Journal of Power Sources 191 (2009) 176–183

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Lead-acid battery use in the development of renewable energy systems in China

Yu Chang[a], Xianxian Mao[b], Yanfang Zhao[c], Shaoli Feng[d], Hongyu Chen[a,*], David Finlow[a]

[a] Key Lab of Technology on Electrochemical Energy Storage and Power Generation in Guangdong Universities, School of Chemistry and Environment, South China Normal University, Guangzhou, Guangdong 510006, China
[b] Zhejiang Narada Battery Co., Ltd., Zhejiang, Hangzhou 310013, China
[c] Shenyang Jugu Equipment Co. Ltd., Shenyang 110026, China
[d] Zhejiang Tianneng (Jiangsu) Battery Co., Ltd., Shuyang, China

ARTICLE INFO

Article history:
Received 24 November 2008
Received in revised form 11 February 2009
Accepted 11 February 2009
Available online 21 February 2009

Keywords:
Lead-acid battery
Renewable energy systems
VRLA batteries

ABSTRACT

Policies and laws encouraging the development of renewable energy systems in China have led to rapid progress in the past 2 years, particularly in the solar cell (photovoltaic) industry. The development of the photovoltaic (PV) and wind power markets in China is outlined in this paper, with emphasis on the utilization of lead-acid batteries. The storage battery is a key component of PV/wind power systems, yet many deficiencies remain to be resolved. Some experimental results are presented, along with examples of potential applications of valve regulated lead-acid (VRLA) batteries, both the absorbed glass mat (AGM) and gelled types.

1. Introduction

Global attention has turned to renewable energy sources, such as solar energy and wind power, as the environmental and sustainability problems associated with the ongoing use of coal and oil as primary energy sources are finally being acknowledged. The Chinese government recently launched two major PV projects simultaneously, and wind power, which could very possibly become the third major mode of energy generation, after thermal and hydropower, is also being rapidly developed.

Renewable energy power systems incorporate a power-generating component, an energy storage component, and the requisite control circuitry. PV power systems, for example, comprise solar cell modules, battery packs, and a controller. The solar cell modules convert solar energy into electric power during the day, some of which is provided to the dc/ac loads, the remainder to charge the battery packs. The battery packs must supply power to the dc/ac load when the sun is inaccessible, or the cells require maintenance, and should also be able to provide a large momentary current in order to start equipment such as electric motors. Investigations of previously constructed PV power stations have revealed that the storage batteries were inevitably one of the major reasons for PV power station operating problems [1].

The development of safe, long-life, high-efficiency, low-priced energy storage systems is therefore a high priority. Lead-acid batteries with their advantages of low price, high-unit voltage, stable performance, and a wide operating temperature range, face an exciting challenge as major components in the development of the PV/wind power industry in China.

2. Development of the PV and wind power industries in China [2,3]

As a large, energy-consuming country, China has fully confirmed the strategic importance of renewable energy in its energy supply systems. In 2005 and 2006, the investment in renewable energy increased significantly along with the rapidly enlarging market. The execution of the *Renewable Energy Law of China* on January 1, 2006 [4] marked a milestone in the development of renewable energy in China. The *Renewable Energy Resources Mid-long Term Plan*, unveiled in August 2007, proposed an increase in the proportion of renewable energy resources used, and the promotion of the wind/biomass/solar power generation industries.

2.1. Development of the PV industry in China

The production of solar cells/modules in China hovered around 1% of the global output prior to 2002. Since 2004, the PV industry in China has experienced phenomenal growth; the annual growth rate of the solar cell manufacturing industry has been within the 100–300% range. In 2006 China shared over 10% of the world output, with a production capacity of 1.67 GW, making it one of the most rapidly developing countries in the PV field, and third in the world behind only Japan and Europe. In 2007, China became the world

---

* Corresponding author. Tel.: +86 20 39310183.
E-mail address: battery@scnu.edu.cn (H. Chen).

0378-7753/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2009.02.030

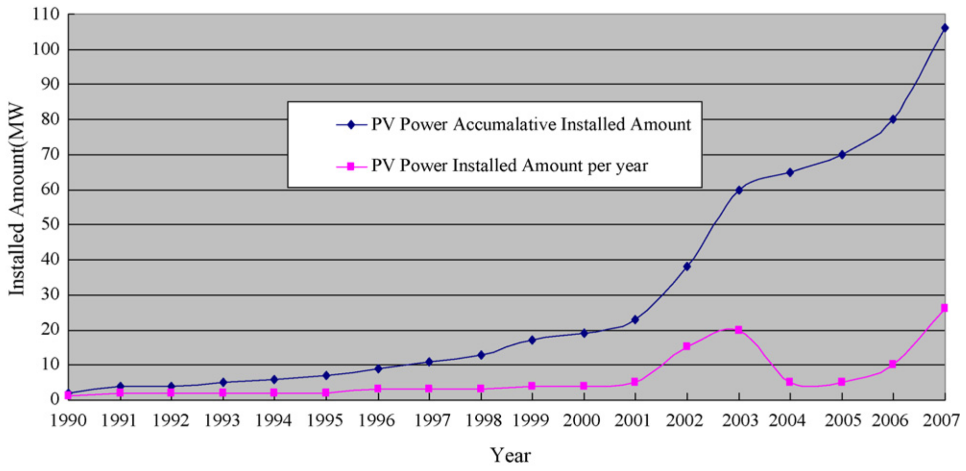

Fig. 1. Development of the PV power generation in China.

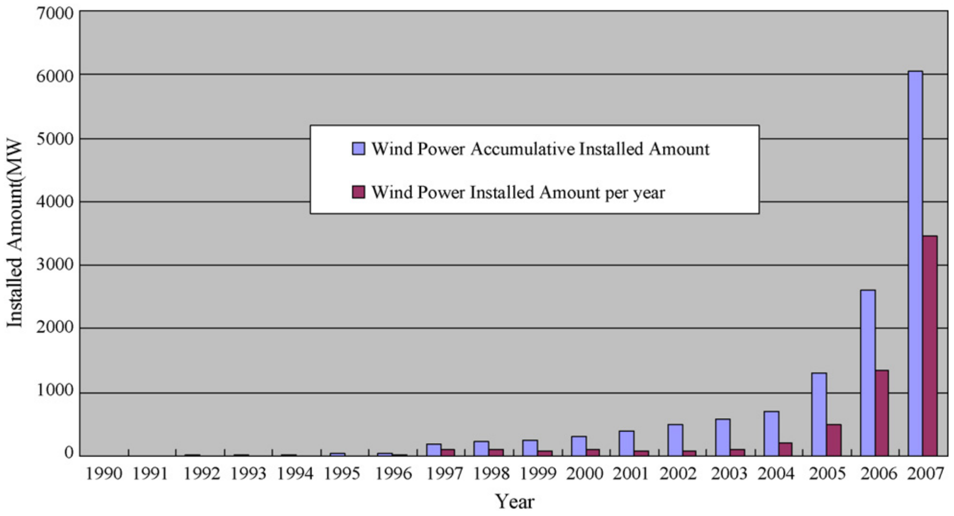

Fig. 2. Wind power-generating capacity in China (MW).

leader in solar cell manufacturing; the output of solar cells in China was 1.09 GW, exceeding Japan's 0.920 GW, and Europe's 1.06 GW. The newly installed capacity of PV units in China was 26 MW, an increase of 160% compared with 2006; the total installed capacity was 106 MW, an increase of 32.5%. By 2010, the predicted output in China will be over 1.50 GW.

2.1.1. *Government projects [5]*

In 2002, the Chinese government allocated several billion RMB from the National Debt Fund for the *Bright Project*, which will supply electric power to 80 million people in the remote, non-electrified, western region of China. Many other projects such as *Extending Broadcasting to Every Village Project and PV Power Station in Tibet* were also launched, rapidly enlarging the PV power generation market in China, and leading to an unprecedented development of Chinese solar cell enterprises.

The huge national project *Electricity to Country*, funded from 2002 to 2004 with 4.7 billion RMB from central and local financial sources, has accelerated the development of the PV industry in China. A series of stand-alone, renewable energy power stations, including PV only, combination wind and solar energy, and small hydropower types, were built in 1065 different counties and towns, in a total of 12 provinces/municipality cities/autonomous regions in western China [6]. Most of these were PV only, employing 17 MW of PV cells. Implementation of the *Roof Plans* project, and the application of solar power generation products, such as road lamps for town construction, hastened the growth, and total domestic PV generation capacity had reached 80 MW by 2006, with approximately 42% of this accounted for by independent PV generation systems, supplying power to those people in remote places not previously covered by power networks.

2.1.2. *The domestic PV market*

Fig. 1 illustrates the development of the PV power generation in China since 1990 [7]. It indicates slow growth in the early years, with an annual growth rate of about 17%; far lower than the global average rate of 30–40% during the same period.

Table 1 indicates the application markets for PV power in China in 2006: the commercial market, including the telecommunication

Table 1
The applications market for PV in China in 2006.

Market classification	Installed amount/MW	Market percentage/%
Rural electrification	30	43.0
Telecommunication and industrial	28	40.0
Solar PV products	10	14.0
Grid-connected generation	2	3.0
Total	70	100

industry and PV products, accounted for 54%; the government-supported rural electrification and grid-connected PV generation for 46%. The 2 MW grid-connected PV generation portion accounted for a mere 3% of the domestic application market, far lower than the global level of 88%. Grid-connected PV generation constituted 86% of the total amount of installed PV capacity in the world in 2005.

2.2. Wind power in China [9]

Wind power generation has increased more rapidly than PV in China. In 2006, 1442 wind turbines with, collectively, 1.33 GW of power capacity were installed—a growth rate of 266% compared with 2005. By the end of 2006, 3307 wind turbines were in operation with a combined capacity of 2.6 GW, 100% more than in 2005; electricity delivered to the grid by wind power was estimated at about 3.86 billion kWh in 2006, compared with 2.2 billion kWh in 2005. China became the fifth largest global user of wind energy in 2007 with a total installed capacity of 6.05 GW. The progress of wind power generation in China is illustrated in Fig. 2.

3. Future energy trends in China

A series of plans and policies, providing government support for the renewable energy industry, were implemented in recent years to adjust and optimize the energy structure in China,. In August of 2007, *Renewable Energy Mid-long Term Plan and The 11th 5-year Plan for Renewable Energy Development* were issued to hasten the exploitation of renewable energy, to increase its proportion to the energy system, and to promote its technological progress plus the industrialization process of PV/wind power generation. The stated goals were to increase the proportion of renewable energy generation to 10% of the total energy usage by 2010 and 15% by 2020 [15].

3.1. Future solar energy trends in China [5–8]

Residential PV generation systems and the mini type PV power station will still be the main direction of development to solve the power supply problem for those in remote districts; the Government plans to generate 200 MW of PV power to ensure that 2 million herdsmen in the remote areas, namely 1/3 of the non-electrified people all over the country, will have sufficient power to sustain basic living conditions.

Learning from the experiences of developed countries, we will install PV power supplies in relatively developed cities, with roof systems for public and other buildings, plus lighting facilities for roads, parks and stations. Also, we will prepare for the large-scale application of grid-connected PV systems. 10–20 MW PV modules have or will be applied every year for many projects such as the *Brightness Programme*, *Household PV Power Supply System*, *Country PV Power Station*, *Qinghai Tibet Railway PV Power Supply System*, *Cathodic Protection PV Power System in West-east Gas Pipeline*, *2008 Olympic Games PV Power Supply System*, *Xi-Xin Project of Village-village Connected Radio and Television Engineering PV Power Supply System*, *Grid-connected PV System and the PV Supply System* for communication applications. All of these policies and projects offer a broad market for PV/wind energy systems, and the total additional annual capacity of PV systems in these fields will reach 400 MW in 2010 and 1.8 GW in 2020.

Power supply to the remote areas will be a long-term task, limited by the natural and economic conditions. Independent PV power generation for rural electrification will maintain a stable market share, whereas small-sized PV application products such as yard lights will continue to develop rapidly due to increasing global prosperity [8].

The strategic target for domestic PV power generation is an annual, installed capacity of several tens of MW, and an accumulative capacity of about 500 MW by 2010, mainly to meet with the power supply requirements of the residents in remote districts and the pilot PV power generation demonstrations for the *Urban Roof* systems. The *Urban Roof* system, large-scale desert power stations, and grid-connected power generation in other forms are planned to be developed before 2020, when the annual installed amount may be over 100 MW, and total capacity will reach 1.5–2 GW. After 2020, the PV industry will begin to develop on a larger scale, with annual installed and accumulative amounts expected to reach approximately 1 and 10 GW, by 2030. Commercial development on a large scale will be realized by the end of 2050 with 20 GW annual installed amount in the 20 years and 400 GW accumulative.

3.2. Potential applications for batteries in PV systems

There are four major markets in China:

1. *Lighting systems*, which account for about 60% of the market; solar energy storage batteries can be used in road lamps, lawn lights, yard lights, corridor lamps, and landscape lighting systems in cities.
2. *PV/wind power stations* to store and regulate the power generated to ensure consistent operation. The investment for batteries often accounts for about 20% of the total cost of the station. It is estimated that batteries will be updated about two to five times during the normal 20-year operating lifetime of a station [10], thus a large number of batteries, especially lead-acid batteries, would be needed.
3. *Construction*, namely the integration of PV power generation into the building; solar panels are installed on the roof to receive the sun's energy and convert it into power, to be stored in the batteries, or supplied directly to the users, or to the power grid, if necessary. This not only makes full use of the power from the PV system, but also plays a role in the peak power regulation. Building-integrated photovoltaic (BIPV), embodying a combination of innovative architectural design ideas and modern high-technology power generation systems, opens a new architectural field, and promotes PV industrialization and application on a large scale in towns.
4. *The automobile industry in the form of electric vehicles*. Future development of solar-powered vehicles will generate have a great market demand for matching batteries. Although the market size at present is relatively small due to some technological reasons (the lack of durability of current batteries, the large required area of the solar panels, etc.), it is predicted that solar vehicles and automobiles will be extensively used in western China as the government pays increasing attention to the exploitation of renewable energies. The matching batteries will occupy an important position in the solar industry system, leading to significantly expanded demand.

3.2.1. Battery types

The types of batteries used in PV systems are lead-acid, sodium-sulfur (NaS), lithium-ion (Li-ion), electric double-layer capacitors (EDLCs), etc. Lead-acid batteries, by virtue of their low cost and good performance, account for 75% of the PV/wind power system market. This proportion is predicted to decrease with the development of new types of batteries in the future [11–13]. For example, a 0.8 billion $US market for large-sized Li-ion batteries for automobiles and power-storage systems is expected by 2011, based upon demand for the hybrid-powered Prius car in 2008. Its market size is predicted to grow from 60 million $US in 2005 to 150 million $US in 2011. However, by virtue of its low cost and the mature level of industrialization, lead-acid batteries will continue to have a

Table 2
Comparison of open flooded and floating VRLA batteries.

Floating-charge VRLA batteries		Open flooded batteries	
Advantages	Disadvantages	Advantages	Disadvantages
Non-flowing electrolyte			Flowing electrolyte
Sealed			Not sealed
No liquid leakage, acid fumes, or equipment corrosion	High/low temperature properties		Acid fumes during charge/discharge; equipment corrosion
Unnecessary to add water or acid	Short deep cycle life	Long cycle life	Frequent need to add acid and water
Flexible installation			Vertical installation only
Small footprint			Large footprint
Low self-discharge			High self-discharge
PbCaSn alloy meets the environmental requirements			PbSb alloy pollutes environment

dominant advantage in industrialization development in the short-term in China; in the mid-term it will maintain a share due to its low cost; longer term it will continue to be of importance where batteries with high specific energy (energy/unit mass) are not needed. The dominant position of lead-acid batteries in PV systems may decline, but demand will increase with the rapid development of the PV industry. According to incomplete statistics, the total number manufactured, sales volume, and export value of lead-acid batteries in 2005 in China were 706.5 million, 5 billion, and 0.82 billion $US respectively. Export value and volume increased by 40% and 35%, respectively, compared with 2004. The total output of lead-acid battery capacity reached 903.5 million kVAh, increasing at an annual rate of 7–10% in 2007, and the export value exceeded 1 billion $US. It is predicted that the output and the export value of lead-acid batteries in PV systems will exceed 1.3 billion kVAh and 1.5 billion $US respectively in 2011 by virtue of the growth of the PV/wind industry in China. Statistics indicate that the number of lead-acid batteries in PV/wind systems account for about 5% of the entire lead-acid battery market, as shown in Fig. 3. With the support of national policies and strategies on renewable energy, lead-acid batteries in PV/wind systems will share 10% of the total lead-acid battery market in 2011 [14].

As energy-storage systems generally account for approximately 30% of the cost of PV systems, the market for energy-storage batteries is expected to reach 13 billion $US by 2020. Since lead-acid batteries are used in 75% of PV systems, their market could be close to 10 billion $US, which equals twice the total value of lead-acid batteries manufactured in 2005 (note that this is just for new PV power system installations). As batteries should generally be updated two to five times during the 20-year operating lifetime of PV/wind stations, the market for batteries, especially the lead-acid type, would be larger during the station's operating period. According to current rates of development and established plans, the installed capacity of PV systems will increase to 1.5–2 GW by 2020. After 2030, large-scale development will come into being. The installed capacity will reach approximately 1 GW every year and the accumulated installed capacity 10 GW. By 2050 the commercial scale development will hasten, with an installed capacity of 20 GW every year [15]. Driven by the rapidly expanding use of PV power generation, the market for batteries in PV systems will be booming in the future.

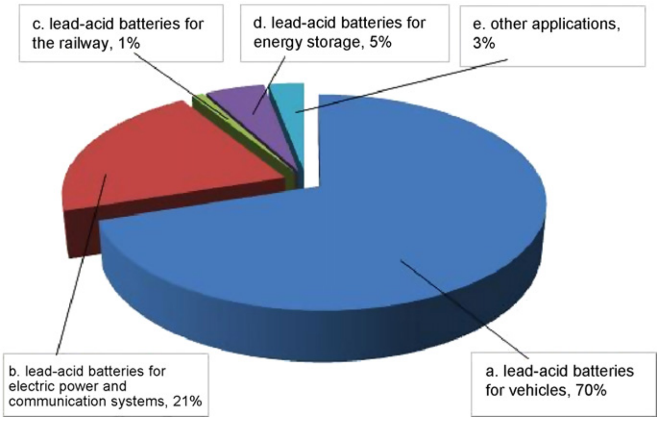

Fig. 3. The distribution, by market, of lead-acid batteries in China in 2007.

Lead-acid batteries, especially the floating valve regulated lead-acid (VRLA) design or the improved one based on VRLA, and the open flooded types, have a dominant advantage in PV/wind power generation systems at present by virtue of their particular technology and cost advantages. The advantages and disadvantages of traditional open batteries and sealed VRLA batteries are presented in Table 2.

As Table 2 illustrates, significant maintenance is required for flooded batteries, plus the PbSb alloys create environmental pollution. Therefore, VRLA batteries employed PbCaSn alloy for sealing will be preferentially selected as the backup power to floating charge for PV systems. However, floating-charge VRLA batteries still have many deficiencies in the energy-storage field [16,17].

4. The deficiencies of VRLA batteries employed in PV systems

4.1. Short cycle life

The floating-charge VRLA batteries in China are primarily designed to meet the conditions and requirements of backup power supply systems for power, post and telecommunication systems. The required lifetime of PV systems is 20 years, and the lifetime of batteries is expected to be 5–8 years. The DOD of batteries in PV systems is generally about 20%, with an expected maximum of 3000 cycles. VRLA batteries cannot satisfy these requirements, thus improvements must be made.

4.2. Poor high/low temperature performance

PV power generation systems have been largely used in western China, where the conditions are severe and the range of outdoor temperature is typically −35 to +55 °C. The recommended ambient conditions for efficient battery operation are: a temperature range of −10 to +40 °C, at up to 90% relative humidity, and a maximum elevation of 4500 m. VRLA batteries are very sensitive to ambient temperature, which significantly influences battery life. Experience with floating-charge batteries has demonstrated that the lifetime is halved for each 10 °C increase, once the ambient temperature exceeds 25 °C. As temperature decreases, the discharge capacity is greatly reduced. Generally VRLA batteries can only discharge about 70% of their actual capacity at the temperature of −10 °C [18,19].

4.3. Sulphation

The charging mode with PV cells is discontinuous, thus undercharging of the battery is inevitable. Operation in an undercharged condition leads to sulphation of the negative electrode, which, over an extended period, will cause failure of the battery. The harm caused to VRLA batteries by undercharge is more serious for than that by overcharge. Available information indicates that the failures of tubular batteries in remote PV/wind systems were mainly caused by sulphation of the active materials [20]. The major reasons for failure of flat plate batteries are: the softening and passivation of the positive active materials; grid corrosion; and sulphation of the negative active materials. What's more sulphation is the dominant reason for batteries failure.

5. Potential improvements to energy storage batteries

5.1. The grid alloys

Lead–antimony, PbSb, alloy has been generally employed as the grid material of traditional open batteries, because its corrosion products effectively improve adhesion between the grid and the active material, thereby prolonging the charge and discharge cycle life. PbSb alloys have not been used as the positive grid in VRLA batteries, however, as the battery could not be sealed due to Sb dissolving from the positive electrode and being deposited on the negative electrode, thereby decreasing the evolution overpotential of H_2, resulting in increased evolution of hydrogen during periods of overcharge and storage. Also, antimony adsorbed on the active materials at the anode decreases the evolution overpotential of O_2, decreasing the decomposition voltage of water. As a result, the water is easily decomposed during charging, and the speed of self-discharge is accelerated during storage. Early types of VRLA batteries incorporated lead–calcium, PbCa, alloys, but this led to a premature loss of capacity, mainly due to the development of nonconducting interfacial layers between the grids and the active materials. Initially, tin, Sn, was added to the alloy to maintain higher conductivity at the interface between the corrosion layer and the positive active materials (PAMs), preventing formation of the passivation layer, and thereby restraining premature capacity loss [21]. The latest research shows that the conductivity of the corrosion layer increases significantly when the Sn content in the alloy is increased to 1–1.5%. The corrosion rate also decreases with the increase of Sn content, thus the conductivity of the interface between the anode grid and the active materials greatly improves, especially following deep discharge of the battery.

Nandu Co., Ltd., has conducted many studies on grid alloys. The results of electrochemical performance and verification tests with experimental batteries have both shown that when element X (proprietary to Nandu) was added to the PbCaSn alloy, grids had low interfacial resistance, the conductivity of the corrosion layer on the positive plate interface increased, and the cycle life was equivalent to that with PbSb alloy.

5.2. The paste formulas

The paste formulas play a big role in the discharge capacity and the cycle life of batteries. For PV system applications it is necessary to increase the cycle life of the positive paste, decrease the sulphation rate on the negative electrode, and enhance the discharge performance of the negative electrode at low temperatures.

5.2.1. Improving the performance of the interfacial corrosion film between the positive active materials and the grid

The properties of the interfacial corrosion film between the positive active materials and the grid are significant factors in battery cycle life. The interfacial non-conducting, or low conductivity, layers between the grid and the positive active materials, having high resistance, increases in temperature during charging or discharging, causing the active materials near the grids to expand, and thereby limiting the battery capacity. To improve the conductivity and elasticity of the corrosion film, some high valence oxides could be added to the positive active materials to make the corrosion layer more elastic; fewer cracks would therefore form under stress. During battery cycling, the polyvalent ions enter the corrosion film, increasing the probability of forming a linear hydrated polymer chain, as well as the number of gels in the corrosion layer, thereby improving the contact between the active materials and the grids, and prolonging the battery cycle life.

5.2.2. Enhancing the mechanical strength of the positive active materials

Many studies have shown that the active material grains cluster during the charge/discharge periods of a deep cycling operation, diminishing the specific surface area and the porosity of the active materials. Furthermore, adhesion between the active grains decreases, causing the positive active materials to soften and expand, eventually leading to battery failure. By virtue of their good agglutination to the paste, bonding emulsions could be added to the positive active materials to enhance their mechanical strength.

5.2.3. Improving the negative paste formula

Negative plate sulphation has been one of the main failure modes of batteries in energy-storage systems. The addition of acetylene black, as a conductive material, to the cathode reduces this phenomenon due to its high dispersity and ability to selectively absorb organic compounds. Acetylene black also changes the conductivity of the swelling layer and increases the charge acceptance capability.

5.3. The use of high temperature and humidity curing

Curing is typically carried out at a temperature of 50 or 80 °C at present. The phase formed by the former process is mainly $3PbO\cdot PbSO_4$ (3BS) while that by the latter is mainly $4PbO\cdot PbSO_4$ (4BS). The content of 4BS and 3BS in the active materials has a great influence on the capacity and the life of a battery. The corrosion layer in a 4BS plate formed by curing at the higher temperature provides good adhesion between the grids and the PAM, plus the active materials have a mesh structure, effectively enhancing the battery cycle life.

5.4. Assembly technology

The positive active materials swell easily during cycling, causing the resistance between the active materials to increase. PbO_2 cannot recharge after the active materials have softened and the battery has discharged, resulting in a decrease in PbO_2 capacity. The deeper the battery discharge, the greater the swelling of the active materials, and the decrease of capacity. Applying an assembly pressure greater than 40 kPa, to restrain swelling of the active materials, increases cycle life.

5.5. Improving the exhaust valve

Most solar energy storage systems have been used in western China, where the elevation is about 3000–5000 m. The frequency of opening of the exhaust valve therefore increases due to the lower ambient pressure, with a corresponding loss of water. The exhaust valve must be redesigned to adjust to varying ambient pressure.

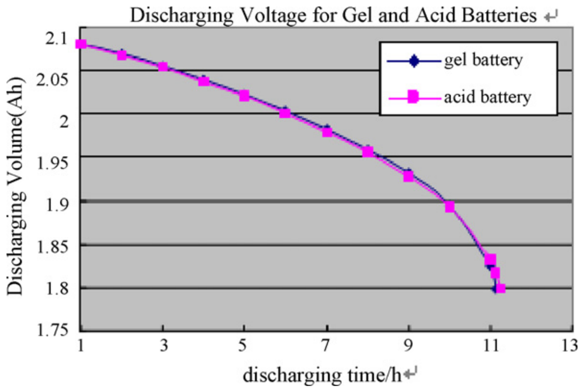

Fig. 4. The 10 h discharging voltage comparison between gel and acid batteries at 25 °C.

5.6. *Advantages of gel VRLA batteries*

The heating problem of solar energy storage batteries has been more serious than that of the traditional open batteries because the former were often used at high temperatures. During the period of recombination of O_2 and H_2, additional heat is generated within the battery. AGM batteries have lower absorbing/emitting capacity due to their relatively small amounts of electrolyte. If the temperature of the operating environment is too high, or the voltage of the charging appliances is out of control, the charge rate will increase too rapidly, and the temperature of the electrolyte will increase. As the temperature in the battery rises, the internal resistance declines, and the charging current will further increase. Iteration would lead to thermal runaway, with significant water loss, resulting in battery failure. The changes of voltage during a 3 h current discharge for general VRLA batteries in a 48V300Ah PV system over 3 years of battery service life are shown in Fig. 4. The discharge voltage was inconsistent, and 50% of the batteries failed, greatly affecting the operation of the PV system.

The advantages of gel batteries are as follows:

- A quasi-flooded electrolyte design is used, and the heat capacity is large. The possibility of thermal runaway is greatly reduced, and homogeneity is good.
- Gel electrolytes eliminate acid stratification.
- Gel electrolytes eliminate electrolyte leakage.
- Good resistance to deep discharge and capacity recovery following overdischarge.
- Have a wider range of operating temperature and good low temperature discharge capacity.
- Provide long cycle life.

6. The performance comparisons between general lead-acid batteries and polymer gel ones

6.1. *The preparations for tests*

6.1.1. *The used samples*

AGM plate batteries with H_2SO_4 as the electrolyte, battery types: 2V500Ah for tests and 2V300Ah as backup power for PV systems.

Optimized AGM plate batteries with H_2SO_4 as the electrolyte, battery types: 2V500Ah for tests and 2V300Ah as backup power for PV systems.

6.1.2. *The test equipment*

USA BITRODE recharge and discharge machine, the type: LCNS-200-12.

Table 3
Comparison of capacities for two types of batteries at different temperatures.

Testing items	500 Ah polymer gel batteries	500 Ah general lead-acid batteries
10 h capacity at 25 °C/Ah	529.6	533.7
10 h capacity at 0 °C/Ah	467.9	467.7
10 h capacity at −20 °C/Ah	308	290.6
10 h capacity at −30 °C/Ah	189.8	154.7
10 h capacity at −40 °C/Ah	125.4	64.2
Sealing reaction efficiency/%	99.9	99.9

6.2. *The results comparisons*

6.2.1. *The capacity comparison at different temperatures*

The capacities for two types of batteries were tested at 25, 0, −20, −30, −40 °C, respectively, plus sealing reaction efficiencies. The results are shown in Table 3. And the discharging voltages were also tested at 25, 0, −20, −40 °C, respectively, as shown in Figs. 4–7.

The results indicate that polymer gel batteries take much more advantages on the low temperature capacity, lower the temperature, greater the advantages.

Generally the reaction rate of active materials, the same with the ionic diffusion velocity, will decrease at low temperatures. So the passivation will be easily caused on negative which dues to the decrease in the discharging capacity at low temperatures. Gelled electrolyte will abate the passivation of negative for its adsorption effect, which improve the discharging performance of polymer gel batteries at low temperatures.

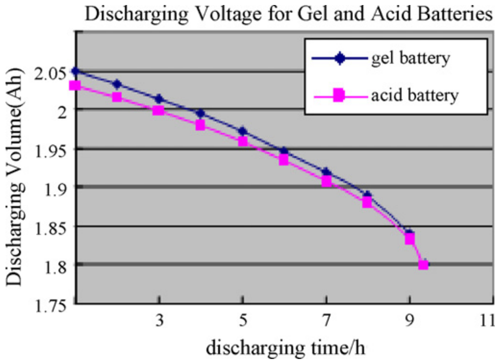

Fig. 5. The 10 h discharging voltage comparison between gel and acid batteries at 0 °C.

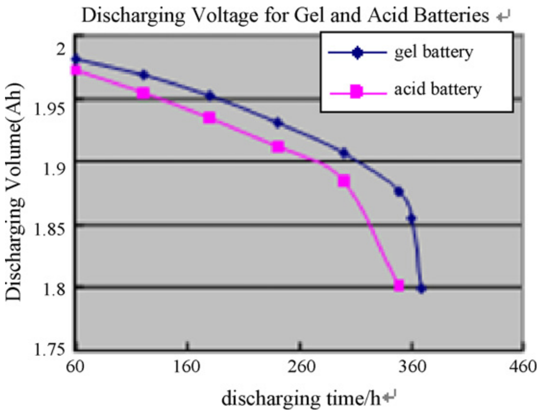

Fig. 6. The 10 h discharging voltage comparison between gel and acid batteries at −20 °C.

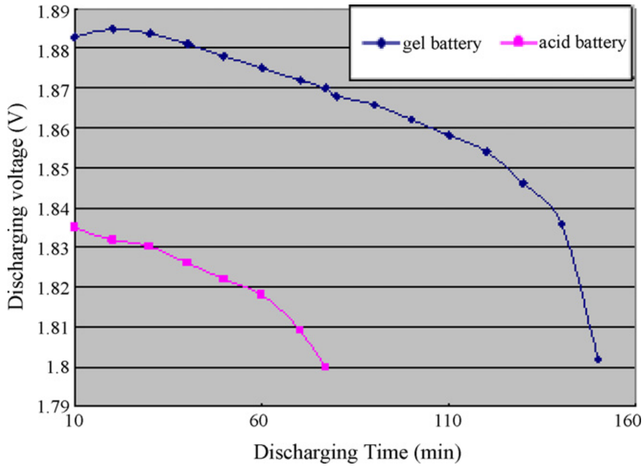

Fig. 7. The 10 h discharge comparison between gel and acid batteries at −40 °C.

6.2.2. *The comparison in floating charging acceptance ability*

The two types of batteries were cyclically charged and discharged, with six batteries every group, testing at 25 °C. The batteries were charged for 24 h with 10 A current and the limited voltage 2.25 V each one, while discharged with 10 A current till the voltage became 1.8 V each one. The charging acceptance ability coefficient is defined as the ratio of the discharging capacity in every circulation and the former charging capacity. As shown in Fig. 8, the polymer gel batteries have better charging acceptance ability than the general LA ones in 50 times cycle when floating charging.

6.2.3. *The comparison in cycle life at high temperature*

The cycle life at high temperature of these two types of batteries were tested at 40 °C in high temperature box with six batteries every group. The batteries were charged for 24 h with 10 A current and the limited voltage 2.25 V each one, while discharged with 10 A current till the voltage became 1.8 V each one. End the test when the testing capacity was low to 80% of the nominal capacity. The results were shown in Fig. 9.

The results indicate that polymer gel batteries have longer cycle life and better reliability than general acid batteries, simulating the outdoor environment with high temperature of 40 °C where PV system is employed.

The results indicate that gel-type batteries have more advantages than the general acid ones as the appropriate energy-storage batteries for PV systems through the comparisons in capacities at different temperatures, charge acceptance abilities and cycle lives at 40 °C.

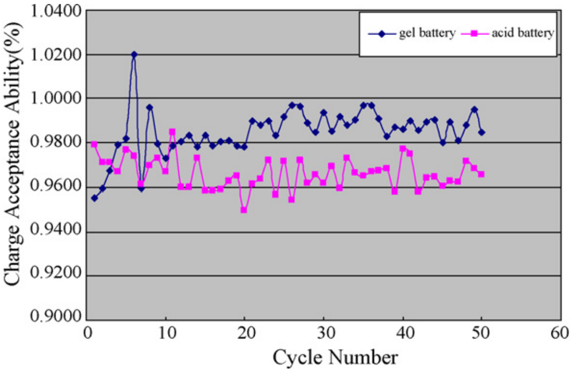

Fig. 8. The charge acceptance ability of gel and acid batteries.

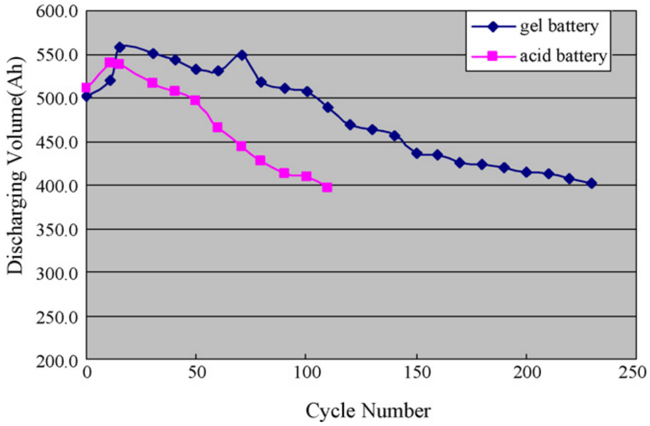

Fig. 9. The cycle life of gel and acid batteries at 40 °C.

7. The application comparisons between general lead-acid batteries and polymer gel ones

The application client was the backup PV system for communication. One battery pack was 48 V 300 Ah. Solar energy provided the power to the loads during the day, the remainder to charge the battery packs. While the battery packs supplied power to the loads at night. The two base stations were in the same district, with the same equipments, one station employed by gel batteries and the other by general LA batteries. After 3 years of service, the client tracking discharging tests were done with 3 h current, namely 75 A. The testing way was to test the discharging voltage of every battery in the given time. The results, as shown in Figs. 10 and 11, indicate that the discharging voltage was inhomogeneous for general LA batteries only after discharging for 1 h, and 50% batteries failed. While the discharging voltage was extremely homogeneous and no battery failure occurred after discharging for 1 h and the same even for 2 h.

8. Maintenance of VRLA batteries

The “maintenance-free” claim for VRLA batteries is misleading. General lack of knowledge has led to inadequate maintenance of VRLA batteries, resulting in the damage, capacity decline, and failure of batteries. Correct maintenance requires:

(a) *Employing remote monitoring systems*. A single, performance-decreasing battery could be immediately identified, maintained

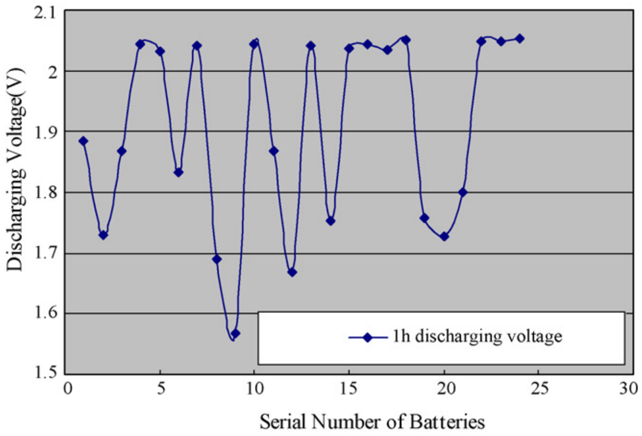

Fig. 10. The change of discharge voltage for general VRLA batteries in PV systems.

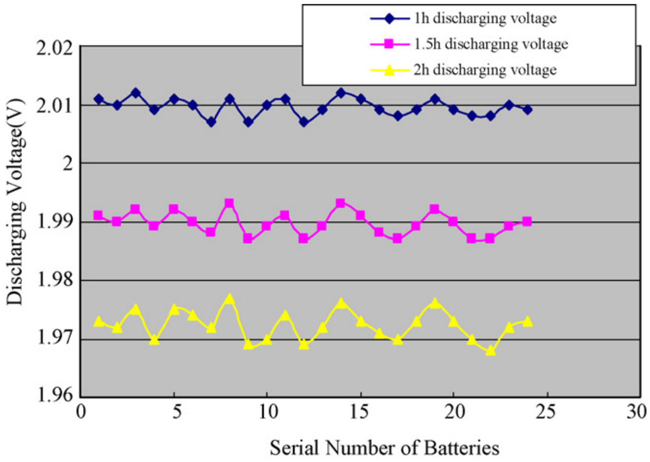

Fig. 11. The change of discharging voltage for hybrid gel VRLA batteries in PV systems.

or quickly replaced, in order to keep the battery group homogeneous, stable, and performing acceptably.

(b) *Providing a good operating environment for the batteries*. The system room should preferably be built underground, with heat insulation provided to maintain the temperature between 25 and −8 °C when the outdoor temperature is 45 to −30 °C, thereby prolonging battery life.

(c) *Employing an intelligent controller*. Temperature compensation should be provided to match the charge and discharge requirements of the batteries at different temperatures.

(d) *Overall system design*. A compatible system of solar panels, controllers and batteries in the energy-storage system is essential. An appropriate battery capacity should be chosen according to the load, plus the environment in which it will operate, with a reasonable margin of safety incorporated.

9. Conclusion

The Chinese government has fully confirmed the strategic importance of renewable energy in its energy supply systems. Many new policies have been issued to hasten the exploitation of renewable energy, to increase its proportion to the energy system, and to promote its technological progress plus the industrialization process of PV/wind power generation. It is suggested that the PV market in China has tremendous potential to increase in the future due to this vigorous support. With the accumulative market capacity predicted to be close to 45 billion $US by 2020, PV/wind energy development will be a major emphasis for the next 10 years.

VRLA batteries, in particular the gelled-electrolyte type, will be the leading contenders for the energy storage component of renewable energy power generation systems.

References

[1] M.-d. Li, Failure of a battery Causing the 110 KV Substation Breaking down, Rural Electrification 9 (2003) 28.
[2] Z.-y. Wang, J.-f. Li, China Renewable Energy Development Report 2007, Chemical Industry Press, 2007.
[3] China Energy Development Report 2007, China Energy Development Report, Editional Board, China WaterPower Press, 2007.
[4] The Summary of PRC, Renewable Energy Law, Chinese Battery Industry 10 (2) (2005) 17.
[5] X.-l. Luo, L.-z. Wu, X.-t. Jiang, et al., Solar cell and application, Journal of Wuhan University of Science and Engineering (10) (2005) 36–38.
[6] L.-c. Tian, Analysis on the status of solar cell market competition, Advanced Materials Industry 8 (2004) 40–44.
[7] D.-q. Zhao, L.-x. Qiu, C.-p. Liao, Analysis on the development status of Solar PV Industry, High Technology and Industrialization 2 (2007) 55–57.
[8] M.-h. Zhu, H. Shi, Two Drivers Promote PV industry in China with a Broad Prospect.(2008). http://www.newenergy.com.cn.
[9] Y.-d. Li, G.-f. Yuan, The status and the prospect of wind power in China, Electric Age 3 (2006) 16–19.
[10] Q.-x. An, J.-l. Zhu, X.-s. Gong, Batteries for PV power station, Solar Energy 2 (2004) 27–28.
[11] M. Wu, The status and the trend of lead acid batteries industry in China, China Electrical Equipment Industry 3 (2007) 30–35.
[12] Y.-g. Ma, Prediction of lead acid market demands in China in 2005, China Non-ferrous Metals Industry 3 (2005) 56–57.
[13] X.-g. Hu, Present situation and prospect of the lead-acid battery market in China, Chinese Battery Industry 6 (2006) 190–195.
[14] Aanalysis on battery industry market in China. Chinese Battery Industry 11(3) (2006) 190–193.
[15] Renewable Energy Mid-long Term Plan, Development & Reform Commission of China (2006) 105–116.
[16] X.-x. Mao, W.-m. Xiang, Z. Tang, A discussion on technical performance of VRLA batteries used in solar PV power system, Battery 1 (2003) 22–24.
[17] Qiang-xin An, Ji-ling Zhu, VRLA batteries in PV power station, Solar Energy 3 (2003) 18–20.
[18] D.-k. Qiu, H.-y. Yu, Application of VRLA batteries in Xizang District Energy System, Battery 4 (2003) 152–154.
[19] H.-l. Chen, Design and maintenance for lead acid batteries in stand-alone PV power station in Alpine Region, Qinghai Science and Technology 6 (2004) 23–25.
[20] Y.-p. Shi, Y.-y. Wang, P.-f. Li, Research on the charge and discharge control methods, Acta Energiae Solaris Sinica 26 (1) (2005) 86–89.
[21] W.-h. Zhang, Y.-z. Zhang, Measures on lead acid batteries capacity recovery in stand-alone PV power station, Photovoltaic Engineering (2006) 35–38.