

Technical and Cost Evaluation on SMES for Electric Power Compensation

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Abstract—RASMES (Research Association of Superconducting Magnetic Energy Storage) in Japan developed a road map of SMES for fluctuating electric power compensation of renewable energy systems. Based on the progress of large superconducting coils, the technical status is already established to develop the several MWh class SMES for frequency control, load fluctuation compensation, and generation fluctuation compensation. With integrated operations of several dispersed SMES systems, it is expected that the 100 MWh class SMES for load fluctuation leveling (peak cut) can be introduced in the period of 2020-30, and the first 1 GWh class SMES for daily load leveling can be installed in the period of 2030-40. From the results of Japanese national projects, experimental device developments and SMES design studies, if the output power of SMES is 100 MW, the target cost of SMES can be evaluated with 2000 USD/kW of the unit cost per output power (the unit cost per kW).

Index Terms—Cost estimation, power compensation, renewable energy, superconducting magnetic energy storage.

I. INTRODUCTION

FROM the view point of CO₂ reduction, renewable energy is very promising as an important energy source in the future electric power system. However, power fluctuations of the renewable energy systems may cause the instability of electric power systems, and restricts the introduction of the renewable energy sources into the power systems. Therefore, in order to compensate the power fluctuations, the development of large scale energy storage systems is also very important in the future electric power system.

IEA (International Energy Agency) is developing future scenarios for CO₂ reduction toward 2050, and remarks the importance of large scale energy storage systems for renewable energy systems. By request of IEA, RASMES (Research Association of Superconducting Magnetic Energy Storage) in Japan investigated the technical status of SMES, and developed a road map of SMES toward 2050. As a collaborative research of RASMES, the authors summarized the concluding results of the road map based on the progress of large superconducting coils and the cost estimation of SMES systems in this paper.

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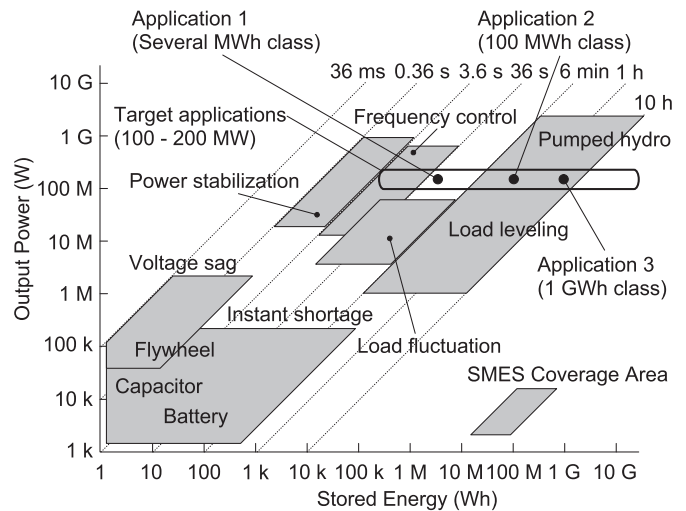


Fig. 1. Target applications of SMES for fluctuating electric power compensation of renewable energy systems. The several MWh class SMES (Application 1) is used for frequency control, load fluctuation compensation, and generation fluctuation compensation with a compensation time of around 1 minute. The 100 MWh class SMES (Application 2) will be applied to load fluctuation leveling (peak cut) with a compensation time of half to 1 hour. The 1 GWh class SMES (Application 3) enables daily load leveling with a compensation time of 5 to 10 hours.

II. APPLICATION AND VALIDITY OF SMES

A. Target Applications of SMES for Power Compensation

Fig. 1 shows the target applications for fluctuating electric power compensation of renewable energy systems. By assuming the unit capacity per SMES system as 100 to 200 MW, three systems are categorized according to the stored energy as follows:

- 1) Several MWh class SMES (Application 1),
- 2) 100 MWh class SMES (Application 2), and
- 3) 1 GWh class SMES (Application 3).

The several MWh class SMES will be used as a frequency controller and a power fluctuation compensator. For instance, a power-spectrum analysis of horizontal wind speed was carried out by Van der Hoven in 1957 [1]. The analysis results were reported that the wind speed fluctuations included two major variations; the relatively long-term fluctuation occurred in a period of 50 to 200 hours (2 to 8 days), and the short-term fluctuation occurred in a period of half to 3 minutes. Therefore, SMES can be applied to power compensation against the short-term fluctuations of the wind power generation. Additionally, due to a lack of the frequency control capability, if the introduction of renewable energy systems is restricted, SMES

TABLE I
OUTLINE OF SMES FOR POWER COMPENSATION.

	Application 1 (Several MWh class)	Application 2 (100 MWh class)	Application 3 (1 GWh class)
Purpose	Frequency control Load fluctuation compensation Generation fluctuation compensation	Load fluctuation leveling (peak cut)	Daily load leveling
Output power	100-200 MW	100-200 MW	100-200 MW
Compensation time	100 seconds	half-1 hour	5-10 hours
Stored energy	3-6 MWh (10-20 GJ)	50-100 MWh (180-720 GJ)	0.5-2 GWh (1.8-7.2 TJ)
Estimation of the required coil numbers for one SMES system. (Assume that half of the total stored energy is available.)			
In a case of assembly with 100 kWh coils	60-120 coils	–	–
In a case of assembly with 1 MWh coils	6-12 coils	100-400 coils	–
In a case of assembly with 10 MWh coils	–	10-40 coils	100-400 coils

can enhance the frequency control capability of the power system instead of governor free operations of hydro power systems and thermal power systems.

On the other hand, the 100 MWh class SMES will be applied to load fluctuation leveling for peak demand with a compensation time of half to 1 hour. In this case, the load leveling over 1 hour will be compensated by output power control of high efficiency thermal power systems and/or demand control.

The 1 GWh class SMES enables daily load leveling. In general, thermal power systems are used for the middle power supply, and generate energy losses during start and stop operations depending on power demands. Additionally, the thermal stress variations caused by the start and stop operations will determine the lifetime of the thermal power systems. Compensating the power demand variations by using SMES, the thermal power systems can provide constant power, which will lead to the improvement of efficiency and the CO₂ reduction.

Table I summarizes the outline of SMES for each application. As a case study, the required number of superconducting coils for one SMES system is also shown in Table I. This number is not the product of SMES coils by 2050.

B. Effective Use of SMES by Exploiting Its Inherent Features

The energy density of SMES is lower than that of the other energy storage system such as battery, double layer capacitor and flywheel [2]. However, the output power density of SMES is about 100 times higher than that of redox flow battery, and about 10 times higher than those of lead acid battery, NaS battery and double layer capacitor [2]. These results mean that SMES can provide large electric power instantaneously.

Fig. 2 shows schematic diagrams of charge/discharge operations of energy storage systems. Battery, pumped hydro storage and CAES (compressed air energy storage) require bias power due to their lifetime problems, and only enables power control during charge or discharge operations. On the other hand, SMES enables rapid-cycling charge/discharge operations. Therefore, SMES is very promising as a power stabilizer for compensating rapid-cycling power fluctuations. Although flywheel can also be applied to a power stabilizer because of its higher output power density, flywheel is not

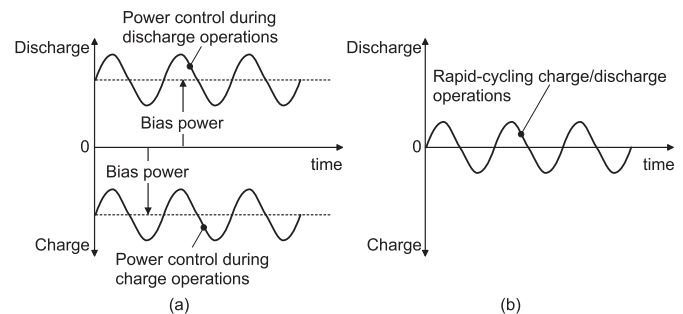


Fig. 2. Schematic diagrams of charge/discharge operations of energy storage systems. Battery, pumped hydro storage and CAES require bias power due to their lifetime problems (a). SMES and flywheel enable rapid-cycling charge/discharge operations (b).

suitable for a long-term high-efficiency storage system due to mechanical losses.

From above features, 100 MWh class SMES (Application 2) can also be used as a frequency controller and a power fluctuation compensator (Application 1). Similarly, the application area of 1 GWh class SMES (Application 3) overlaps those of several MWh class SMES (Application 1) and 100 MWh class SMES (Application 2). Therefore, with integrated operations of several dispersed SMES systems, the stored energy of SMES can be continuously enlarged. These feasible operations are remarkable features of SMES.

Additionally, SMES can be incorporated into customer power systems, meaning that SMES can reinforce the energy security for the customer sites by using the stored energy of large scale SMES. This feasible effect is also a remarkable feature of SMES.

III. ROAD MAP OF SMES

A. Technical Status of Japanese SMES Systems

In recent years, Japan has remarkable results of SMES projects. For instance, a 5 MVA/5 MJ SMES system was developed for lightning protection such as instantaneous voltage dip compensation [3]. From the field test results at a large advanced LCD TV plant in Japan, the effectiveness of the SMES system was verified [4]. As a next step of this work, a 10 MVA/10 MJ SMES system was also developed and tested at the same site.

TABLE II
PROGRESS OF LARGE SUPERCONDUCTING COILS.

Project	Coil shape	Magnetic energy (GJ)	Coil current (kA)	Year of completion	Application
BEBC	Solenoid	0.800	5.700	1972	Particle detector
LCT	Toroid	0.944	10.200-17.760	1985	Fusion
LHD	Helical	0.9	13.0	1997	Fusion
CSMC	Solenoid	0.64	46	2000	Fusion
ATLAS	Toroid	1.08	20.5	2007	Particle detector
CMS	Solenoid	2.6	19.1	2007	Particle detector
LHC	Saddle	8.8	11.850-11.870	2008	Particle accelerator
JT-60SA	Toroid	1.5	25.3	2014	Fusion
ITER-TF	Toroid	41	68	2014	Fusion
ITER-CS	Solenoid	6.000	40.5-45	2015	Fusion

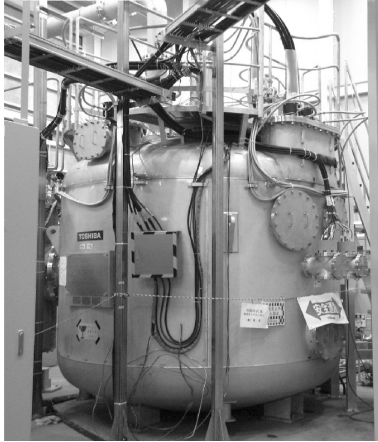


Fig. 3. Photograph of the cryostat for the 10 MVA/20 MJ SMES prototype (Photo by RASMES.).

Furthermore, the New Energy and Industrial Technology Development Organization (NEDO) has also managed R&D programs of SMES as a Japanese national project since 1991. From 2004 to 2007, a 10 MVA/20 MJ SMES prototype for a 100 MW commercial system was developed. Fig. 3 shows a photograph of the cryostat for the 10 MVA/20 MJ SMES prototype. This prototype was tested at an actual power system including hydro power generators in order to compensate the fluctuating power load from a metal rolling factory [5].

B. Progress of Large Superconducting Coils

Table II summarizes the achievement and development plan of large superconducting coils for various applications. Large superconducting coils have been applied to particle detectors for high energy physics and magnetic confined nuclear fusion experimental devices since 1960s.

The big European bubble chamber (BEBC), the ATLAS, and the compact muon solenoid (CMS) were developed for particle detectors. The BEBC has the stored energy of 800 MJ at the central magnetic field of 3.5 T [6]. The large hadron collider (LHC) is a superconducting particle accelerator, and consists of 1232 dipoles ($6.93 \text{ MJ} \times 1232 = 8.5 \text{ GJ}$) and 386 quadrupole magnets ($790 \text{ kJ} \times 386 = 0.3 \text{ GJ}$) [7]. The large barrel toroid of the ATLAS particle detector at the LHC has 1.08 GJ with dimensions of 20.1 m in outer diameter and 25.3 m in axial length, respectively [8]. The solenoid of the CMS detector at the LHC has the largest magnetic energy of 2.6 GJ

with dimensions of 12.5 m in length and 6 m in inner diameter [9], [10].

The large coil task (LCT), the large helical device (LHD) and the central solenoid model coil (CSMC) were developed for magnetic confined nuclear fusion experimental devices. The LCT is an international collaboration under the auspices of IEA among United States, EURATOM, Japan and Switzerland to develop large superconducting toroidal field magnets with a total stored energy of 944 MJ [11]. The LHD is a superconducting heliotron type device, and has large helical coils with the magnetic energy of 0.9 GJ [12]. The CSMC was developed as one of engineering design activities for the international thermonuclear experimental reactor (ITER) project, and was successfully tested by charging up to 13 T and 46 kA with a stored energy of 640 MJ [13].

The JT-60SA (JT-60 super advanced) will be operated as a satellite facility for ITER. The toroidal field (TF) coils for the JT-60SA will have 1.5 GJ magnetic energy with the operating current of 25.3 kA [14]. The ITER magnet system will be assembled by 2015 [15]. The TF coils will have 41 GJ magnetic energy with the conductor current of 68 kA [16]. The CS coils will have 6 GJ magnetic energy with the magnetic field of 13.5 T [13].

C. Large Electric Power Transfer Experiment Using Large Superconducting Coil (An Excitation Test of the CSMC)

As an excitation test of the CSMC, Naka Fusion Research Establishment of Japan Atomic Energy Research Institute (Japan Atomic Energy Agency) successfully tested the large power transfer experiment between the CSMC and the JT-60 flywheel generator (P-MG, 500 MVA-1300 MJ) using the JT-60 vertical field coil power supply. Fig. 4 shows a schematic illustration of the CSMC [13], and the experimental results of the large power transfer test [17].

In the excitation test, 450 MJ of the stored energy was transferred with back-and-forth in 12 seconds as shown in Fig 4-(b). By discharging the 500 MJ rotational energy of flywheel generator, the CSMC was excited up to 450 MJ of the magnetic energy, and the magnetic energy of the CSMC was absorbed into the flywheel generator again. Although the main purpose of this test was development of the superconducting pulsed coil for ITER, this operation is corresponding to a 75 MW class SMES operation.

From the variation of the rotational energy of the flywheel generator, the transfer efficiency was estimated as 87% from

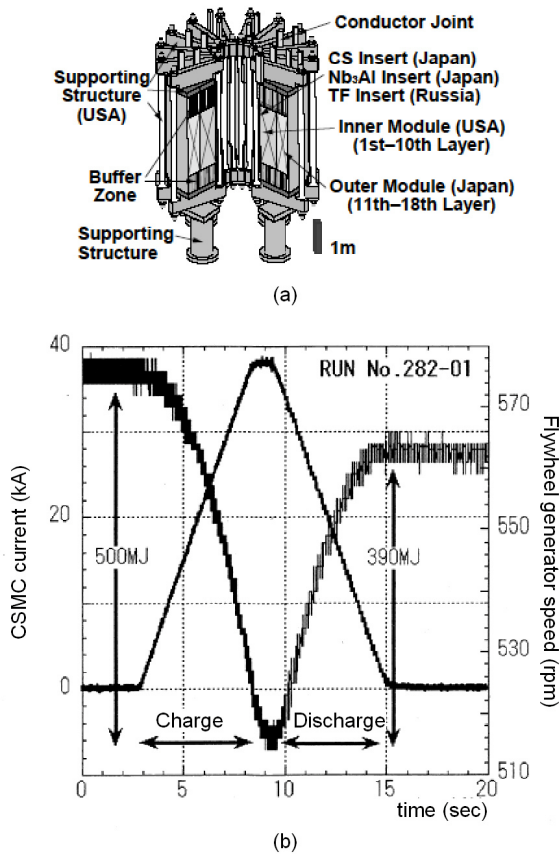


Fig. 4. Schematic illustration of CSMC (Referred from [13].) (a), and the experimental results of the large power transfer test between the CSMC and the JT-60 flywheel generator (Referred from [17].) (b). 450 MJ of the stored energy was transferred with back-and-forth in 12 seconds. (The authors translated the notations of the experimental results from Japanese into English.)

the CSMC to the flywheel generator, and 78% in round trip. From the view point of power applications, these results verify to establish the energy transfer of large electric power using not only flywheel but SMES, and made the higher efficiency of flywheel and SMES clear.

D. Installation Periods of SMES Systems

Fig. 5 summaries the status of large superconducting coils and shows the estimated installation period of SMES systems. At present, the 1 GJ class large superconducting coils have been enough developed in the field of the particle detectors for high energy physics experiments and magnetic confined nuclear fusion. This progress shows that the technical status of the 100 kWh (360 MJ) to 1 MWh (3.6 GJ) class superconducting coils is already established. As shown in Table I, these sizes of superconducting coils can be used for several MWh class SMES systems. Therefore, based on the 10 MVA/20 MJ SMES prototype and the CSMC, it is possible at present to introduce the several MWh class SMES for the application 1: that is for the frequency control, the load fluctuation compensation, and the generation fluctuation compensation.

The ITER magnet system will be constructed by 2015 [15],

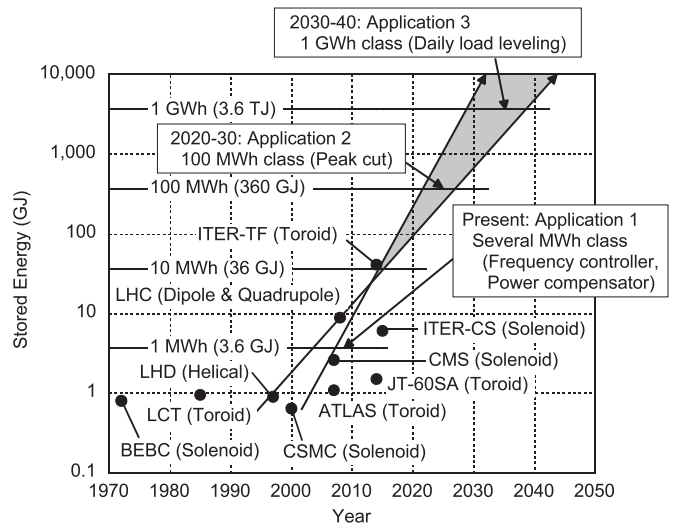


Fig. 5. Road map of SMES based on the achievement and status of large superconducting coils. The darker hatch indicates the estimated installation periods of SMES systems. The outline of SMES system for each application is summarized in Table I.

meaning that the refrigeration and power conversion systems for 10 MWh (36 GJ) class superconducting coils will be also established. Therefore, it is expected that the 100 MWh class SMES for the application 2: that is for load fluctuation leveling (peak cut) can be introduced in the period of 2020-30.

After sufficient experience with the operation of the ITER magnet system has been gained, the development of 100 MWh class SMES for the application 2 will be enough achieved. Therefore, it is expected that the first 1 GWh class SMES for the application 3: that is for daily load leveling can be installed in the period of 2030-40.

IV. COST EVALUATION

A. Target Cost Evaluation

As a Japanese national project from 1999 to 2003, the NEDO estimated target costs of SMES systems for the commercialization, and carried out economical design studies of 100 MW/15 kWh SMES for power system stabilization and 100 MW/500 kWh SMES for load fluctuation compensation and frequency control, including model coil developments [18]. The concluding results of the SMES cost estimation, including capital cost and operating cost for 30 years, were 690 USD/kW in the 100 MW/15 kWh SMES case, and 1970 USD/kW in the 100 MW/500 kWh SMES case.

Fig. 6 summarizes the unit cost per stored energy (the unit cost per kWh) estimated from the results of the prototype SMES systems of the NEDO projects [18], the experimental device developments and the SMES design studies [19]–[22].

Green summarized the actual cost data of particle detector magnets (solenoid type), and introduced the following cost equation [23]:

$$\text{Cost(M\$)} = 0.95 \times [\text{Energy(MJ)}]^{0.67} \tag{1}$$

The actual cost dependence on the stored energy calculated from (1) is also shown in Fig. 6. Since most of detector

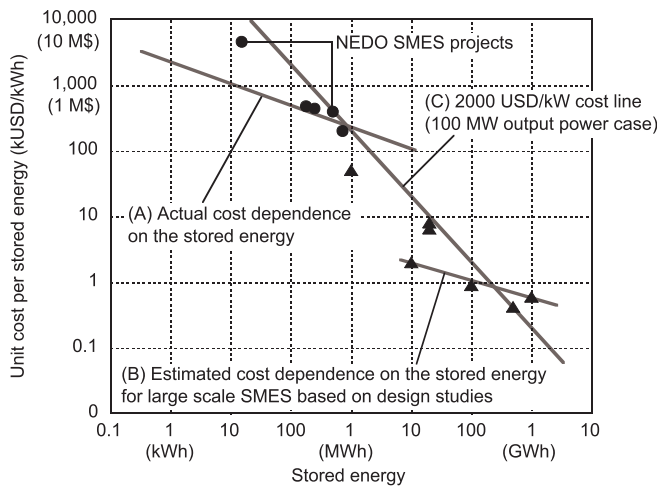


Fig. 6. Cost estimation of SMES as a function of stored energy. The black circles indicate the concluding results of the NEDO projects [18], and the actual cost of the experimental device developments. The black triangles indicate the estimated cost based on the SMES design studies [19]–[22]. The lines (A) and (B) show the unit cost per stored energy (USD/kWh) lines. The line (A) is the actual cost dependence based on the actual coil data of particle detector magnets (solenoid type) given by (1) [23]. The line (B) is the estimated cost dependence based on the results of the SMES design study with toroid configurations [20]. The line (C) shows 2000 USD/kW of the unit cost per output power line in the 100 MW output power case.

magnets were developed for a specific purpose, in the case of SMES use, this cost dependence will be decreased by the effect of mass production.

From the results in Fig. 6, if the output power of SMES is 100 MW, the target cost of SMES can be estimated with 2000 USD/kW of the unit cost per output power (the unit cost per kW). The prospects in the target cost achievement was successfully verified by the field tests of a 10 MVA/20 MJ prototype which is a successive stage of the NEDO project during 2004 to 2007 [5]. However, in the case of large scale SMES, since the cost estimation of more than 1 MWh class SMES is based on the conceptual design studies, the unit cost per stored energy (the unit cost per kWh) should also be evaluated.

B. Case Study for Daily Load Leveling

As a case study, life cycle cost estimation, including capital cost, operating cost and maintenance cost, is compared among pumped hydro storage, NaS battery and SMES. The conditions of the comparative examination are as follows:

- 1) The rated output power is 100 MW (2 MW × 50 units in the NaS battery case),
- 2) The stored energy is 1 GWh (100 MW of the rated output power×10 hours of the compensation time),
- 3) Based on the results in Fig. 6, the unit capital cost per kW is selected as 2000 USD/kW. In the SMES case, 4000 USD/kW of the unit cost is also evaluated.
- 4) Energy cycle efficiency η is defined as

$$\eta = \frac{\text{Stored energy}}{\text{Stored energy} + \text{Average loss}} \times 100(\%). \quad (2)$$

In this estimation, η are considered as 70% in the

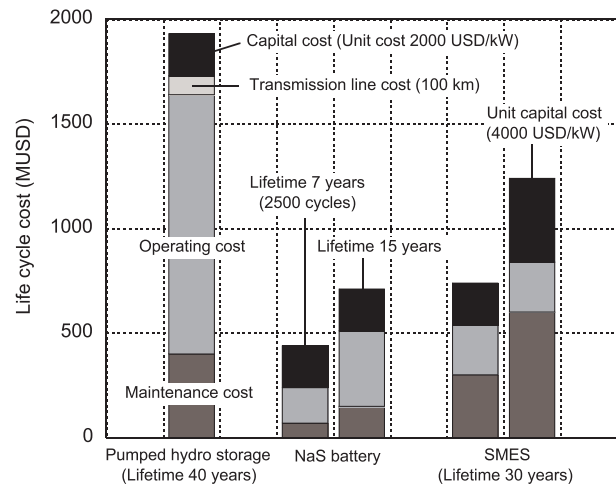


Fig. 7. Comparison of the life cycle cost of energy storage systems for daily load leveling. The stored energy is 1 GWh (100 MW×10 hours). The unit capital cost per kW of each storage system is selected as 2000 USD/kW. In the SMES case, 4000 USD/kW of the unit cost is also evaluated. Pumped hydro storage includes the construction cost for new power transmission lines. NaS battery will additionally require the disposal cost.

pumped hydro storage case, 75% in the NaS battery case, and 90% in the SMES case, respectively.

- 5) After average loss is estimated from (2) and converted into electric price, the operating cost is calculated from the electric price. The unit electric price is selected as 0.2 USD/kWh, which is a typical Japanese electric price. Additionally, it is considered that the charge/discharge operation is one cycle per day.
- 6) The annual maintenance cost is 5% of the capital cost.
- 7) The life cycle cost consists of the capital cost, the operating cost and the maintenance cost. Due to the site limitation problem, the cost of the pumped hydro storage includes the construction cost for new power transmission lines to customer power system. In this examination, the distance of the new transmission line is 100 km, the unit cost for the construction is considered as 9 USD/kW·km.
- 8) Finally, the annual cost of each storage system is compared. The annual cost is defined as the life cycle cost divided by the lifetime. In this examination, the lifetimes are considered as 40 years in the pumped hydro storage, 2500 cycles (almost 7 years) and 15 years in the NaS battery cases, and 30 years in the SMES case.

Based on these conditions, the comparative examination results are summarized in Figs. 7 and 8.

Compared with pumped hydro storage, SMES may lower the operating cost because of higher efficiency, and reduce the annual cost for the same capital cost to 50-60% of that in the pumped hydro storage case. Even when the capital cost of SMES is twice, it may be possible to reduce the annual cost compared with pumped hydro storage. Especially, if long distance transmission lines are required by constructing pumped hydro storage systems, the validity of SMES can be particularly expected. Since CAES also has the problem of site limitation, it can be considered that the cost evaluation of

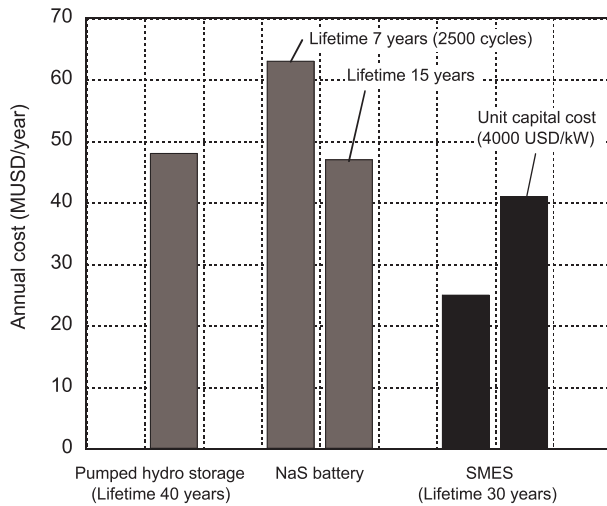


Fig. 8. Comparison of the annual cost of energy storage systems for daily load leveling with the stored energy of 1 GWh. The annual cost is defined as the life cycle cost divided by the lifetime. The life cycle costs are based on Fig. 7. The unit capital cost is considered as 2000 USD/kW. In the SMES case, 4000 USD/kW of the unit cost is also evaluated.

CAES will be almost as that of pumped hydro storage.

On the other hand, since the lifetime of NaS battery is shorter than that of SMES, the annual cost of NaS battery will be twice that of SMES for the same capital cost. Additionally, in the case of NaS battery, the disposal cost will be required. Due to this, the annual cost of SMES will be significantly lower than that of NaS battery even when the capital cost of SMES is twice that of NaS battery.

Although the further investigations concerning the validity of the cost evaluation are required, it can be expected that SMES will be the most feasible option as an energy storage system for daily load leveling.

V. CONCLUSIONS

As a collaborative work of RASMES in Japan, a road map of SMES for electric power compensation was developed. Based on the technical status of large superconducting coils and the results of the SMES cost estimation,

- 1) The technical status is already established to develop the several MWh class SMES for frequency control, load fluctuation compensation, and the generation fluctuation compensation,
- 2) With integrated operations of several dispersed SMES systems, it is expected that the 100 MWh class SMES for load fluctuation leveling (peak cut) can be introduced in the period of 2020-30, and the first 1 GWh class SMES for daily load leveling can be installed in the period of 2030-40,
- 3) If the output power of SMES is 100 MW, the target cost of SMES can be evaluated with 2000 USD/kW of the unit cost per output power (the unit cost per kW).

However, in the case of large scale SMES, since the cost estimation of more than 1 MWh class SMES is based on the conceptual design studies, the unit cost per stored energy (the unit cost per kWh) should also be evaluated. In this case,

the life cycle cost of each energy storage system should be estimated by including its features such as site limitation, efficiency and lifetime.

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