Large-Scale Electrical Energy Storage Systems

Shohji Tsushima

Abstract Large-scale electrical energy storage systems with electrochemical batteries offer the promise for better utilization of electricity with load leveling and the massive introduction of renewable energy from solar and wind power. In this chapter, an overview of large-scale energy storage systems is presented, together with the current and future states of electricity demand in Japan. The present status and perspectives of NaS batteries and redox flow batteries are discussed as massive electrical energy storage systems. The technical challenges that remain to further achieving high energy efficiency and cost reduction are also described.

Keywords Energy storage • Redox flow battery • NaS battery • Renewable energy • Electricity supply

1 Introduction

Large-scale electrical energy storage systems [1] have garnered much attention for increasing energy savings. These systems can be used for electricity load leveling and massive introduction of renewable energy sources with intermittent output, which contribute to reduced nuclear power generation and less fossil fuel consumption.

According to perspectives on energy published by the government of Japan [2, 3], targeted values of overall installed capacity for photovoltaic power generation and wind-generated electricity are 33 GW in 2020 and 63 GW in 2030. This corresponds to electricity generation at 39.6 TWh in 2020 and 74.8 TWh in 2030, which are 3.7 and 7.3 % of estimated total electricity demand, respectively. To maintain a stable supply of electricity to the electrical grid, large-scale electricity storage systems that operate together with these renewable sources are needed, because both solar and wind power generation are inherently intermittent.

Electricity demand varies considerably throughout a day or year. Thermal power plants that can be operated at large turndown ratio with swift response are generally

---

S. Tsushima (✉)
Osaka University, Osaka, Japan
e-mail: tsushima@mech.eng.osaka-u.ac.jp

Y. Kato et al. (eds.), *Energy Technology Roadmaps of Japan*,
DOI 10.1007/978-4-431-55951-1_7

used to follow demand. Pumped-storage hydropower plants are also used to satisfy demand by storing off-peak electricity for later use. Response times of these plants are very different.

Massive introduction of solar and wind power for generation of electricity might lead to an unstable electricity supply. In 2014, several electric power companies in Japan announced that they would temporarily halt acceptance of applications for the feed-in-tariff system with solar and wind power generation. Large-scale electricity storage systems can play a central role in this purpose in the coming decade and have been developed worldwide using batteries, compressed air, flywheels, super capacitors, superconducting materials, and others.

Among these, electrochemical battery systems have several advantages, i.e., fast response to charge or discharge electricity in the grid, less limitation on construction location, short installation time, and versatility from large- to small-scale energy storage. However, further improvement in energy efficiency and cost reduction are of primary importance for practical use of these systems.

In this chapter, we focus on sodium–sulfur (NaS) batteries, including sodium ion and redox flow batteries for large-scale (megawatt) electricity storage. We also discuss future perspectives and emerging issues for further R&D.

2 Present Status

2.1 Potential Economic and Environmental Benefits

There are economic and environmental incentives for the introduction of large-scale electricity storage systems. Figure 1 gives a typical electricity demand (generation) profile for a sunny summer day in Japan. Base, intermediate, and peak loads are identified. Base load generation has been primarily by nuclear power plants in Japan but, in 2012, nuclear power plants contributed 1.7 % of

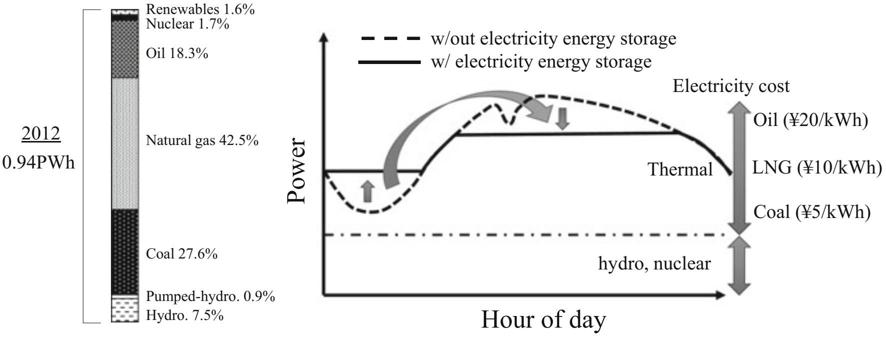


Fig. 1 Electricity supply in 2012 and schematic of typical electricity demand profile for a sunny summer day in Japan

overall electricity supply. Therefore, thermal power plants play a major role in covering the entire demand load [4].

Thermal power plants can be operated using a variety of fossil fuels, oil, liquid natural gas (LNG), and coal. Prices for these fuels vary, so optimal control for operation of these power plants is needed for improved fuel economy. Assuming that electricity prices for oil-fueled, LNG-fueled, and coal-fueled power plants are ¥20/kWh, ¥10/kWh, and ¥5/kWh, respectively, oil-fired power plants should be operated only for peak loads, because of their poor fuel economy.

By introducing large-scale electricity storage systems, we can increase electricity generation by operating low-cost power plants at night instead of high-cost power plants in daytime for peak demand. Differences in electricity cost depending on the type of power plant can generate economic benefits attributable to large-scale electricity storage, although roundtrip efficiency during the storage and supply of electricity is $<100\,\%$.

Under present conditions, pumped-storage hydropower plants are widely used as large-scale electrical energy storage. In Japan, the total capacity of these plants was estimated at ~20 GW [5], and almost 1 % of total electricity supply was provided by the plants in 2012 (Fig. 1).

Regarding environmental impacts, lowering fossil fuel consumption and reductions in CO_2 emissions are feasible by introducing large-scale electrical energy storage. Obviously, systems for such storage aid massive utilization of renewable energy, which suppresses fossil fuel consumption.

All the above factors motivate installation of large-scale battery systems in the grid. However, state-of-the-art battery technologies do not fully satisfy the demands, so further improvement of energy efficiency and cost reduction is needed.

We have seen a wide variety of affordable battery systems for massive energy storage. In a report released by the Japanese Ministry of Economy, Trade and Industry in 2012 [6], the installation cost of battery technologies was compared with pumped-storage hydropower plants as follows: pumped-storage hydropower = ¥23,000/kWh, NaS battery = ¥40,000/kWh, lead–acid battery = ¥50,000/kWh, nickel metal hydride battery = ¥100,000/kWh, and lithium ion battery = ¥200,000/kWh. As addressed later, the redox flow battery (RFB) is also a candidate for large-scale electricity storage. The installation cost of RFBs of all-vanadium type was estimated as the same or slightly higher than that of an NaS battery. Another cost estimation presented in the United States is shown in Table 1 [7, 8].

Adding to initial installation cost, battery life, and economy during operation and maintenance as well as environmental impact upon disposal become important factors that determine the overall life cycle cost of the system. The International Energy Agency estimates 310 GW of additional grid-connected electricity storage capacity needed in 2050 [1]. As a large-scale electricity storage system, the NaS battery has been already commercialized. Two demonstration projects in which renewable energy (solar or wind power) is integrated with battery systems (lithium ion or vanadium RFB) are underway in Japan, to show their feasibility for stable supply of electricity with those renewables.

Table 1 Electrical energy storage characteristics (Adapted from Ref. [7])

Technology option	Maturity	Capacity (MWh)	Power (MW)	Duration (h)	% Efficiency (total cycles)	Total cost ($/kW)	Cost ($/kWh)
Pumped hydro	Mature	5400–14,000	900–1400	6–10	80–82 (>13,000)	1500–2700	250–270
Sodium sulfur	Commercial	300	50	6	75 (4500)	3100–3300	520–550
Advanced lead–acid	Commercial	200	50	4	85–90 (2200)	1700–1900	425–475
Vanadium redox flow	Demonstration	250	50	5	65–75 (>10,000)	3100–3700	620–740
Li-ion	Demonstration	0.25–25	1–100	0.25–1	87–92 (>100,000)	1085–1550	4340–6200

In the following sections, we address two promising candidates, the NaS battery and RFB, as large-scale battery systems.

2.2 *Sodium–Sulfur (NaS) Batteries*

An NaS battery uses beta alumina ceramic for the electrolyte, with sodium and sulfur as active materials for the negative and positive electrodes. NaS batteries typically operate at temperatures ~300 °C to maintain the electrode materials in a molten state. Figure 2 shows a schematic of an NaS battery cell [9]. The working voltage of the battery is 1.78–2.08 V at 350 °C [9, 10]. NGK Insulators, Inc., has commercialized an NaS battery since 2002 and has installed over 450 MW of the system worldwide. Cell performance is dominated by ohmic resistance of the electrolyte plus activation resistance of the positive electrode, both of which are responsible for 90 % of overall resistance in the cell [11]. Energy efficiency of an NaS battery is 75 % [12]. Comparison of energy efficiency among secondary batteries is by no means straightforward, although values are available as shown in Table 1 [7]. A battery system generally requires balance of plants (BOPs), which need supplemental energy input for operation. The operation of BOPs reduces overall energy efficiency of the battery system. Energy conversion efficiency of AC/DC converters should also be considered. Moreover, energy loss from cell operation is greatly affected by the current density of the cell. Energy efficiency of the system varies greatly with them.

Fig. 2 Schematic of NaS battery cell

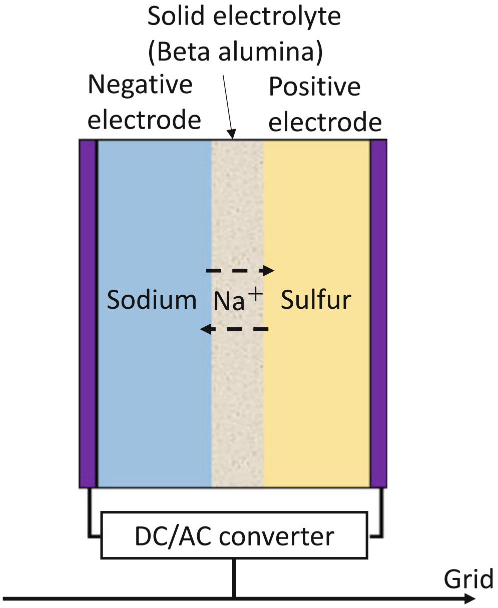
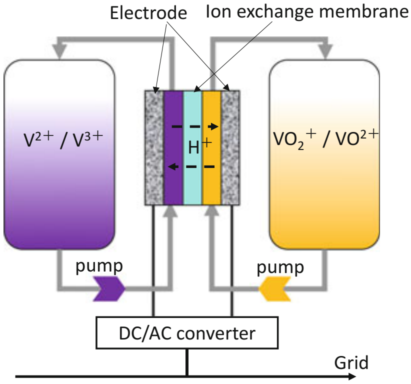


Fig. 3 Schematic of redox flow battery (all-vanadium type)



2.3 *Redox Flow Batteries (RFB)*

RFBs use redox processes of active species in solution that are stored in external tanks (Fig. 3) [13]. They thus provide a unique feature of system scalability, i.e., independent sizing of energy and power, suitable for large-scale applications. A variety of redox pairs have been tested and there have been industrial demonstrations with iron–chromium (Fe^{2+}/Fe^{3+} and Cr^{3+}/Cr^{2+}) or all-vanadium (V^{2+}/V^{3+} and VO^{2+}/VO_2^{+}) systems. An all-vanadium RFB ($E^{eq} = 1.26$ V under normal conditions) shows an advantage, in that the reduction of its capacity caused by crossover of active species across the ion exchange membrane is suppressed. Sumitomo Electric Industries Co. Ltd. has built demonstration plants, such as wind power (30.6 MW), RFB (4 MW × 1.25 h), photovoltaic power (100 kW), and RFB (1 MW × 5 h) [14, 15].

More recently, there has been rapid growth of RFB installation by other companies. A 2009 report by the National Renewable Energy Laboratory [16] gave AC conversion energy efficiency at 72 % and DC conversion efficiency at 80 %.

3 Technology Roadmap

3.1 *NaS Batteries*

An NaS battery using beta alumina ceramic electrolyte has already been commercialized, but still faces challenges of performance and cost for massive market penetration. Further improvement of cell performance would be very effective in achieving these demands, because better cell performance enhances roundtrip efficiency of the battery and reduces stack size, with less cost for materials. Energy loss in an NaS battery is mainly in the ceramic electrolyte and positive electrode. Ionic conductivity of the beta alumina ceramic electrolyte is 0.4 S/cm at 350 °C [17] and can be improved by designing and synthesizing novel ionic conductive materials. Thinning the solid electrolyte is another potential approach to reduce ohmic resistance of the electrolyte, but its mechanical durability should be maintained. Energy loss in the positive electrode can also be reduced. Ohmic and activation polarizations ascribed to the electrode have not been fully explored regarding its structure. The reaction distribution and ionic/electronic transport in the porous electrode under cell operation remain unknown and could be further optimized by modifying electrode structure.

In another type of sodium–beta alumina batteries, the solid-state halide electrode (cathode) is used with metallic sodium (anode) and the ceramic electrolyte. Higher cell potential can be achieved using nickel chloride ($NiCl_2$: $E = 2.58$ V vs. Na at 300 °C) in the cathode [18]. This type of battery has been developed as Zero-Emission Battery Research Activity cells and is operated at high temperature (~300 °C) to maintain favorable ionic conductivity of the sodium–beta alumina membrane.

More recently, low- and/or room-temperature operation of sodium ion batteries has attracted much attention because of advantages such as low-cost and high-capacity energy storage systems. In NaS batteries, molten sulfur, sodium, and the polysulfide compounds are highly corrosive at elevated temperatures ~350 °C, and containers and seals must be resistant under these conditions [19]. Low-temperature operation of the battery could mitigate this concern and simplify the system with fewer BOPs needed, reducing cost. However, electrochemical reaction and ionic conductivity in the cell are inactive and are reduced at low temperatures.

All-solid-state batteries are another choice, providing an opportunity to be free from flammable electrolytes that cause safety concerns. A sodium battery operating at 200 °C using a sodium (Na) superionic conductor [20] as the electrolyte was recently described [21]. The use of superionic glass–ceramic electrolytes was reported for room-temperature sodium batteries [22]. Cell performance and ionic conductivity of the solid electrolyte remain to be improved for practical applications, thereby offering promising opportunities for further research.

In summary, NaS batteries are promising candidates for large-scale electrical energy storage, with further cost reduction and higher energy efficiency. Meanwhile, low- or room-temperature sodium ion batteries face many challenges, from fundamentals to applications. It is necessary to advance R&D for the enforcement of early proof examination regarding the low-temperature sodium ion battery to explore the R&D target and develop strategic roadmaps in the future.

3.2 RFB

For the RFB, all-vanadium and iron–chromium systems lead in industrialization. For greater introduction, improvement of energy efficiency and cost reduction is required. Improvement of battery energy efficiency leads to downsizing the entire system and can reduce cost. To decrease energy loss in RFBs, porous structure in the electrodes and flow patterns in the cell are influential in determining cell performance, and electrochemical activity of the electrode surface is also vital. In recent years, RFB cell performance has been improved by introducing fundamental knowledge and technologies established in proton exchange membrane fuel cells [23, 24]. Systematic research toward the most suitable electrode for RFBs for reducing kinetic and transport loss in the electrode, with less pressure drop in the battery system, should be promoted. Also encouraged is the exploration of electrode materials for enhanced electrochemical activity, with a wide electric potential window free from hydrogen and oxygen evolution under cell operating conditions.

Further cost reduction for the membrane can be expected by introducing a cheaper hydrocarbon system than the conventional fluorine-based electrolyte membrane. It is necessary for the electrolyte membrane to suppress crossover of active redox species between the electrodes. Durability is also a concern for a hydrocarbon membrane implemented in RFBs for long-term operation.

Implementation of the aforementioned approaches can improve energy efficiency, reduce cost, and advance RFBs, with market penetration by 2020 and greater penetration later.

Easy recycling of active species in RFBs is attributed to the unique geometry of the battery system, in which redox species dissolved in liquid electrolyte are stored in external tanks and supplied to the cell. Although material recycling is not a major concern, vanadium electrolyte still represents a third of total capital cost according to the literature [25]. Therefore, a search is necessary regarding a new reaction system. In recent years, a metal-free organic–inorganic aqueous flow battery system has been proposed [26]. New redox systems not only widen the choice of available materials but also improve electrochemical properties beneficial to RFBs with high power and energy densities.

Regarding the above, it is effective to promote concentrated R&D while gathering knowledge. Further, for the promising reaction system, it is necessary to examine systematization at an early stage. Early-stage demonstration tests give profound insights into system performance and durability, which are readily fed back to fundamental research. R&D by laboratories in the fields of systematic screening materials and cell design offer promise to large-scale electrical energy storage systems.

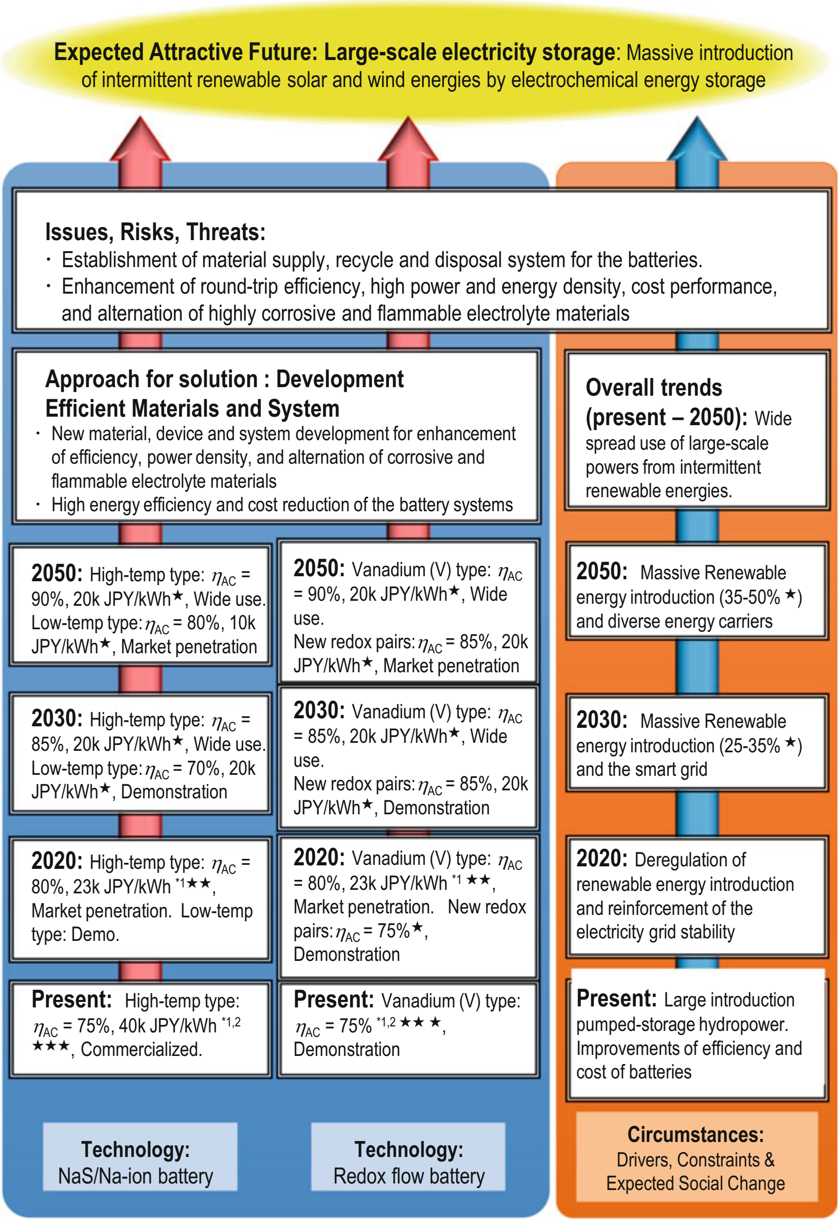
4 Benefits and Future Vision

A large-scale electricity storage system does not produce energy in itself, but is significant in energy conversion and storage for efficient utilization of electricity generated by fossil fuel consumption and/or nuclear energy. Further implementation of renewable energy in society can be ably supported by such storage systems. Moreover, CO_2 emission could be further reduced. If we assume a life cycle CO_2 emission intensity of 738 g-CO_2/kWh for oil-fired power plants and 474 g-CO_2/kWh for LNG-fired, combined-cycle power plants [27], it is much better to use LNG for electricity generation. Although electrical energy storage systems generate some fraction of energy loss during charge and discharge of electricity, e.g., 30 % loss by pumped-storage hydropower plants, shifting oil-fired to LNG-fired power plants with the electrical energy storage will still reduce overall CO_2 emission.

Energy loss associated with energy conversion and storage by large-scale electricity storage is inevitable. However, various energy technologies including the storage systems provide a versatile choice for a sustainable and low-carbon society. Toward this goal of robust mixes of energy technologies, the large-scale batteries such as NaS and RFBs surveyed in this chapter are expected to be key devices. This is because they can mitigate temporal intermittency and spatial inhomogeneity of renewable energy sources, yielding profound benefits for stable supplies of electricity to the grid. We must also discuss which sectors should be responsible for massive introduction of the large-scale electrical energy storage systems, with due consideration of economic benefits and risks.

We recognize that available material resources, electricity demand affected by the future population and national economy activity of Japan, international competitiveness of Japanese manufacturing, system updates, and the establishment of material recycling and disposal with sustainable growth are potential risks to the future diffusion of large-scale batteries in the country. Given this recognition, it is mandatory to promote more R&D.

Government support and initiatives are required for formulation of an electricity rate system that creates economic advantages during the stage when system cost does not decline sufficiently, as well as a stable supply of electric power with introduction of renewable energy in the early period. Such a system should become widespread as a social infrastructure supporting the smart grid by about 2030, and contributions are anticipated regarding risk reduction for future fossil fuels and rare resource acquisition. Furthermore, the energy carrier should diversify by 2050, and large-scale electricity storage will become a social infrastructure indispensable to electric energy supply. Further expectations are of renewable energy introduction and contributions to the realization of a low-carbon society through sustainable energy supply, plus CO_2 emission reduction in the economy from primary energy diversification via massive battery systems (Fig. 4).



Expected Attractive Future: Large-scale electricity storage: Massive introduction of intermittent renewable solar and wind energies by electrochemical energy storage

Issues, Risks, Threats:

- Establishment of material supply, recycle and disposal system for the batteries.
- Enhancement of round-trip efficiency, high power and energy density, cost performance, and alternation of highly corrosive and flammable electrolyte materials

Approach for solution : Development Efficient Materials and System

- New material, device and system development for enhancement of efficiency, power density, and alternation of corrosive and flammable electrolyte materials
- High energy efficiency and cost reduction of the battery systems

2050: High-temp type: η_{AC} = 90%, 20k JPY/kWh★, Wide use. Low-temp type: η_{AC} = 80%, 10k JPY/kWh★, Market penetration

2030: High-temp type: η_{AC} = 85%, 20k JPY/kWh★, Wide use. Low-temp type: η_{AC} = 70%, 20k JPY/kWh★, Demonstration

2020: High-temp type: η_{AC} = 80%, 23k JPY/kWh *1★★, Market penetration. Low-temp type: Demo.

Present: High-temp type: η_{AC} = 75%, 40k JPY/kWh *1,2 ★★★, Commercialized.

Technology: NaS/Na-ion battery

2050: Vanadium (V) type: η_{AC} = 90%, 20k JPY/kWh★, Wide use. New redox pairs: η_{AC} = 85%, 20k JPY/kWh★, Market penetration

2030: Vanadium (V) type: η_{AC} = 85%, 20k JPY/kWh★, Wide use. New redox pairs: η_{AC} = 85%, 20k JPY/kWh★, Demonstration

2020: Vanadium (V) type: η_{AC} = 80%, 23k JPY/kWh *1 ★★, Market penetration. New redox pairs: η_{AC} = 75%★, Demonstration

Present: Vanadium (V) type: η_{AC} = 75% *1,2 ★★ ★, Demonstration

Technology: Redox flow battery

Overall trends (present – 2050): Wide spread use of large-scale powers from intermittent renewable energies.

2050: Massive Renewable energy introduction (35-50% ★) and diverse energy carriers

2030: Massive Renewable energy introduction (25-35% ★) and the smart grid

2020: Deregulation of renewable energy introduction and reinforcement of the electricity grid stability

Present: Large introduction pumped-storage hydropower. Improvements of efficiency and cost of batteries

Circumstances: Drivers, Constraints & Expected Social Change

*1 Ref. [6]
*2 Ref. [7]

Abbreviations:
Demo.: demonstration

Fig. 4 Roadmap for NaS/Na-ion and RF batteries

References

1. International Energy Agency (2014) Technology roadmap: energy storage
2. Ministry of Economy, Trade and Industry in Japan (2009) Long-term energy demand perspectives
3. Agency for Natural Resources and Energy in Japan (2012) Energy supply in 2030 on strategic energy plan
4. Agency for Natural Resources and Energy in Japan (2015) Energy white paper 2014
5. Ministry of Economy, Trade and Industry in Japan (2012) Report on Energy demand and supply
6. Ministry of Economy, Trade and Industry in Japan (2012) Storage battery strategy
7. Electric Power Research Institute (2010) Electric energy storage technology options: a white paper primer on applications, costs, and benefits, 1020676
8. Akhil AA, Huff G, Currier AB, Kaun BC, Rastler DM, Chen SB, Cotter AL, Bradshaw DT, Gauntlett WD (2013) DOE/EPRI 2013 Electricity storage handbook in collaboration with NRECA, Sandia Report SAND2013-5131
9. Oshima T, Kajita M, Okuno A (2005) Development of sodium-sulfur batteries. Int J Appl Ceram Tech 1(3):269–276. doi:10.1111/j.1744-7402.2004.tb00179.x
10. Lu X, Xia G, Lemmon JP, Yang Z (2010) Advanced materials for sodium-beta alumina batteries: status, challenges and perspectives. J Power Sources 195:2431–2442. doi:10.1016/j.jpowsour.2009.11.120
11. NGK Insulators, Ltd (2004) Development of NAS battery cells and modules. NGK Rev 60:10
12. Mizutani T (2009) Innovative technological developments in electricity storage, Hannover messes – World energy dialogue
13. Alotto P, Guarnieri M, Moro F (2014) Redox flow batteries for the storage of renewable energy: a review. Renew Sustain Energy Rev 29:325–335. doi:10.1016/j.rser.2013.08.001
14. Shigematsu T (2011) Redox flow battery for energy storage. SEI Tech Rev 73:4–13
15. Shibata T, Kumamoto T, Nagaoka Y, Kawase K, Yano K (2013) Redox flow batteries for the stable supply of renewable energy. SEI Tech Rev 76:14–22
16. Steward D, Saur G, Penev M, Ramsden T (2009) Lifecycle cost analysis of hydrogen versus other technologies for electrical energy storage, NREL/TP-560-46719
17. NGK Insulators, Ltd (2004) Development of solid electrolyte. NGK Rev 60:4–9
18. Sudworth JL (2001) The sodium/nickel chloride (ZEBRA) battery. J Power Sources 100:149. doi:10.1016/S0378-7753(01)00891-6
19. Ellis BL, Nazar LF (2012) Sodium and sodium-ion energy storage batteries. Curr Opin Solid St M 16:168–177. doi:10.1016/j.cossms.2012.04.002
20. Fergus JW (2012) Ion transport in sodium ion conducting solid electrolytes. Solid State Ion 227:102–112. doi:10.1016/j.ssi.2012.09.019
21. Lalère F, Leriche JB, Courty M, Boulineau S, Viallet V, Masquelier C (2014) An all-solid state NASICON sodium battery operating at 200°C. J Power Sources 247:975–980. doi:10.1016/j.jpowsour.2013.09.051
22. Hayashi A, Noi K, Sakuda A, Tatsumisago M (2012) Superionic glass-ceramic electrolytes for room-temperature rechargeable sodium batteries. Nat Commun 3:856. doi:10.1038/ncomms1843
23. Aaron DS, Liu Q, Tang Z, Grim GM, Papandrew AB, Turhan A, Zawodzinski TA, Mench MM (2012) Dramatic performance gains in vanadium redox flow batteries through modified cell architecture. J Power Sources 206:450–453. doi:10.1016/j.jpowsour.2011.12.026
24. Tsushima S, Kondo F, Sasaki S, Hirai S (2014) Efficient utilization of the electrodes in a redox flow battery by modifying flow field and electrode morphology. Proc 15th Int Heat Transfer Conf. doi:10.1615/IHTC15.ecs.009326, IHTC15-9326
25. Carnegie R, Gotham D, Nderitu D, Preckel PV (2013) Utility scale energy storage systems. State Utility Forecasting Group, Purdue University, West Lafayette

26. Brian H, Marshak MP, Suh C, Er S, Gerhardt MR, Galvin CJ, Chen X, Aspuru-Guzik A, Gordon RG, Aziz MJ (2014) A metal-free organic–inorganic aqueous flow battery. Nature 505:195–198. doi:10.1038/nature12909
27. Imamura E, Nagano K (2010) Evaluation of life cycle CO_2 emissions of power generation technologies: update for state-of-the-art plant, CRIEPI Research Report: Y09027