A Techno-economic Analysis on Spinning Reserve Services of Battery Energy Storage Systems for Thermal

Qiangqiang Liao, Peng Zhou, Zhiqin Wang, Youlang Zhang, and Jie Zhang

***Abstract*—Some new battery energy storage techniques are suitable for spinning reserve services for thermal power plants due to their quick response to millisecond time scale adequate to balance instantaneous load fluctuation. Technical and economic performances of three kinds of batteries including lithium ion battery, sodium-sulfur battery and vanadium redox flow battery (VRFB) are discussed as illustrations of standby supply of thermal power plants. As the spinning reserve power sources, they can achieve remarkable economic benefits in the life cycle despite their high power costs and energy costs. The reserve capacity of battery energy storage systems can improve generation rates of thermal power plants, decline gross coal consumption rates, decrease generating cost and the emission of carbon dioxide and pollutants, thus playing a significant role in energy conservation and emission reduction.**

***Index Terms*—Energy storage battery, spinning reserve, techno-economic analysis**

I. Introduction

In view of unexpected inadequacy of power load in an emergency, as a rule each power plant keeps a certain amount of load reserve capacity to increase the output at any time to the rated capacity, aiming to balance the instantaneous load fluctuations and load forecast error. This is part of the spinning reserve, also known as the generation standby. Therefore, the energy storage system as a standby supply for thermal power plants is to reserve a certain load reserve capacity (most of the time, it does not generate electricity and only increases the output in the instantaneous load fluctuations) and have it transferred to the energy storage system, thereby achieving full load power generation to the thermal power plant. Load reserve capacity of a thermal power plant is the configuration in accordance with 2% to 5% of the maximum load of the plant. This portion of the power load is in standby mode, so the thermal power unit cannot run at maximum load. As the energy storage battery has a response speed of milliseconds, the load fluctuations can be quickly balanced at any time. In order to achieve the maximum power operation of thermal power plants, some countries began to configure battery energy storage system (BESS) for thermal power plants. If the reserve capacity of a thermal power plant is left to the energy storage system, the generation capacity of the power plant will be maximized. Corvus Corporation of Canada produced a set of ternary-material lithium-ion BESS with a capacity of 2,200 kWh as a standby supply for a thermal power company in China [1]. With the rapid development of battery energy storage techniques, some new batteries such as lithium-ion battery, sodium-sulfur battery and vanadium redox flow battery (VRFB) have been used as capacity standby supply for a thermal power plant.

The study of the techno-economic and environmental benefits of energy storage system is a hotspot. Xiu *et al.* [2] studied the control strategy of energy storage technology for peak load shaving, and established a mathematical model to evaluate the investment economy of energy storage system. Liu *et al.* [3] proposed a sensitivity pricing method for energy storage and reserve for large-scale wind power systems. Yu *et al.* [4] demonstrated the superiority of installing the energy storage device on the user side in the smart grid system through the economic analysis from the point of reducing the planned power station capacity and reducing the electricity expenses. Sathre *et al.* [5] held that under base-case modeling conditions, second-life battery use in California has the potential to reduce greenhouse gas emissions by about 7 Mt CO_2 per year in 2050. Comparing the production cost of a plant (without energy storage) outlined in a previous model with updated model, Olateju *et al.* [6] found that the added energy storage unit has reduced the hydrogen production cost from \$9.21/kg H_2 to \$9.00/kg H_2. Although there are various energy storage systems in electric power systems, Amrouche *et al.* [7] found that flywheels, batteries and super capacitors can be applied for power quality and short duration needs, but in other applications, it is possible to use batteries, flow batteries, fuel cells or Metal-Air cells. Darcovich *et al*. [8] provided the basis for techno-economic commentary on how to assess large-scale Li-ion batteries for effective electrical storage purposes in micro-cogeneration systems, and the impact of the nature of the control strategy on the battery service life. Belmonte *et al.* [9] argued that the energy storage system based on Li-ion battery is a more mature technology than the hydrogen-based, and its cost is more competitive than that of the hydrogen-based system. Nottrott *et al*. [10] held that it is viable economically if the cost of lithium-ion battery in the demand side application is controlled at \$400-500/kWh. Obara *et al.* [11] held that energy storage technology using the organic hydride system is economically inferior to the sodium-sulfur battery owing to large losses associated with the water electrolyzer and

Manuscript received March 5, 2017; revised August 3, 2017. This work was supported by the Natural Science Foundation of Shanghai (17ZR1411200), Alliance Plan of Shanghai Municipal Promotion Association for Transformation of Scientific and Technological Achievements (LM201658) and Social Science Programs of the Education Ministry (16YJAZH035), China.

Qiangqiang Liao is with Shanghai Key Laboratory of Materials Protection and Advanced Materials in Electric Power, Shanghai University of Electric Power, Shanghai, China (e-mail: 13371895959@163.com).

Peng Zhou is with Shanghai University of Electric Power, Shanghai, China (e-mail: 295028823@qq.com)

Jie Zhang is with State Grid Shanghai Municipal Electric Power Company, Shanghai, China (e-mail: 1012500664@qq.com).

doi: 10.18178/jocet.2018.6.3.466

dehydration reactor. Walawalkar *et al*. [12] argued that the application of sodium sulfur battery energy in New York City energy arbitrage service is profitable. Liao *et al*. [13] held that the discharge price of NAS BESS has an advantage over Shanghai's electricity price in industrial and commercial peak periods when its construction cost descends to 1,000yuan/kWh. Lucas *et al.* [14] presented a model using MATLAB/Simulink, to demonstrate how a VRFB based storage device can provide multi-ancillary services, focusing on frequency regulation and peak-shaving functions showing that the VRFB storage device can regulate frequency effectively due to its fast response time, while still performing peak-shaving services. Baumann *et al.* [15] argued that small scale hydrogen systems and VRFB are far from being cost competitive in energy storage. Ahmadi *et al*. [16] compared lithium-ion BESS with natural gas-powered energy storage systems and found that the former had less greenhouse gas emissions. However, little research has been done on the technical and economic aspects of BESS on the generating side. This paper discusses the economic and environmental benefits of lithium-ion battery, sodium-sulfur battery and VRFB as the capacity standby supply for the thermal power plant.

II. Techno-Economic Analysis of Standby Power Supply for BESS

A. Lithium ion (Li-ion) Batteries

Chile is the early country which put lithium-ion BESS of thermal power plant standby power. A 12MW/4MWh lithium-ion BESS, as a standby supply of thermal power plants or transmission accidents, was installed in the Los Andes Substation in the Atacama Desert in northern Chile in 2009 to maintain grid stability. The system instantaneously provides an output of 12MW for 20 minutes, sparing the system operator more time to solve problems or start other standby supply device. In addition, a 20MW/5MWh high-efficiency lithium-ion BESS was installed in the Angamos thermal power plant (2 × 260MW) on the Pacific coast of northern Chile, and commercially operated in May 2012. The system consists of approximately 1 million lithium-ion battery cells, which are divided into 10 groups; the capacity of each group is 2MW. The energy storage system provides advanced standby capacity so the thermal power plant can generate more than 20MW of electricity at any time during a year. Otherwise, the thermal power plant needs reserve 20MW of spinning reserve capacity for accidental transmission interruption, power generation shutdown, and other accidents that will decrease the power supply capacity. This hybrid system allows the thermal power plant to reduce the necessary spinning reserve capacity, so the thermal power plant can operate at a higher generation rate. The energy storage system increases Angamos power plant capacity by 4%, or 130GWh in electricity production a year [17]. The two energy storage systems whose lithium-ion batteries are supplied by the corporation of A123 Systems are invested by AES Gener, Chile's second-largest power generation company. The corporation of AES Gener will install the third set 20MW/6.3MWh lithium-ion BESS configuration with 532 MW Cochrane thermal power plants in the Mejillones area in northern Chile.

Take the 20MW/5MWh Li-ion BESS of Angamos thermal power plant as an example to analyze the technical and economic value of the energy storage system. As for the investment costs of BESS, prices of the lithium-ion batteries vary widely in various countries and different periods. The wind power-energy storage battery project in West Virginia Laurel Mountain in U.S.A. is a good case to discuss the matter. The price of lithium-ion BESS serves as a platform to measure the benefits brought by using lithium-ion BESS in Chile Angamos thermal power plant. The lithium ion BESS in the Laurel mountain area of West Virginia supplied by A123 Systems too, has a capacity of 32MW/8MWh and an energy storage project budget of $28.8 million [18], equivalent to the power cost of $900/kW, and the energy cost of $3,600/kWh. Lithium-ion battery system capacity of Chilean Angamos thermal power plant is 20MW/5MWh while West Virginia Laurel wind storage project lithium-ion battery system capacity is 32MW/8MWh. The power / energy ratio is 4. The battery capacity is similar and both are from the company of A123 system. The price of lithium-ion battery in Laurel project can be referenced. Therefore the investment cost of 20 MW lithium-ion BESS of Angamos power plant is $\$1.8\times10^7$. The released 20 MW capacities can generate 130GWh per year due to the energy storage system of assuming the duties of spinning reserve capacity [17]. As the Chilean Ministry of Energy reported, the average real-time electricity price in San Diego in the last five years was $0.167/kWh [19], so the income of 130GWh electricity was $\$2.171\times10^7$. Cost-recovering needs 0.83 years for the 20MW lithium-ion BESS as a standby supply of Angamos power plant. That is to say, the economic benefits derived from the additional quantity of electricity every year not only can recover the invested costs of the energy storage system but also have a surplus. Admittedly, the energy storage system has the cost of charging. However, the energy storage system, as a backup power supply, will remain in the full charge state but unused most of the time. It does not discharge until the power grid is unbalanced. Therefore, the charging cost of the energy storage system as a backup function is negligible in comparison with the benefits of the full production of electricity in the power plant. Generally, the service life of lithium-ion BESS is more than 10 years. What is more, the corporation of Samsung SDI gives 20 years of guarantee for its 5MW/5MWh lithium-ion BESS installed in a German renewable energy power utility company named WEMAG AG [20]. Therefore, it is technically and financially feasible that lithium-ion BESS be used as the application of standby power for the thermal power plant. It is an effective approach to improving the generation rate of the thermal power plant.

B. Sodium Sulfur Batteries

In June 2011, Tohoku Electric Power Company of Japan announced the construction of 80MW/500MWh sodium-sulfur BESS configuration with two sets of 600MW power stations in Akita Prefecture in Japan, aiming at improving the power supply capacity. The system consists of forty sets of 2MW sodium sulfur batteries, and the total output power is 80MW, which can serve about 50,000 households for 1 day considering the daily 10kWh electricity consumption per household. We have good grounds to evaluate the construction cost of the sodium-sulfur BESS. It was reported that a sodium sulfur BESS equipped with a 34MW/244.8MWh was finished in Futamata wind power plant in Japan in the year of 2008, whose total construction cost is about 100 billion yen [21]. Power cost of NaS BESS is about $2,941/kW and its energy cost is about $408.5/kWh in the light of 100 yen nearly equivalent to 1 dollar in 2008. Therefore, construction cost of the 80MW sodium-sulfur BESS is 2.35×10^8. Considering annual power generation hours 6,500h for a power plant in general, the power plant per year can offer additional 5.2×10^8 kWh electricity if its reserve capacity of 80 MW devolves upon an 80 MW NAS BESS. Data from Sumitomo commercial survey in 2007 showed that the average price of electricity was $0.1773 per kWh in Tokyo, Japan [22]. So the annual income of additional electricity is 9.22×10^7. As a standby supply, the sodium sulfur BESS requires 2.55 years to recover its construction cost. The sodium-sulfur battery has a long cycle life. For example, cycle life can reach 2,500 times when the depth of discharge (DOD) is 100%, 4,500 times when 90%, 6,500 times when 65%. Basically, 15 years of service life can be guaranteed [23]. Thus, sodium-sulfur BESS also has a high economic value as a reserve supply of generation side.

C. Vanadium Redox Flow Batteries (VRFB)

In 2011, a 32MW coal-fired power plant in Painesville city, Ohio, USA, was equipped with a 1MW/8MWh VRFB energy storage system. The investment of energy storage project is $9,462,623 [24], the power cost is $9,462.6/kW and the energy cost $1,182.8/kWh averagely. In the cost structure, electrolyte accounted for 27%, ion exchange membrane 6%, reactor 9%, converter 9%, processing system 11%, engineering construction 17%, civil engineering and construction 7%, project management 11%, and other items 3% [25]. The system was produced by the Ashlawn energy company and its design life lasts 30 years. The main functions of the energy storage system are load tracking, peak shifting, spinning reserve and so on.

According to a report released by the U.S. Energy Information Center in January 2010, the average price of electricity is $0.13/kWh [26] in the U.S. Assuming that the annual power generation hours are 6,500 h for a power plant, its release of 1MW capacity can provide more power generation 6.5×10^6 kWh annually, the benefit of which is 8.45×10^5. As the reserve supply, the VRFB energy storage system takes 11.2 years to recover its cost. Despite the long investment cycle, it has a long cycle life, basically 30 years. Therefore, VRFB energy storage system, as a standby power supply, also has a high economic value. The technical and economic value of different energy storage systems can be seen from Table I.

TABLE I: TECHNICAL AND ECONOMIC COMPARISION ON THE SPINNING RESERVE SERVICES OF BESS FOR THERMAL POWER PLANTS

Country	Types of battery energy storage systems	Power cost($/kW)	Energy cost ($/kWh)	Service Life (years)	Cost recovery period (years)
Brazil	20MW/5MWh lithium ion battery	900	3600	10	0.83
Japan	80MW/500MWh sodium sulfur battery	2941	408.5	15	2.55
United States	1MW/8MWh VRFB	9462.6	1182.8	30	11.2

III. ENVIRONMENTAL BENEFITS OF STANDBY SUPPLY OF BESS

The increase in power generation rate will reduce coal consumption, power generation costs, carbon dioxide and pollutant emissions from coal-fired power plants. Fig. 1 is the dependence of generated output on coal consumption for a 300MW subcritical thermal power unit, demonstrating that more generated output, less coal consumption. The relationship between the standard coal consumption y and g generated output x is shown as follows:

$$y = 215.54995\, e^{-x/99.5222} + 302.87255 \quad (1)$$

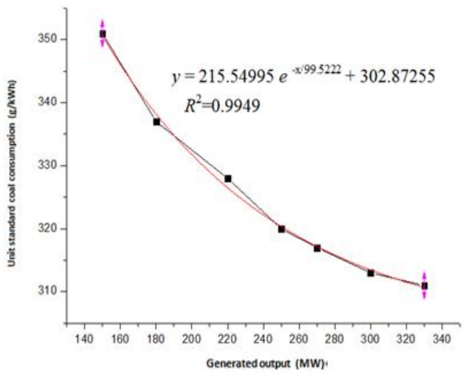

Fig. 1. Dependence of generated output on coal consumption for a 300MW subcritical thermal power unit.

If 2%, 3% and 5% of the installed capacity is set for its reserve capacity in a 300MW subcritical thermal power unit, the generating capacity will be reduced to 294MW, 291MW and 285MW, respectively. However, if the storage battery capacity replaces the corresponding reserve capacity of thermal power plants, the 300 MW thermal power unit can generate electricity at full capacity. According to Formula (1), the coal consumption for power generation is calculated to amount to 314.11g/kWh, 314.45g/kWh and 315.17g/kWh respectively when generating capacity is 294MW, 291MW and 285MW respectively, increasing by 0.66g/kWh, 1.00g/kWh and 1.72g/kWh respectively in comparison with coal consumption at 300MW (313.45g/kWh). Assuming that the 300MW power unit has the annual power generation hours of 6,500 h, the annual electricity production is 1.91×10^9kWh, 1.89×10^9kWh, 1.85×10^9kWh respectively when the generating capacity is 294MW, 291MW and 285MW respectively. The amount of standard coal saved annually is 1,260.6 tons, 1,890 tons, 3,182 tons respectively when the generating capacity from 294MW, 291MW, 285MW increases to 300MW owing to the standby supply of BESS. The calculation of gas emissions is based on the burning of per ton of standard coal with the emission of 2.6 tons of carbon dioxide, 0.024 tons of sulfur dioxide and 0.007 tons of nitrogen oxide. So the annual amount of energy conservation and emission reduction for a 300 MW units is shown in Table II. As is shown in Table II, the thermal power unit not only saves energy but also significantly reduces the emissions of carbon dioxide and pollutants after equipped with the standby supply of BESS.

TABLE II: THE ANNUAL AMOUNT OF ENERGY CONSERVATION AND EMISSION REDUCTION FOR A 300 MW SUBCRITICAL THERMAL POWER UNIT AFTER THE SPINNING RESERVE SERVICES OF BESS

Battery capacity (MW)	Saving standard coal (tons)	CO_2 emission reduction (tons)	SO_2 emission reduction (tons)	NO_X emission reduction (tons)
6	1260.6	3277.6	30.25	8.82
9	1890.0	4914.0	45.36	13.23
15	3182.0	8273.2	76.37	22.27

IV. CONCLUSIONS

(1) The case analysis shows that lithium ion batteries, sodium sulfur batteries, VRFB, as a standby supply of thermal power plants can obtain good economic benefits during their life cycle.

(2) The reserve capacity of BESS can help improve the power generation rate of thermal power plants, reduce the coal consumption of power generation, the cost of power generation, the emissions of carbon dioxide and pollutants.

ACKNOWLEDGMENT

The work was sponsored by the Natural Science Foundation of Shanghai (17ZR1411200), Alliance Plan of Shanghai Municipal Promotion Association for Transformation of Scientific and Technological Achievements (LM201658) and Social Science Programs of the Education Ministry (16YJAZH035), China.

REFERENCES

[1] Z. W. Tan, "Large-scale lithium battery is more to force (in Chinese)," *China Energy News*, February 28, 2011.

[2] X. L. Xiu, J. L. Li, and D. Hui, "Capacity configuration and economic evaluation of energy storage system used in peak load and valley load of power grid (in Chinese)," *Electric Power Construction*, vol. 34, no. 2, pp. 1-5, 2013.

[3] K. Liu, K. Zhang, and J. Zhong *et al*. "Economic evaluation of wind storage system based on price sensitivity analysis (in Chinese)," *Automation of Electric Power Systems*, vol. 37, no. 1, pp. 143-148, 2013.

[4] S. D. Yu, Y. F. Hua, and Z. Y. Hu, "Economic analysis of user-side energy storage device in smart grid system (in Chinese)," *Automation*, vol. 35, no. 2, pp. 62-64, 2013.

[5] R. Sathre, C. D. Scown, and O. Kavvada, "Energy and climate effects of second-life use of electric vehicle batteries in California through 2050," *Journal of Power Sources*, vol. 288, pp. 82-91, 2015.

[6] B. Olateju, A. Kumar, and M. Secanell, "A techno-economic assessment of large scale wind-hydrogen production with energy storage in Western Canada," *International Journal of Hydrogen Energy*, vol. 41, no. 21, pp. 8755-8776, 2016.

[7] S. O. Amrouche, D. Rekioua, T. Rekioua, and S. Bacha, "Overview of energy storage in renewable energy systems," *International Journal of Hydrogen Energy*, vol. 41, no. 45, pp. 20914-20927, 2016.

[8] K. Darcovich, B. Kenney, and D. D. MacNeil, "Control strategies and cycling demands for Li-ion storage batteries in residential micro-cogeneration systems," *Applied Energy*, vol. 141, pp. 32–41, 2015.

[9] N. Belmonte, V. Girgenti, and P. Florian, "A comparison of energy storage from renewable sources through batteries and fuel cells: A case study in Turin, Italy," *International Journal of Hydrogen Energy*, vol. 41, no. 46, pp. 21427-21438, 2016.

[10] A. Nottrott, J. Kleissl, and B. Washom, "Energy dispatch schedule optimization and cost benefit analysis for grid-connected, photovoltaic-battery storage systems," *Renewable Energy*, vol. 55, no. 7, pp. 230-240, 2013

[11] S. Obara, Y. Morizane, and J. Morel, "Economic efficiency of a renewable energy independent microgrid with energy storage by a sodium sulfur battery or organic chemical hydride," *International Journal of Hydrogen Energy*, vol. 38, no. 21, pp. 8888-8902, 2013.

[12] R. Walawalkar, J. Apt, and R. Mancini, "Economics of electric energy storage for energy arbitrage and regulation in New York," *Energy Policy*, vol. 35, no. 4, pp. 2558-2568, 2007.

[13] Q. Q. Liao, B. Sun, and Y. Liu *et al*, "A techno-economic analysis on NaS battery energy storage system supporting peak shaving," *International Journal of Energy Research*, vol. 40, pp. 241–247, 2016.

[14] A. Lucas and S. Chondrogiannis, "Smart grid energy storage controller for frequency regulation and peak shaving, using a vanadium redox flow battery," *International Journal of Electrical Power and Energy Systems*, vol. 80, pp. 26–36, 2016.

[15] L. Baumann and E. Boggasch, "Experimental assessment of hydrogen systems and vanadium-redox-flow-batteries for increasing the self-consumption of photovoltaic energy in buildings," *International Journal of Hydrogen Energy*, vol. 41, no. 2, pp. 740-751, 2016.

[16] L. Ahmadi, M. Fowler, and S. B. Young, "Energy efficiency of Li-ion battery packs re-used in stationary power applications," *Sustainable Energy Technologies and Assessments*, vol. 8, pp. 9–17, 2014.

[17] R. Peltier. (May 2013). 2012 plant of the year: AES coal-hybrid plant in Chile. [Online]. Available: www.powermag.com

[18] The world's largest lithium battery wind energy storage projects in the United States put into operation (in Chinese). (October 2011). Gao gong lithium grid. [Online]. Available: http://www.gg-lb.com/asdisp2-65b095fb-6108-.html

[19] Chilean capital Santiago in the past five years the average price of 167 US dollars per megawatt (in Chinese). (November 2012). Xin shi newspaper. [Online]. Available: http://www.mofcom.gov.cn/aarticle/i/jyjl/l/201211/20121108417644.html

[20] German photovoltaic energy storage subsidies came into effect, Younicos plans to develop 5MW commercial power station. Solar zoom (in Chinese). (May 2013). [Online]. Available: http://www.solarzoom.com/article-28426-1.html

[21] The Agency for Natural Resources and Energy (in Japanese). (February 2009). Current status and efforts of storage battery technology. [Online]. Available: http://www.docin.com/p-215273021.html

[22] H. Y. Yu. (December 2008). International pricing basis: clothing meters card (in Chinese). [Online]. Available: http://blog.sciencenet.cn/home.php?mod=space&uid=2037&do=blog&id=50505

[23] CEC Energy Storage Workshop. (February 2005). Overview of NAS Battery for Load Management. [Online]. Available: http://www.energy.ca.gov/research/notices/2005-02-24_workshop/11%20Mears-NAS%20Battery%20Feb05.pdf

[24] Electricity Advisory Committee. (May 2011). Energy Storage Activities in the United States Electricity Grid. [Online]. Available: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/FINAL_DOE_Report-Storage_Activities_5-1-11.pdf

[25] J. Startari. (March 2011). Painesville Municipal Electric Power Vanadium Redox Battery Demonstration Project. [Online]. Available: http://www.sandia.gov/ess/docs/pr_conferences/2011/3_Startari_Painesville_Vanadium_Redox_battery.pdf

[26] Most of the electric elasticity reflect the humanistic care (in Chinese). (November 2011). *Nanjing Daily.* [Online]. Available: http://finance.jrj.com.cn/industry/2011/11/26145211655742.shtml

Qiangqiang Liao was born in Jiangxi, China in October 1971. He is now a professor in the field of battery energy storage techniques in Shanghai University of Electric Power in Shanghai, China.

His current research focuses on the inter relationship between battery energy storage techniques and smart grid. He has taken over several projects financed by government grants for battery energy storage technologies and achieved significant achievements.

Prof. Liao has owned a couple of Shanghai science and technology progress awards.

Peng Zhou was born in Hubei, China on Sept. 15, 1993. He is now a postgraduate student majoring in environmental chemical engineering with Shanghai University of Electric Power in Shanghai, China. His current research focuses on electric energy storage applications and technologies.