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A review on technology maturity of small scale energy storage technologies[★]

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Abstract. This paper reviews the current status of energy storage technologies which have the higher potential to be applied in small scale energy systems. Small scale energy systems can be categorized as ones that are able to supply energy in various forms for a building, or a small area, or a limited community, or an enterprise; typically, they are end-user systems. Energy storage technologies are classified based on their form of energy stored. A two-step evaluation is proposed for selecting suitable storage technologies for small scale energy systems, including identifying possible technical options, and addressing techno-economic aspects. Firstly, a review on energy storage technologies at small scale level is carried out. Secondly, an assessment of technology readiness level (TRL) is conducted. The TRLs are ranked according to information gathered from literature review. Levels of market maturity of the technologies are addressed by taking into account their market development stages through reviewing published materials. The TRLs and the levels of market maturity are then combined into a technology maturity curve. Additionally, market driving factors are identified by using different stages in product life cycle. The results indicate that lead-acid, micro pumped hydro storage, NaS battery, NiCd battery, flywheel, NaNiCl battery, Li-ion battery, and sensible thermal storage are the most mature technologies for small scale energy systems. In the near future, hydrogen fuel cells, thermal storages using phase change materials and thermochemical materials are expected to become more popular in the energy storage market.

1 Introduction

Energy storage is considered to play a critical role in the futures of energy systems, particularly electricity systems, since it can improve the management of distribution networks, reducing costs and improving efficiency. In general, energy storage technologies can be classified by their functions or forms of energy stored in the system. This paper categorizes energy storage technologies based on the form of the stored energy, namely electrical energy storage (supercapacitors; superconducting magnetic energy storage), mechanical energy storage (pumped hydro; compressed air; flywheels), chemical energy storage (batteries; flow batteries; hydrogen fuel cells and metal-air batteries; solar fuels), and thermal energy storage (sensible heat storage; latent heat storage; thermochemical heat storage) [1,2].

In this paper, we focus on applications for small scale systems. Small scale energy systems can be categorized as ones that are able to supply energy in various forms for a building, or a small area, or a limited community, or an enterprise; typically, they are end-user systems. Capacity of the systems normally can be expected as less than 1 MW for electricity, or a few MW in terms of thermal supply [3]. A large number of reviews on different energy storage types for various systems can be found, i.e., [1,2,4–13]. These reviews have been normally done with regard to systems at medium or large scale, but very a few of them specify technology choices for small scale energy systems. Also, other papers tend to present some certain types of energy storage for particular applications at small scale level, such as [14–17]. Thus, there is a need for a systemic review of energy storage technologies for small scale energy systems. Furthermore, current selection of energy storage technologies is mainly influenced by technical specifications of the systems, with market review being included limitedly. This paper, therefore, aims at providing an overview on storage technologies that are suitable for small scale energy systems, and proposing a holistic way of selecting storage technology for small scale energy systems, with technology maturity and market development being taken into consideration.

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Table 1. Overview on status of development and application of storage technologies.

Storage technology	Status of development and application
Batteries	Batteries are one of the most widely used electrical energy storage technologies in industry and daily life. Batteries that are evaluated in this paper include lead-acid, nickel (NiCd and NiMH), sodium sulphur (NaS), sodium nickel chloride (NaNiCl or ZEBRA) and lithium ion (Li-ion). While lead-acid is a popular storage choice for power quality, uninterruptible power supply (UPS) and some spinning reserve applications, it is limited in use for energy management. Li-ion battery is applied widely in the small portable devices market, as well as electric vehicles, furthermore the Tesla Powerwall has been introduced for households. NiCd battery can be found in power tools, portable devices, emergency lighting, UPS, telecoms, and generator starting, while NiMH has a wealth of applications from portable products to electric vehicles and potential industrial standby applications, such as UPS devices. NaS battery has been economically used in combined power quality and peak shaving applications. With its technology being similar to NaS battery, NaNiCl is mostly applied in electric vehicles demonstrations, for instance, Rolls Royce has used NaNiCl to replace lead-acid in surface ships applications [1,2].
Flow batteries	A flow battery is a form of a battery in which the electrolyte contains one or more dissolved electroactive species flowing through a power cell or reactor. There are three different electrolytes currently utilized in design of flow batteries: vanadium redox battery (VRB), zinc bromine battery (ZnBr battery), polysulphide bromide battery (PSB). VRB is suitable for a wide range of energy storage applications for electricity utilities and industrial end-users, such as enhanced power quality, UPS, peak shaving, increased security of supply and integration with renewable energy systems. ZnBr battery was developed by Exxon in the early 1970s, and several kWhs ZnBr batteries have been constructed and tested for the past decades; 50 kWh modules for renewable energy application can be currently found in the market. On the other hand, PSB is being verified in the laboratory, as well as demonstrated at multi kW scale in the UK [1,6,8].
Hydrogen fuel cell and metal air battery	A fuel cell is an electrochemical energy conversion device [7]. A hydrogen cell uses hydrogen as fuel and oxygen as oxidant. Hydrogen fuel cells can be implemented in systems scaling from kW scale to multi-MW capacity. Other fuels include hydrocarbons, alcohols and metal. Other oxidants can be air, chlorine and chlorine dioxide [1,18]. Metal-air battery can be considered as a special type of fuel cell which utilizes metal as the fuel and air as the oxidant. It is the most compact and potentially the least expensive batteries, as well as environmentally benign. Although many manufacturers offer refuel units (in which the consumed metal is mechanically replaced and processed separately), few developers offer an electrically rechargeable battery [1,2,4].
SCES	Supercapacitors energy storage (SCES) can have both the characteristics of traditional capacitors and electrochemical batteries. SCES is suitable for short-term storage applications; typical applications in power quality consist of pulse power, hold-up/bridging power to equipment, solenoid and valve actuation in factories, UPS devices. Research and development of SCES has been very active in recent years. The integration of a short-term electrical energy storage device in the form of a supercapacitor in an induction generator has been studied in order to smooth the fast wind-induced power variations [2,8,10].

Table 1. (continued).

Storage technology	Status of development and application
SMES	Super-conducting magnetic energy storage (SMES) is suitable for short-term storage in power and energy system applications and it is expected to have an important role in the increased use of intermittent renewable energy [1,2,8]. Recently, numerous research and development has been performed to reduce the costs of the systems, and to develop materials which are less cryogenically sensitive [10].
Micro CAES	Compressed air energy storage (CAES) uses compressed air to store energy generated at one time for use at another time. Although there are only two CAES applications at large scale around the world [2], small scale CAES has recently gotten a lot of attention. The micro-CAES is a technology for electrical and thermal energy storage, it could improve energy efficiency and optimizing operating efficiency while safeguarding the environment. It can be used as an alternative to the battery for industrial applications, such as UPS and back-up power systems [2,15,19].
Micro PHS	Pumped hydroelectric energy storage (PHS) can be categorized into large, small, micro, and pico. A small pumped hydroelectric energy storage may have a capacity of up to a few MW; however, there is no such standard definition or very clear capacity division. A micro PHS may have a capacity of up to 100 kW and could provide power to isolated or small communities and may also be connected to grids where wind and other renewable sources of energy are being used. A pico size PHS can be used for plants of installed capacities of less than 5 kW. These are used to store the energy produced from wind or solar photovoltaic systems for remote communities where the power requirement is only for a few [4,5,10].
Solar fuels	Solar fuel is a relatively new technology to electrical energy storage. Methods to produce solar fuels include natural photosynthesis, artificial photosynthesis, and thermochemical approaches [2]. Research in solar fuels has recently undergone significant advances, making it possible for it to become cost-effective for energy storage applications in the near future [1].
Thermal energy storage	Thermal energy storage (TES) covers a variety of technologies that store available heat energy using different approaches in insulated repositories [2]. TES systems can store heat or cold to be used later under varying conditions such as temperature, location or power. TES is utilized in order to overcome the mismatch between energy generation and energy use. There are three types of thermal energy storage system, namely sensible heat storage, latent heat storage, and thermochemical storage. Latent heat TES takes on phase change materials (PCMs) as the storage media and uses the energy absorption or emission in liquid-solid transition of these PCMs at constant temperature. On the other hand, thermochemical energy storage using thermochemical materials (TCMs). The most important challenge with TCM is to find the appropriate reversible chemical reaction for the energy source used [4,12,20].

Table 2. Characteristics of small scale energy storage technologies.

Storage technology	Power rating, MW	Energy rating	Response time	Suitable storage duration	Energy density, Wh/kg	Power density, W/kg	Operating temperature, °C	Self-discharge, %/day
Micro PHS	0–0.1	1–24 h+	s–min	Hours–months	0.5–1.5			≈0
Micro CAES	Up to 1	1–24 h+	5–15 min	Hours–months	30–60			≈0
Hydrogen fuel cell	0.001–50	s–24 h+	min	Hours–months	800–104	500+		0.5–2
Metal air	0–0.01		s–24 h+	Hours–months				Very small
Solar fuels	0–10		1–24 h+	Hours–months				≈0
Fly-wheels	0.002–20	15 s–15 min	s		5–130	400–1600	–60	20–100
SMES	0.01–10	ms–5 min	ms		0.5–5	500–2000		10–15
SCES	0.01–1	ms–1 h	ms		0.1–15	0.1–10	–125	2–40
Lead-acid	0.001–50	s–3 h		Minutes–days	30–50	75–300		0.1–0.3
Li-ion	0.001–0.1	min–h		Minutes–days	75–250	150–315		0.1–0.3
NiCd	0.001–40	s–h		Minutes–days	40–60	150–300		0.2–0.6
NaS	0.5–50	s–h		Seconds–hours	150–240	90–230	300–350	20
ZEBRA	0.001–1	min–h		Seconds–hours	125	130–160	300	15
VRB	0.03–7	s–10 h	ms	Hours–months	75		0–40	0–10
ZnBr	0.05–2	s–10 h	ms	Hours–months	60–80	50–150		1
PSB	0.001–0.015		s–10 h	Hours–months				
Sensible TES	0.001–280		1–8 h	Hours–months	80–120			< 1
PCM	0.001–1			Minutes–months	50–150			
TCM	0.001–1			Minutes–days	120–250			

Storage technology	Round-trip efficiency	Life time, years	Cycles	Power cost, USD/kW	Energy cost, USD/kWh	Capital cost, UScent/kW /cycle	O&M cost, USD/kWh
Micro PHS	75–85	50–100	2×10^4–5×10^4	550–4000	65–165	0.1–1.4	0.004
Micro CAES	42–54	25–40	5×10^3–2×10^4	440–1280	11–130	2–4	
Hydrogen fuel cell	20–50	5–15	10^3+	610–1770	1–16	6000–20 000	0.0019–0.0153
Metal air							
Solar fuels							
Fly-wheels	85–95	20+	10^5–10^7	110–330	1105–3870	3–25	≈0.004
SMES	95	20	104	110–440	770–7740		0.001
SCES	85–98	20+	10^4–10^6	110–440	330–4430	2–20	0.005
Lead-acid	3–15	100–1000	200–650	55–330	22–110	≈50[a]	
Li-ion	5–15	10^3–10^4+	700–3000	220–1990	16–110		
NiCd	15–20	1000–3000	350–1000	220–1105	22–110	≈20[a]	
NaS	10–15	2000–4500	700–2000	220–995	9–22	≈80[a]	
ZEBRA	10–14	2500+	100–200	75–165	5–11		
VRB	5–20	10^4+	2500	110–1105	5–88	≈70[a]	
ZnBr	5–10	2000+	500–1800	110–775	5–88		
PSB					5–88		
Sensible TES	10–20		500–3000		0.1–11		
PCM	5–15				11–57		
TCM	5–15		1000–3000		9–112		

[a] USD/kW/year. Data taken from [1,2,4,6,10,20–22]. Exchange rate between EUR and USD based on the average monthly rate in 2016, 1 EUR = 1.106 USD, data retrieved from http://www.x-rates.com/average/.

Table 3. Key driving factors in energy storage market.

Aspects	Driving factors			
	Entry	Exit	Innovation	Growth
Technical	– Availability of reliable grids – Backup security	Lack of suitable locations (i.e., PHS)	– Extended use of renewable energy sources – Transformation of energy sector (including new applications such as electric mobility) – Technological discoveries and breakthroughs	Synergy between RE systems (i.e., solar PVs) and energy storage
Economic	– Benefits from using different tariffs at different time – Network investment return – Demand management incentives	Cost-effectiveness of the system	Changes in energy storage needs, and patterns of access are changing (move in the direction of quick and powerful response to the needs of the grid)	– Demand charge reduction for commercial and industrial customers – Advanced economics
Environmental	Change from utilization of fossil fuels to electricity (i.e., electric mobility)	Environmental concerns/ toxicity of materials	Environmental concerns/ toxicity of materials	Trend for a sustainable lifestyle
Regulatory	– Regulatory framework and roadmap – Frequency regulation in selected markets – State-level incentives	Changes in regulatory framework and policies	Changes in regulatory framework and policies	– Regulatory framework and roadmap – State-level incentives

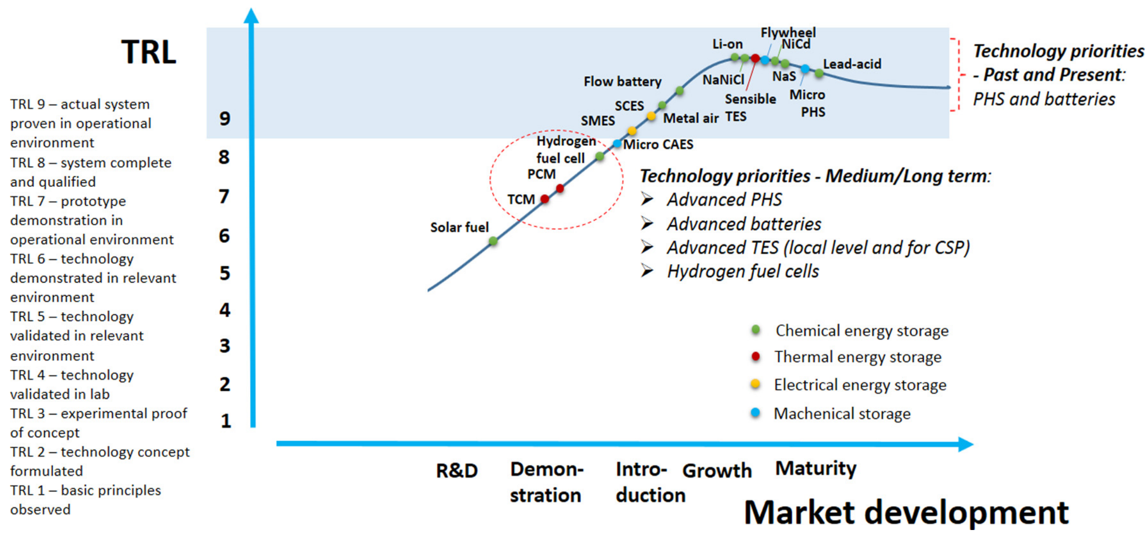

Fig. 1. Technology maturity curve of energy storage technologies for small scale energy systems. Data extracted and analysed from [2–4,6,10,12,20,24,26,31].

2 Energy storage types for small scale energy systems

With the advancements in energy storage technologies, almost all storage technologies can be applied at small scale level. These technologies are identified in the aforementioned classification, with micro compress air storage and micro pumped hydro storage being included, instead of their large-scale forms. This section will provide an overview on current development and application of energy storage technologies for small scale systems, as displayed in Table 1. While the overview does not focus on the configuration of the technologies, their characteristics are presented in Table 2.

3 Methodology

With significant improvements in energy technology field for the past decades, it is important to include level of technology maturity, as well as priorities in research and development (R&D) in the domain, when it comes to selecting storage technology for energy systems. This paper proposes a two-step evaluation for selecting suitable energy storage technology for small scale energy systems, as described in the following subsections.

3.1 Step 1: Identify possible technical options

In this step, by looking at technical requirements of the concerned system, possible technical options will be addressed. The technical characteristics of different storage technologies are compiled from available publications, including scientific papers, reports from established organizations. Table 2 summarizes technical and economic features of these technologies.

3.2 Step 2: Address techno-economic aspects

Techno-economic aspects mentioned in this section include methods to identify key driving factors and to illustrate technology maturity curve of the technologies, as well as sources for market forecast. By considering these assessments, a technology with suitable level of maturity or being one of the technology priorities can be chosen from the possible technical options.

3.2.1 Methods for reviewing the energy storage market

This paper applies principles in market dynamics analysis and literature review to address driving factors in the energy storage market. Within the framework of product life cycle, the stages of entry, exit, growth, and innovation of all energy storage types are investigated [23]. By reviewing revolutions in the market of energy storage following this product life cycle, driving factors which are responsible for the entry, exit, innovation, and growth of the storage technologies are identified and divided into four aspects, namely technical, economic, environmental, and regulatory. The review is based on several sources, from journal papers, international reports to economic journals, i.e., [3,4,7,12,24–26]. Additionally, market forecast for energy storage takes into account technology priorities from the past to the present, and projections for the direction of energy storage development in the future from available articles and official reports, in order to describe a general picture of the energy storage market in the next years. Finally, it is noticed that life cycle cost assessment is not included in the scope of this paper.

3.2.2 Methods for constructing the technology maturity curve

Technology maturity curve is depicted by assessing two parameters for each storage technology: technology readiness level (TRL) and stage of market development. The TRLs are a type of measurement system used to assess the maturity level of a particular technology. There are nine TRLs, where TRL 1 is the lowest and TRL 9 is the highest [27]. Based on the description of the levels, the TRL of each storage technology is recognized by investigating different reviews on energy storage technologies where the current state of technology development is marked; in case there are several references, the more recently released one is chosen. At the same time, stages of market development are evaluated according to R&D, demonstration, introduction, growth, and maturity. Similar to the evaluation of the TRLs, a compilation of numerous references is conducted, not only from literature, but also from searching for real applications in the market.

4 Results and discussions

In this section, results are presented, along with discussions.

4.1 Energy storage market review

Identified driving factors that dominate the energy storage market are displayed in Table 3. As can be seen in the table, technical, economic, and regulatory factors play a critical role in shaping the energy storage market. However, environmental concerns have also contributed to transiting the market. Technology priorities in the field of energy storage are indicated in Figure 1 [3,24,28]. According to [26], by 2030, the most attractive business opportunities are on decentralized island/off-grid storage. Other interesting business cases include applications in centralized conventional stabilization and centralized balancing energy, decentralized transmission and distribution deferral and industrial peak, and centralized black-start. Energy storage will be one key technology for the future, and its market volume value is expected to increase dramatically over the next few decades. However, there is a large difference in the predictions from different reports and statements. For instance, a study from [29] reported a projection from US analysts Pike Research that the potential market for energy storage systems could be about 122 billion USD by 2021, of which, they estimated the market potential for molten salt thermal energy storage for 2020 to be at least 1 billion USD.

4.2 Technology maturity curve

Figure 1 illustrates current status of energy storage technologies based on evaluation of their TRLs and stages of market development. The fact that market development for a mature technology declines over time is displayed by the curve. Compare this curve with the report conducted by [30], almost all storage technologies analysed in this paper are ranked similarly; the curve in this paper added solar fuel, micro CAES, micro PHS, PCM, and TCM. Regarding PCM and TCM thermal storages, their levels of maturity presented here are almost identical to that in the work done by [22].

4.3 Discussion for the selection process

The technology maturity curve implies that for small scale electricity systems, lead-acid, micro PHS, NaS battery, NiCd battery, flywheel, NaNiCl battery, Li-ion battery are the most mature technologies, thus implementation of these storages will likely meet with less difficulties, while implementing micro CAES, flow battery, metal air, SCES and SMES may be more complicated, since they are less experienced in the market. On the other hand, hydrogen fuel cells can be chosen as the technology for the near future, while solar fuels can be considered at a later time. With regard to small scale thermal systems, sensible thermal storage is a well proven choice; however, in the next decade, PCM and TCM are expected to become more popular in the market.

5 Conclusions

The review indicates that selection of an energy storage technology for energy systems should be based on not only technical requirements for the systems, but also maturity level of the storage technology level in the energy storage market, priorities in research and implementation, driving factors in the market. To conduct this, the paper proposes a two-step evaluation: identifying possible technical options and addressing techno-economic aspects. Lead-acid, micro PHS, NaS battery, NiCd battery, flywheel, NaNiCl battery, Li-ion battery, and sensible thermal storage are the most mature technologies for small scale energy systems. In the future, hydrogen fuel cells, PCM, and TCM are expected to grow considerably in the energy storage market.

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