotechnical Commission’s white paper on electrical energy storage. Each technology has a certain coloured range for the above properties. Some ranges overlap, but on the whole EES technologies are very distinct from each other. Not all EES systems are commercially available in the ranges shown at present, but according to [10] all are expected to become important. Moreover, most of the technologies could be implemented with even larger power output and energy capacity, as all systems have a modular design.

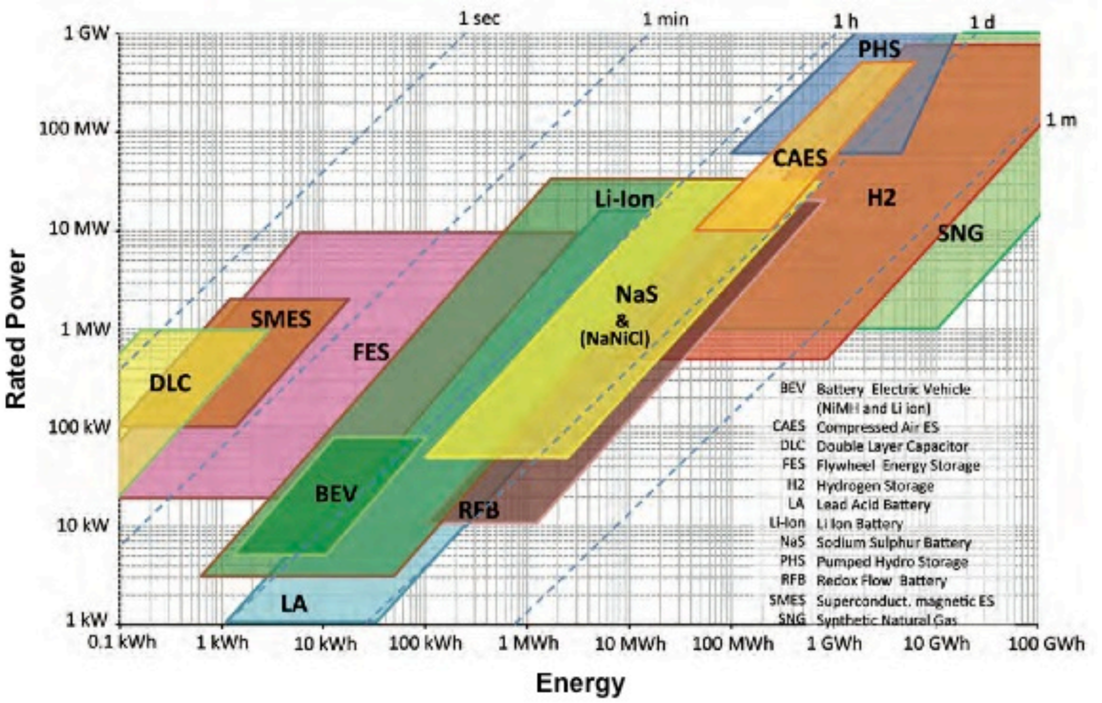

Figure 1: Rated power, energy content and discharge time of EES technologies [10]. The predicted range in future applications is also comprised.

### Spatial requirements for EES technologies

Rechargeable Zinc-Air systems have the highest potential for space saving in the future, exhibiting a remarkably high energy density value. Hydrogen storage has the highest energy density among the currently commercial storage technologies and thus a very small footprint. Zinc-Air batteries are expected to be introduced to the market in 2013/14. Figure 2 below presents a volume comparison considering the power and energy densities of each EES technology. The higher the power and energy density, the lower the required volume. Highly compact EES technologies can be found at the top right. Large area and volume-consuming storage systems are located at the bottom left. PHS, CAES and flow batteries have a low energy density and are volume consuming storage systems. On the contrary, Li-ion batteries have both a high energy density and high power density, which is why Li-ion is currently used in a broad range of applications.

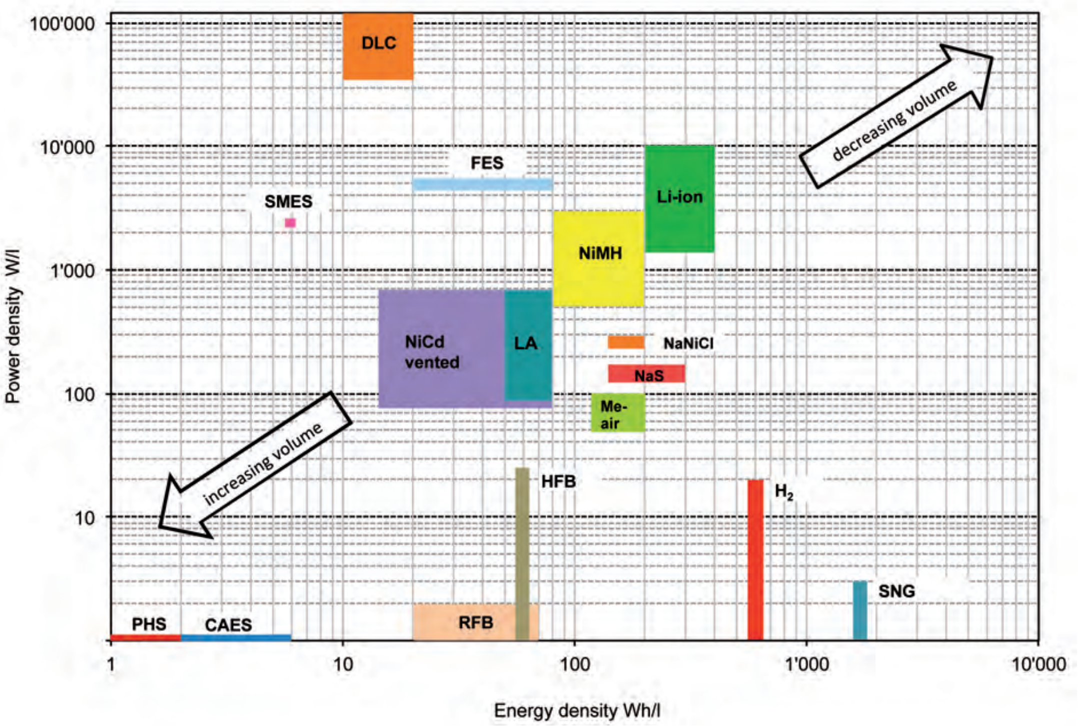

Figure 2: Impact of power and energy density on the volume that EES systems require in the built environment [12].

The parameters explained above along with others have been gathered in a comprehensive table, including information for each of the EES technologies discussed in this study. Therefore, Table 1 is the main outcome of this study and includes the most important characteristics of EES technologies.

Table 1: Characteristics of EES technologies

| | PHS | CAES | Hydrogen | Flywheel | SMES | EDLC | Conventional batteries | | | Advanced batteries | | | Flow batteries | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Pb-acid | NiCd | NiMH | Li-ion | NaS | NaNiCl | V-redox | ZnBr | Zinc-Air |
| Power rating MW | 100-5000 a | 100-300 a | <50 a | <20 a,d | 0.01-10 a,d | 0.01-1 a | <70 b | <40 a | $10^{-6}$-0.2 d | 0.1-5 c | 0.5-50 a | <1 a | 0.03-7 a | 0.05-2 a | several o |
| Energy rating kWh | 2x$10^5$-5x$10^6$ d | 2x$10^5$-$10^6$ d | >$10^5$ θ | 10-5x$10^3$ d | $10^{-1}$-$10^2$ d | $10^{-3}$-10 d | $10^2$-$10^5$ d | $10^{-2}$-1.5x$10^3$ d | $10^{-2}$-500 d | $10^{-2}$-$10^5$ d | 6x$10^3$-6x$10^5$ d | 120-5x$10^3$ d | 10-$10^4$ | 50-4x$10^3$ d | x$10^3$ o |
| Discharge time | h-days a,θ | h-days a,β | s-days a | 15s-15min a | ms-5min a | ms-1h a | s-3h a | s-h a | h θ | min-h a,c | s-h a,v | min-h a | s-10h a | s-10h a | 6h o |
| Response time | s-min a,c,d | 1-15 min a,d | ms-min v | ms-s a,c,e,u | ms a,c,v,u | ms a,v,u | ms u,v,θ | ms t,u,θ | ms u,β,θ | ms-s c,u,θ | ms t,u,θ | ms u,β, | <1 ms d | <1ms t | ms o,u,θ |
| Specific energy Wh/kg | 0.5-1.5 a,d | 30-60 a | 33,330 θ | 5-130 a | 0.5-5 a | 0.1-15 a | 30-50 a,d | 45-80 d | 60-120 d | 100-250 c,d | 150-240 a | 125 a | 75 a,b | 60-80 d | 400 q |
| Specific power W/kg | Not appl. | >PHS | >500 a,u | 400-1600 a,d | 500-2000 a | 0.1-10 a,d | 75-300 a | 150-300 a | 700-756 θ,λ | 230-340 c | 90-230 a | 130-160 a | N/A | 50-150 a,d | 1350 θ |
| Energy density kWh/m$^3$ | 0.2-2 θ | 12 d,t | 600 (200 bar) θ | 20-80 θ | 6 θ | 10-20 θ | ~75 b | <200 c | <350 c | 250-620 c | <400 z,θ | 150-200 d, | 20-35 d | | 800 q |
| Power density kW/ m$^3$ | 0.1-0.2 θ | 0.2-0.6 θ | 0.2-20 θ | 5000 θ | 2600 θ | 40000-120000 θ | 90-700 θ | 75-700 θ | 500-3000 θ | 1300-10000 θ | 120-160 θ | 250-270 θ | 0.5-2 θ | 1-25 θ | 50-100 θ |
| Operating temp °C | Ambient | Ambient | 80-100 or 1000 b | -20 to +40 a,d | -270 to -140 d,θ | -40 to +85 a,d | ~27 | -40 to +45 b | -20 to +45 b,d | -10 to +50 d | ~300 c | -40 to 70 a, | 0-40 a,d | 20-50 n,w | 0 to +50 s |
| Self-discharge %/day | ~0 a,d | ~0 a | 0.5-2 a | 20-100 a,b | 10-15 a | 2-40 a | 0.1-0.3 a,k | 0.2-0.6 a | 0.4-1.2 d | 0.1-0.3 a,k | 20 a | 15 a | 0-10 a | 0-1 a,d | N/A |
| Round-trip eff. % | 75-85 b,θ | ≤55 b | 29-49 b | 85-95 a | ≥95 a,m,l,u | 85-98 a,d | 80-90 b,θ | 70-75 b | 70-75 b | 90-98 b,d,e | 85-90 a | 90 a,i | ~75 b,g | 70-75 a,d | 60 r |
| Lifetime (years) | 50-100 a,b,d | 25-40 a,d | 5-15 a | >20 a,d,w | ≥20 a,d | >20 a | 3-15 a | 15-20 a | 5-10 θ | 8-15 a,f,g | 12-20 b | 12-20 b | 10-20 d | 5-10 a,b | 30 o |
| Cycles | >5x$10^5$ c | No limit practically d | >$10^3$ a | $10^5$-$10^7$ a,d | $10^4$ a | >5x$10^5$ b | ~2x$10^3$ b | 1.5x$10^3$ d | 3x$10^2$-5x$10^2$ d | >4x$10^3$ d,e | 2x$10^3$ to 4.5x$10^3$ a | $10^3$-2.5x$10^3$ d | >13x$10^3$ b | >2x$10^3$ a | >2x$10^3$ (>$10^4$) o |
| Inv. power cost €/kW | 500-3600 a,d | 400-1150 a,d | 550-1600 a | 100-300 a | 100-400 a | 100-400 a | 200-650 a | 350-1000 a | 120%xNiCd d | 700-3000 a | 700-2000 a | 100-200 a | 2500 a,d | 500-1800 a | ~785 o |
| Inv. energy cost €/kWh | 60-150 a | 10-40 d | 1-15 a | 1000-3500 a | 700-7000 a | 300-4000 a | 50-300 a,b | 200-1000 a | 120%xNiCd d | 200-1800 a | 200-900 a | 70-150 a | 100-1000 a | 100-700 a | ~126 o |
| Space requirement m$^2$/kWh | 0.02 v | 0.10-0.28 v | 0.005-0.06 v | 0.28-0.61 v | 0.93-26 v | 0.43 v | 0.06 v | 0.03 t | 0.02? | 0.01? | 0.019 v | 0.03? | 0.04 t | 0.02 v | <0.005? |
| Environmental impact | high d | high v | low v,u | no d,v,w | low v | low i | medium d | medium d | low d | very low i,j | very low d,t | N/A | low d | low d | low o,p,q,u |
| Commercial use since | 1929 x,y | N/A | 2010 π | 2008 ξ | 2000's d | 1980s i | 1870 d | 1915 θ | 1995 θ | 1991 d,e,h | 1998 t | 1995 θ | 1998 d | 2009 t | 2013/14 o |
| Recharge time | min-h b | min-h σ | instantaneous v | <15 min d | min ϕ | sec to min d | 8-16h d | 1h d | 2-4h d | min-h c | ~9h ζ | 6-8h ω | min θ | 3-4h t | N/A |
| Memory effect | N/A | N/A | N/A | no μ | N/A | no w | no h | yes a,h,i,t,u | yes a,h | no c,d,h | no l | no ω | no ς | no w | no α |
| Maintenance | low d,x | low x | high i | low k,w | medium d,u | very low a,d | low k,x | high d | high d | no d | low k,x | no d | low g,t | high x | low o |
| Recyclability | Not appl. | Not appl. | 2-3? | 4 j | N/A | 4 θ | 5 b,i,j | 4-5 d,j | 4-5? | 4 d,l,j | 5 t,w | 5 d,ω | 5 d | 5 d | 3 i |
| Technical maturity | mature t,v,θ | medium t,v | early t,v,θ | mature t,θ | early t,θ | medium t | mature t,θ | mature (portable) θ | mature (mobile) θ | mature (mobile) b,t | medium t | mature (mobile) ψ | medium a,t | medium a,t | early θ |
| Transportability | no d | no d | yes w | yes δ | yes ε | yes a | yes e | yes τ | yes d | yes e | yes e | yes e | no d | yes d,e | yes e.p |
| Cumulative energy demand (MJ/kWh) | N/A | N/A | 5,501 j | 30,449 j | N/A | N/A | 652 j | 1,372 j | N/A | 1,156 j | N/A | N/A | 774 j | N/A | 710 j |
| Applications | Load leveling, emergency reserve, seasonal storage a,t,u | Load shifting, load leveling, grid support, seasonal storage a,t,u | Seasonal storage t | UPS, power conditioning, pulse power, RE generation management, spinning reserve, voltage regulation t,u | Power quality, UPS, reactive power support t | Power ride-through & brigding, power factor correction, voltage support t | UPS, power quality, spinning reserve, load leveling, frequency & voltage regulation a,u | UPS, generator starting, spinning reserve, grid stabilization t | Hybrid electric vehicles a | Power reserve, frequency regulation, grid stabilization t | RES generation management, load leveling a,t | Transport sector (fleet vehicles) a | UPS, Load leveling, RE stabilization, seasonal storage, backup power, power quality t | Power quality, seasonal storage t | Seasonal storage, power quality t |

**Notes for Table 1:**

- Hydrogen's operating temperature of 80-100°C relates to polymer electrolyte fuel cells, while that of 1000°C to solid electrolyte fuel cells [7].
- Zinc-Air energy storage system refers to rechargeable flow battery technology; it is an emerging technology, which has been developed very recently.
- The power price reported for hydrogen relates to gas turbine based generator. The power price for fuel cells is in range of 2,000-6,600 €/kW [6].
- Environmental impact and maintenance are classified on a 5-point scale (high/medium/low/very low/no)
- The recharge time for each technology is proportionate to the size of the system
- Space requirement and recyclability ratings are based either on literature or own judgement (indicated with a question mark in this case). For recyclability, a 5-point scale is used (1 to 5) where 1=poor, 5=excellent.
- Space requirement: SMES, lower value accounts for large SMES and higher value accounts for micro-SMES. Flywheels, low value for high-speed flywheels and higher value for low-speed flywheels. CAES, lower value for CAES storage in aquifer and higher value for CAES in vessels. Hydrogen, lower value for $H_2$ engine and higher value for $H_2$ fuel cell.
- The space requirement for Li-ion electricity storage is found in the literature 0.03 $m^2$/kWh [11]; this figure seems to be quite big though considering the energy density of Li-ion batteries currently found in the literature, so an adjustment on this figure is made (0.01 $m^2$/kWh).
- Technical maturity: diabatic CAES storage according to [10] is a mature technology, while adiabatic CAES is at an early development stage
- Cumulative energy demand: only the energy input for the material supply is included
- The hyphen in some inputs (e.g. in row *energy rating kWh*) is indicative of "to". It is used as a sign to indicate the range.
- N/A = Not available in the literature, Not appl. = Not applicable
- Colour coding (related to the characteristic described in each row): green=most favourable(s), yellow=second most favourable(s), orange=least favourable(s)
- There is at least one reference provided for each cell that is placed on the top right corner of each cell. The cells that do not have a reference are assumptions. All the references for Table 1 are provided in the end of the paper under the references section in brackets.

## Opportunities for EES technologies

No single EES technology scores high in all the parameters presented above. Batteries can address all application areas, although they are not always the least expensive option [13]. Li-ion batteries offer good power capability, high energy density up to 620kWh/m$^3$, high efficiencies, light weight and small footprint, but they are still expensive. Further R&D is required to prove their suitability for large-scale applications including solar and wind plants. There are also safety issues associated with their operation, as is the case for NiCd and NaS batteries. High temperature NiCd and NaNiCL batteries also suffer from memory effect. In addition, Lead-acid batteries are a state-of-the-art technology for photovoltaic energy storage and uninterruptible power supply systems and currently have the lowest invest per kWh. However, they have a relatively limited lifetime and the image of "old" technology [4]. Zinc-air batteries have low materials cost and the highest potential for space saving in the future, exhibiting a remarkably high volumetric energy density value of 800kWh/m$^3$. Yet they suffer from low round-trip efficiencies and there is no such system available in the market yet. Redox-flow batteries are versatile systems and an interesting option for bulk energy storage, but further R&D is required so that their suitability for such applications is demonstrated. Redox-flow batteries are versatile systems and an interesting option for bulk energy storage, but further development is required so that their suitability for such applications is demonstrated. They also have a very low power density.

PHS and CAES systems have long lifetimes and practically unlimited cycle stability, but they are dependent on suitable topographical conditions. Therefore they have a high environmental impact, as they require large areas of land, possibly substituting the existing land use. Moreover, hydrogen storage is a promising technology regarding storage of large amounts of energy up to the TWh range and for long periods of time, but its overall efficiency is still low. Flywheels have excellent cycle stability and long lifetime, high power density, high efficiency and low maintenance requirements, yet they can lose all their stored energy within a day. SMES devices have a very fast response time and rapid discharge rates and a very high power density, but they are very sensitive to temperature. EDLCs are capable of operating over a broad temperature range, have long lifetime, little maintenance, very fast charging and discharging times, but also low specific energy values.

Several factors should be taken into consideration when planning the integration of a storage system in the built environment. The selection of the most preferable technology for a specific application depends on the size of the system, the specific service, the electricity sources and the marginal cost of peak electricity [14].

## EES deployment potential in the built environment

In the future, EES will be primarily used in combination with renewable energy generation in the built environment. There will be an increase in distributed generation with active grids, where consumption and generation are typically close together [10]. As regards building applications, the concept of the Smart House, which is designed to use energy more efficiently, economically and reliably, is expected to integrate EES technologies [15]. Currently lead-acid batteries are mainly used in smart houses, but in the future Li-ion or NaNiCl batteries are expected to play an important role [5].

In addition, the growing synergy of the power supply system and the transport sector is an important point to address for a sustainable future [7, 10]. Hence, the use of battery storage system in plug-in electric vehicles is a means for using existing storage systems, providing large-scale decentralised EES.

## Conclusions

Li-ion batteries and Zinc-air batteries with energy densities of 620 kWh/m$^3$ and 800 kWh/m$^3$ correspondingly seem to be very promising technologies for advanced EES integration in the built environment. Along with these technologies, NaNiCl batteries are also expected to play an important role in buildings because of their high cycle lifetime and high peak power capability. However, there is still room for improvement of the technologies' properties, so as to increase the systems' efficiencies, lower the costs and extend the lifetimes.

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*Note: the bold letters in brackets are associated with Table 1*

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