Vanadium Flow Battery Technology

Dalian Rongke Power Co., Ltd.

Assessment Report

Beijing Energy Club
北京国际能源专家俱乐部

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Assessment of Vanadium Flow Battery Technology of Dalian Rongke Power Co., Ltd.

Beijing Energy Club[1]

In the afternoon of April 23rd, 2016, Beijing Energy Club (BEC) launched the Clean Energy Technology Assessment & Dissemination (TAD) platform. Its first project was an in-depth evaluation on the vanadium flow battery (VFB) technology of Dalian Rongke Power Co. Ltd. (Rongke Power).

Founded in 2008 and with 168 employees, Rongke Power is a world leader in providing VFB solutions and one of the enterprises capable of full-value chain technical services in this field. Its core R&D team, Dalian Institute of Chemical Physics of Chinese Academy of Sciences, started research on flow battery technology early in 2000. The Company established an industrialization platform in 2010 and successfully carried out several demonstration projects of commercial application. It owns complete independent IPR in core technologies including key battery materials, cell stack, complete equipment system and energy storage solutions.

Experts participating in the evaluation included:

- Dr. Gary Zhenguo Yang, Advisor to the Grid Energy Storage Program of U.S. Department of Energy and former Chief Scientist of the Energy Storage Program of Pacific Northwest National Laboratory;
- Mr. Lai Xiaokang, President, Institute of Electrotechnics and New Materials of China Electric Power Research Institute;
- Mr. Ying Guangwei, General Manager of Nanjing Automation Co., Ltd. and former President of Huadian Electric Power Research Institute;
- Mr. Zhang Qiping, Chief Engineer of State Grid Corporation of China;
- Mr. Li Junfeng, Director of National Center for Climate Change Strategy and International Cooperation (NCSC); and
- Dr. Zhai Yongping, Technical Advisor, Energy, Asian Development Bank.

Mr. Shi Dinghuan, former Secretary-General of the Ministry of Science and Technology, Counselor of the State Council and Vice Chairman of the BEC attended the meeting and offered comments.

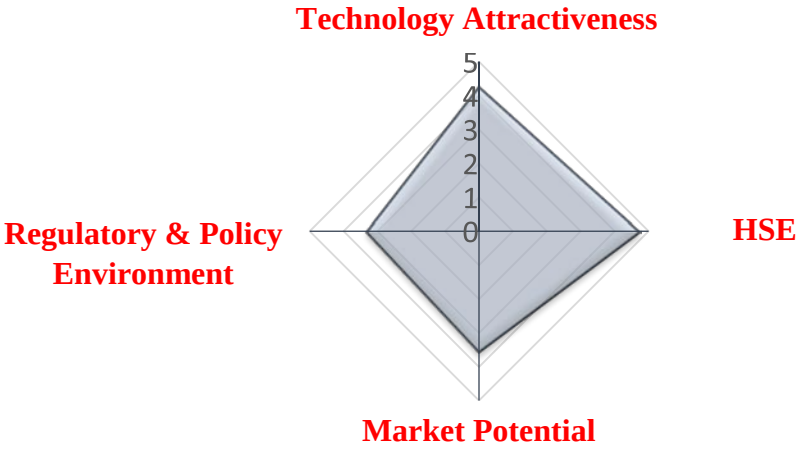
The TAD session started with a presentation by Dr. Zhang Huamin, Vice President and Chief Engineer of Rongke Power on the Company's independently developed VFB technology. This was followed by a briefing by Mr. Wang Zhiming, Vice President of State Grid's Liaoning Electric Power Supply Co., Ltd. on the application of the technology in the local power grid. Afterwards, there were intensive discussions among the experts.

[1] Disclaimer: This Report contains the assessment and analysis made at BEC's TAD session organized by BEC at the request of Dalian Rongke Power Co. Ltd. and shall serve as the reference exclusively for Rongke Power. BEC shall not be held responsible for any risks, losses, damages, costs or expenditures, claims, and/or any other rights of claim that may arise from any investment or other business decisions made by any business organizations or individuals in accordance with the conclusional comments contained in this Introduction.

I. Comprehensive Assessment

The panel of six experts made the evaluation from four dimensions using the Clean Energy Technology Assessment System developed by BEC. These four dimensions are technology attractiveness, market potential, regulatory and policy environment, and health, safety and environment (HSE).

The VFB technology received the scores of 4.26 (out of 5) in terms of technology attractiveness, of 3.53 in terms of market potential, of 3.30 in terms of regulatory and policy environment and of 4.71 in terms of HSE, as shown below.



II. Technology Attractiveness

Evaluation in terms of technology attractiveness of the VFB technology was made from a number of factors, including technology maturity, innovativeness (IPRs and patents), sophistication, as well as strength and weakness compared with similar or alternative technologies. The experts scored 19.6 on average (the full score is 23), equivalent to 4.26 on a 5-point basis.

Technology Maturity

Rongke Power has realized commercial production and carried out more than 30 projects. Its annual capacity is 50MW and will increase to 300MW after its Energy Storage Equipment Industrialization Base is put into operation at the end of 2016. By the end of 2015, the installed capacity of its VFB system reached 12.5MW, with another 1.2MW under construction. Its products are exported to developed countries/regions including the U.S., Europe and Japan. Successful applications include the vanadium flow battery energy storage system in Shenyang Faku Woniushi Wind Power Plant (5MW/10MWh) (the largest in the world as of completion), the MW-grade system in Washington, U.S. (1MW/3.2MWh) (the largest in North America) and the MW-grade system in northern Hamburg (250kW/1MWh) (the largest in Europe). Rongke has capacity across the value chain, a 90% share in the international electrolyte market, and high recognition in application markets (renewable energy grid-connection, peak shaving and microgrid).

Patent

As of March 2016, Rongke had applied for over 140 national patents, including 13 international patents, of which more than 70 were granted. It has formed its independent IPR system covering the entire value chain including battery materials, cell stack, cell system integration and control as well as engineering application.

Rongke Power's VFB technology won numerous awards: 2014 Chinese Academy of Sciences (CAS) Award for Excellent Achievements, the 2015 National Second Award for Technology Invention, one of the Twenty Major Advancements of CAS during the 12th Five-year Plan Period (2011-2015), and the 2015 Award for Indigenous Technology of China. Rongke plays a leading role in formulating the standards for flow battery in China. Thanks to its efforts, two national and three industrial standards in this regard have been promulgated. It also actively takes part in formulation of European standards and leads of the task force of International Electrotechnical Commission.

Comprehensive Sophistication

Compared with other energy storage technologies, VFB provides strong and long-lasting power and applies to fixed large-capacity storage system. It has the following advantages:

- **High safety:** The active materials in the battery are vanadium ions in dilute sulphuric acid solution. The battery works under normal temperature and pressure, featuring simply heat management and freedom from explosion or inflammation.
- **Long cycle life:** High cell consistency allows deep discharge. Energy is stored in the electrolyte solution rather than in the electrodes, theoretically allowing infinite charge/discharge. Capacity attenuation can be restored online or offline.
- **High full-lifecycle cost efficiency:** About 30%~50% of electrolyte solutions can be recycled (depending on duration of storage).
- **Instant and effective charge/discharge:** High-current instant and deep charge/ discharge with high-current, charge/discharge switch within 0.02 second.
- **Power and capacity can be separately designed.** The power level depends on the attribute of cell stack, and the energy on the volume of electrolyte solution. The energy volume ranges from hundreds of kWh to hundreds of MWh, and capacity from hundreds of kW to hundreds of MW, especially suitable for large-scale energy storage.
- **Full-lifecycle environment friendliness:** The electrolyte solution is recyclable and renewable. Vanadium and other materials are abundant and easily processed and can be easily recycled. The technology is an important trend for vanadium utilization. Discarded cells can be easily recycled and disposed of, without pollution to the environment.

Rongke Power has made the following breakthroughs after 15 years' intensive development on all of the above:

- **Mass production of high-performance electrolyte solution:** Rongke developed highly-stable, highly-reactive multi-valence state vanadium ion electrolyte stabilization technology and electrolyte online restoration technology, which solve

the bottleneck of capacity attenuation caused by long-term operation and allow its annual production of 150 MWh electrolyte solution. In recent years, it supplied over 100 MWh electrolyte solution and takes over 90% of the market shares.

- **Manufacture of high-performance carbon-fiber compound dual-electrode:** Rongke developed carbon-fiber compound dual-electrode featuring high toughness and conductance and fitting large power cell stack, which costs 1/40 of graphite dual-electrode and is free of pollutants other than CO_2 after combustion.
- **Design and manufacture of high-performance non-fluorine ion conducting membrane:** Rongke first proposed the ion-screen conducting mechanism to take place of the ion-exchange conducting mechanism, and developed highly alternative, conductive and low cost, environment-friendly non-fluorine ion conducting membrane, which improved the efficiency of vanadium cells. For this, Rongke has been granted more than 50 national and 6 international patents and is spoken highly of in the world.
- **Standardized and modularized cell technology:** Rongke developed 250kW, 125kW, 60kW and 30kW "ALL-IN-ONE" containerized and semi-containerized cells which can be applied both separately and assembled (serial and parallel) to satisfy customer needs for various power and capacity, and support plug-in operation and online remote monitoring.
- **Excellent durability:** The accelerated life test in 2007 showed that the flow battery recorded continuous normal operation for 1,678 days or over 40,000 hours during which it reported 12,420 effective charge/discharge. When the test was ended because of building dismantling, the detected capacity deterioration was as low as 5%. The consumed capacity can be restored technically.

Compared with other batteries, VFBs are large in size and low in storage density due to the solubility of vanadium ions, enabling application in large-scale fixed energy storage systems instead of power supplies. In addition, the auxiliary components such as pipe, pump, valve and heat exchanger imply complex storage system.

The experts concluded that the VFB technology of Rongke Power leads the chemical energy storage field both home and abroad and, together with its complete independent IPR system and full-value chain pattern, it will secure Rongke's leading position in the coming few years.

III. Market Potential

The evaluation was made from factors including market size, market growth rate and economics. The experts scored 10.6 on average (the full score is 15), equivalent to 3.53 on a 5-point basis. It should be noted that during the discussions the experts mainly focused on the domestic market where there has been no clear policy in place to support the application of energy storage in electric power system, therefore the score may not fully reflect the real market growth potential within and out China.

Target Market

The application of VFB is described in detail in the Introduction Report. This Report attempts to describe the potential of target market based on expert conclusions.

VFB technology expects brilliant future in electric power system:

First, ESSs in wind or solar farms sharply reduce wind and PV curtailment during the generation scheme if its capacity equals to 8%-10% of the installed capacity. If allocated at 6% of total installed capacity as frequency—regulating facility to meet the national standard for regular turbine power generation units, it will be easy to alleviate the technical bottleneck constraining the grid connection of renewables.

Second, ESSs installed in substations, with a capacity equaling to 8%-10% of the transformer capacity (i.e. daily average load of the receiving end), will provide 6% frequency-regulating power and 10% peak power, for better economics and higher efficiency of power generator, transmitter and transformer.

Pursuant to the objectives set forth in the 13th Five-year Plan, the installed capacity of wind power will reach 250 GW and that of PV 150 GW, totaling 400 GW as of 2020. Therefore, 8-10% of that will be 32-40 GW, implying a market potential of RMB320-400 billion if the cost is RMB10,000/kW. The capacity of the receiving end (8-10% for daily means) will be even larger because the reference will be the power demand of large cities (e.g. the daily demand is 11 GW in Beijing) instead of power generated by renewable energy. However, research should be made on the economics of the huge-scale energy storage, and it is impossible for flow battery to take 100% share of the market.

Moreover, VFB sees massive opportunities in microgrid, smart grid, distributed wind-PV-storage integrated projects, user-end demand response, alternative power for diesel engine, power supply in remote areas, charging station for electric vehicles and backup power for communication equipment.

The statistics made by China Energy Storage Alliance (CNESA) indicates that a total of 118 energy storage projects (excluding pumped storage, heat storage and compressed air storage) had been carried out in China as of the end of 2015, with the cumulative installed capacity of 105.5MW, accounting for 11% of the world's total. CNESA prediction implies that, as of 2020, the figure (excluding pumped storage and heat storage) will be 14.5GW (conventional prediction based on historical growth, project planning of enterprises and the renewable energy objectives in the 13th Five-year Plan), or even 24.2GW (perfect prediction based on possible supporting policies, the development of energy Internet and restructuring of the electric power system).

International research institutions also made predictions about the market prospect of energy storage technology. McKinsey & Co. says the technology will contribute USD 1 trillion to world economy as of 2025. International consulting firms Piper Jaffrey and Boston Consulting believe the market capacity will be USD 400-600 billion as of 2020. Pike Research says flow battery will take 1/3 of power storage market by 2021.

Although the experts could not give accurate prediction on the market size of Rongke Power, they did expect brilliant market prospect.

Market Growth

The experts said it was hard to give accurate estimation on the growth of the domestic market because the market and the industry were expecting government policies. The market development will be impacted by the timing of the promulgation of policies and the content of policies. Regardless of the uncertainties, the experts agreed that the market growth would be fast or very fast. One of them believed that it would be optimistic and step-by-step growth. The experts did not discuss the international market situation, though Europe, USA, Australia and India are experiencing rapid growth.

Techno-economics

It was unanimously agreed that Rongke Power presented a new and expensive technology, but the dropping down cost allowed strong competitiveness against international rivals.

The experts believed that the technology was new and expensive. However, with the technological progress, the cost of Rongke Power's vanadium flow battery would be sharply reduced and Rongke had strong competitiveness against international rivals. With large-scale industrialized production of vanadium battery and application of its independently developed ion conducting membrane, the cost will drop to RMB2500/kWh by 2020. In addition, the electrolyte solutions, the cost of which accounts for 30-50% of the total of the battery are renewable and recyclable, thus it is possible to further cut down customers' investment cost through financial instruments such as energy management contract and financial leasing.

Pumped storage remains the most economical large-scale energy storage technology. Of available chemical storage technologies, lead acid storage battery made in China is the sole alternative to pumped storage, but is known to be of short life span and high cost per kWh. Compared with pumped storage, all of the new technologies, including flow battery, face a gap of cost per kWh which will be narrowed along with technological progress and mass production.

IV. Regulatory & Policy Environment

The evaluation was made from factors including industry policy support and market development status for the home market. The experts scored 6.6 on average (the full score is 10), equivalent to 3.30 on a 5-point basis.

The importance of energy storage has been elevated to the level of national strategy, while there are no specific incentives available yet. The *Opinions on Further Deepening the Restructuring of Electric Power System* dated March 2015 requires that efforts be made to actively develop microgrid and smart grid technologies integrated with advanced energy storage technology and information technology and improve system consumption and energy utilization efficiency. But the fact is that neither charge/discharge nor auxiliary service nor frequency regulation has fixed price, indicating that there is no pertinent policy in place in the open market.

On March 18, 2016, the *Circular of National Energy Administration on Supporting Peak Shaving in North, Northeast and Northwest China by Power Storage Technology* brings energy storage technology to a defined market – peak shaving support. The Circular sets forth a minimum 10MW/4hours access bar for the storage facilities at the generation side. There is no limit for the consumption side.

As to the application of storage technology, absorbing and improving the grid connection of renewables are key areas, while the core issue is how to promote wide deployment of the technology. The experts believed that, although its importance had been stressed in many documents, storage technology would remain a technical reserve to be demonstrated during the 13th Five-year Plan period. There is yet no sign of large-scale industrialization and commercial dissemination.

V. Health, Safety and Environment (HSE)

HSE evaluation focuses on identification and evaluation of possible health, safety and environment risks of technology in production and application scenarios. The experts scored 13.2 on average (the full score is 14), equivalent to 4.71 on a 5-point basis.

The experts agreed that the VFB of Rongke Power was resource-efficient, environment-friendly, safe, reliable, and free of potential hazards to human health and safety. The battery is quite safe from the aspect of environmental safety and impact. The active materials are vanadium ions in dilute sulphuric acid solution, free from explosion or inflammation or uncontrollable chemical reaction. Vanadium is recyclable metal with nice residual value. The well-developed anti-leakage technology prevents the dilute sulphuric acid solution from leaking. The electrolyte solution can be restored online or offline for recycled use. The electrodes are made of carbon-fiber compound materials (carbon or graphite felt), thus the scrap can serve as fuel, leaving no pollutants but CO_2.

Nevertheless, the electrolyte solution is currently classified as a dangerous chemical substance subject to escorted storage and operation. In addition, a working VFB releases small amount ofhydrogen, thus requiring good ventilation and hydrogen monitoring. In cold areas, the electrolyte solution should be heated for better performance.

VI. Outlook and Risks

Improvement of VFB should focus on cost reduction through increasing energy density by higher electrolyte density and breakthrough in conducting membrane technology.

The experts highly commended the international leadership of Rongke Power's VFB technology and pointed out improvement potentials, including higher efficiency of the battery, better system reliability, expanding the working temperature window, as well as improving the energy control system and stability of auxiliary systems.

Some experts said that the same VFB batteries made in other countries were more expensive than Rongke Power's product by USD200/kWh. They believed that cost reduction depends on further reducing the cost of raw materials and electrical and electronic components, the overall cost reduction brought by scale and automatic production, and cheaper energy management system.

The experts advised that grid-level storage value chain should be fostered. Only through active market access for companies can a better value chain and sound competition climate be built.

The experts also suggested two risks in application of the technology: The first is technical one. The supporting facilities need high-reliability circulation pump, high-

efficiency power converter and good energy management system for the VFBs to be effectively integrated into grid operation. The second is commercial risk. The greatest risk is the lack of business model due to policy unavailability. Flow batteries smooth out grid connection of renewable energy, reduce wind and PV curtailment, but should not challenge other power sources as a means of peak shaving. The advantage lies in its supporting functions and demand response at consumer side, while such functions can hardly form sustainable business model in the absence of pertinent policy and regulatory rules.