Lead-acid and Lithium-ion batteries for electric bikes in China: Implications on the future growth of electric-drive vehicles

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Abstract
Alternative fuel use in China has been rising since the late 90's with the rapid transition to electric bikes. The electric bike market reached nearly 16 million bike/yr in 2006 and is expected to maintain double-digit growth over the next 5 years. E-bike growth has been in part due to improvements in rechargeable valve-regulated lead acid (VRLA) battery technology. Further improvements in technology and a transition from VRLA (the dominant e-bike battery type) to lithium-ion (Li-ion) batteries could have a large impact on the future market growth of this transportation mode in China and abroad. It may also affect the future of battery-powered electric cars.

The paper first introduces the battery industry in China and the two main battery technologies for e-bikes: VRLA and Li-ion. Battery performance and cost for these two types are compared in order to assess the feasibility of a shift from VRLA to Li-ion battery e-bikes. The paper then discusses how batteries are used in electric vehicles (EV) compared to the requirements of e-bikes. Through this comparison, we evaluate the potential for the growing e-bike market in China to enable a transition to small personal electric cars. Critical barriers to this transition are identified.

Acronym List
VRLA – valve-regulated lead acid, SSEB – scooter style electric bike, BSEB – bicycle style electric bike, AGM – absorptive glass mat, FLA – flooded lead acid, 4WV – four wheel vehicle, LAB – lead-acid battery

Introduction
The Chinese electric bike market has expanded more rapidly than any other vehicle mode in the last seven years, from nearly 40,000 in 1998, to an estimated 15 million in 2006 (Jamerson and Benjamin 2005; 2006). Electric bikes are a category of vehicles in China that includes two-wheel bicycles propelled by human pedalling supplemented by electrical power from a storage battery, and low-speed scooters propelled almost solely by electricity (usually with perfunctory pedals to satisfy legal definitions). The two e-bike types, shown in figure 1, include bicycle-style e-bike (BSEB), which resembles a regular bicycle, and scooter-style e-bike (SSEB), which is typically heavier and bigger.

These vehicles have become a popular transportation mode for Chinese consumers because they provide an inexpensive and convenient form of private mobility and are thus an attractive alternative to public transit or regular bicycling. They are promoted by the national and many local governments due to their low energy consumption and zero tail-pipe emissions, especially important in China's congested urban areas. E-bikes are gaining an increasing share of two-wheeled transportation throughout China, and in some cities like Chengdu and Suzhou, have even surpassed the bicycle mode share.
Electric bikes have been by far the most successful battery electric vehicle application in history with estimated cumulative production of approx. 30 million by 2007 (Wang 2006). At the heart of e-bike technology is the rechargeable battery. The core rechargeable battery technology used in e-bikes is valve-regulated lead-acid (VRLA), or “sealed”, and lithium-ion (Li-ion). Advances in VRLA batteries and rising gasoline prices over the past decade have made e-bikes increasingly competitive with gasoline scooters in price and performance (Weinert, Ma et al. 2006). E-bikes using VRLA achieve low cost ($150-300) and adequate range (30-70 km per 8 hr charge). Because most e-bikes use either VRLA or Li-ion, this analysis will focus on these two battery types.

**MOTIVATION**

E-bikes are an extremely energy efficient (approx. 50 mile/kWh) mode of personal transportation with zero tailpipe emissions. Their widespread use in urban areas throughout China has positive effects on local air quality by displacing gasoline-powered scooters.

Urbanization and motorization is rapidly underway in China and income levels are rising. Survey data from three major cities in China indicate that today’s bicycle users (450 million) and e-bike users (30 million) will most likely either purchase an e-bike or an automobile as their next mode of transport (Weinert, Ma et al. 2006). Their choice has far-reaching impacts around the world in terms of CO2 reduction, air quality, and oil price.

The development of battery technology in e-bikes could have two important effects. First, increasing battery development in the e-bike industry could lead to improved performance and reduced costs for batteries in other applications such as hybrid and full electric automobiles. Secondly, improved e-bike performance and reduced cost may lead to cities designed for e-bikes rather than cars, which could have important implications for energy efficiency and greenhouse gas emissions. Life-cycle carbon emissions per km travelled of a gasoline-fuelled car are roughly 5 times greater than of an e-bike (Cherry 2006).

**METHODODOLOGY**

The analysis relies on literature and data from surveying a variety of companies involved in battery production for e-bikes. The authors visited several battery factories making both LABs and LIBs. Batteries from some manufacturers have been laboratory-tested.

**Transportation Battery Applications and Requirements**

Batteries are used for a wide range of applications including consumer electronics, energy, industrial, and transportation. Batteries for transportation applications have much different requirements than most other applications. They are used in three different modes: motive power, auxiliary power, and traction.

Motive power batteries are used to drive automobiles, scooters, and bicycles and thus require high specific energy (Wh/kg) to achieve adequate range. Deep-cycling capability is necessary since it is common for batteries to be discharged to 10-20% SOC. Cost is a driving factor because the battery pack size can be quite large (10-20 kWh for EVs).

Some motive power batteries are used in combination with another power source, such as gasoline engines in the case of hybrid cars or human pedalling on an e-bike. Varying degrees of hybridization are possible with vehicles depending on the electric motor and engine power ratings. High specific power (W/kg) is more important than specific energy (Wh/kg) for hybrid car applications because vehicle acceleration and top speed are more important than range.

Auxiliary power batteries are used in automobiles and motorcycles predominantly for starting, lighting, and ignition (SLI). Power is valued more than energy density and deep discharge capability because SLI batteries are primarily used to provide high bursts of power output to start an engine (approx. 1-5 kW) and rarely discharged more than 20%.

Traction batteries used in fork-lifts and underground mining cars experience heavy-duty operation and thus require high abuse-resistance. These applications typically use flooded Pb-acid (FLA). Table 1 summarizes these battery applications and their requirements.

**The Battery Industry In China**

The total Chinese battery market in China was valued at $12.4 billion in 2006, 35% of which is for rechargeable Pb-acid type. More than 2,000 companies produce 35 million kWh Pb-acid batteries (Center 2006). 300 of these companies specialize in e-bike batteries with an estimated annual production between of 3.5 and 9 million kWh/year. Figure 2 shows the proportions of different battery types in China:

VRLA batteries were first introduced into UPS applications in America and Europe in the 70’s because of their low
maintenance requirements and high reliability over traditional flooded lead-acid (Fouache, S. 1997). The rapid growth in telecommunication and computer networks throughout the world during the 80's created a huge market for this battery type. The VRLA industry finally spread to China in response to their telecommunications boom of the 90's (Wang 1998). Prior to the 90's, the Chinese battery industry produced mainly flooded Pb-acid batteries for agriculture and transport (e.g. trucks, train infrastructure). Between 1990 and 1996, sales of VRLAs grew from 60,000 to 730,000 kWh, primarily for telecommunications applications. In the late 90's, production of small VRLA and flooded SLI batteries grew in response to the growing automobile, gasoline scooter, and electric bike markets (Eckfeld, Manders et al. 2003).

The electric bike battery industry in China is fairly dispersed. Average production volume per company is 11,700 kWh/yr (81,000 modules/yr) per company. Because of this decentralization, it is more difficult for government to regulate production, quality, and environmental impacts. This results in lower quality batteries entering the market, batteries containing toxic performance enhancing materials such as Cadmium, and lead waste issues.2 In 2006, 23 % of the e-bike battery companies inspected did not pass the minimum quality standards set by the national inspection bureau (Center 2006). It is expected that considerable consolidation within the industry will occur, as occurred in the European battery industry during the 90s (Eckfeld, Manders et al. 2003; Razelli 2003).

The advanced battery market in China makes up 15 % of the total market. These companies primarily produce batteries for consumer electronics applications used throughout the world. There are fewer than 10 companies producing Li-ion batteries for electric bikes or vehicles. The first Li-ion battery was commercialized by Sony in 1991 in Japan for use in consumer electronics. It was first used for motive power in 1997 by Nissan in their Prairie Joy EV. Few LAB manufacturers in China are making advanced batteries. From one manufacturer's perspective, Li-ion batteries are still dangerous, costly, and the market for LABs is still large and expanding.

### VRLA Production

Most of the world's small VRLAs (< 25 Ah) are manufactured in Asia and exported around the world due to low labor costs, land cost, and loose environmental standards (Eckfeld, Manders et al. 2003). The process for making large modules is roughly the same as making small modules. Manufacturing is labour intensive yet exhibits low profit margins. Battery quality can be considerably different among manufacturers and is a key distinguishing factor between top brands from the hundreds of smaller competitors. Key differences from company to company are linked to differences in materials (i.e. alloy plate formula, electrolyte formula, AGM material, etc.) and manufacturing (i.e. dust control, quality inspection stations, etc.).

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1. Assumes average module is 12 V x 12 Ah, a typical e-bike battery size
2. Personal communications with one large Chinese battery manufacturer

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<table>
<thead>
<tr>
<th>Application</th>
<th>Function</th>
<th>Battery Size</th>
<th>Technology</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>Portable power</td>
<td>$10^1$-$10^2$ Wh</td>
<td>Li-ion, Ni-MH</td>
<td>Low weight &amp; volume, high energy</td>
</tr>
<tr>
<td>Energy</td>
<td>Remote-area power supply</td>
<td>$10^2$-$10^3$ Wh (Bullock 2003)</td>
<td>FLA, VRLA</td>
<td>Low maintenance, high reliability, long life</td>
</tr>
<tr>
<td>Industrial</td>
<td>Back-up power</td>
<td>$10^2$-$10^3$ Wh</td>
<td>Ni-MH, Li-ion</td>
<td>High specific power</td>
</tr>
<tr>
<td>Transportation</td>
<td>Motive Power (hybrid)</td>
<td>$10^2$-$10^3$ Wh</td>
<td>VRLA, Ni-MH, Li-ion</td>
<td>High specific energy, low cost</td>
</tr>
<tr>
<td></td>
<td>Motive Power (battery only)</td>
<td>$10^2$-$10^3$ Wh</td>
<td>FLA, VRLA</td>
<td>low cost, high reliability</td>
</tr>
<tr>
<td></td>
<td>Auxiliary power (SLI)</td>
<td>$10^2$ Wh</td>
<td>VRLA, FLA</td>
<td>Abuse tolerant, long life, low cost</td>
</tr>
<tr>
<td></td>
<td>Traction</td>
<td>$10^3$ Wh</td>
<td>FLA, VRLA</td>
<td>Abuse tolerant, long life, low cost</td>
</tr>
</tbody>
</table>

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Figure 2: China Batteries

Table 1: Battery Applications (Dell and Rand 2001)
LI-ION PRODUCTION

LIBs, whether for electric vehicles, electric bikes, and consumer electronics, are all produced using similar processes, described in depth in Gaines 2000. Hence, a single manufacturer can produce battery sizes for a wide range of applications, from portable consumer electronics to EVs (Broussely 1999). LIBs can be designed for high power or high energy depending on cell size, thickness of the electrode, and relative quantities of material used (Gaines and Cuenca 2000). High power cells are generally smaller in order to dissipate the higher heat load. Both types use the same current collectors and separators. Lithium resources are abundant in China. As of 2000, they were the 2nd largest producer of Lithium in the world and in 2004 produced 18,000 metric tons (Ober 1999; Tse 2004).

Batteries For E-Bikes

This section describes VRLA and Li-ion batteries for use in e-bikes and identifies the most important battery characteristics in this application. Based on the thriving market, today's batteries appear to satisfy the cost, range, weight, and other requirements demanded by e-bike users.

VRLA

In 2005, 95 % of e-bikes in China used VRLA, and 5 % used Li-ion (Jamerson and Benjamin 2005). VRLA battery packs consist of three to four 12 V modules (12, 14 or 20 Ah capacity) for a total voltage of 36 or 48 V and energy capacity of 0.4-1 kWh. VRLA for e-bikes differ from SLI VRLAs used in automotive applications in that they are able to be deep-cycled. E-bike batteries are typically of the absorbptive glass mat (AGM) type, meaning they use an absorbed sulphuric acid electrolyte in a porous separator, as opposed to a gelled silica/acid separator in Gel-type VRLAs. Whereas standard SLI automotive batteries are typically only discharged 10-15 %, deep-cycle batteries for motive applications like e-bikes are discharged 80-90 % (Mosely 2004). Battery makers claim the key distinguishing factor of their batteries is lifetime and stability (i.e. mean time before failure). Most domestic manufacturers do not report defect rate of their products, but one study by a battery manufacturer reports a 3-9 % defect rate of e-bike batteries from three domestic manufacturers.

LITHIUM ION

Li-ion battery packs for e-bikes range from 24 V-37 V with capacity of 5-60 Ah. The market for Li-ion e-bikes in China is still small. In Japan and Europe however, Li-ion and Ni-MH are the dominant battery type, though annual e-bike sales (200,000/yr and 100,000/yr, respectively) are significantly lower than in China (Jamerson, 2006).

E-BIKE BATTERY REQUIREMENTS

VRLA is the current dominant technology in e-bikes. LIB and Ni-MH battery manufacturers are trying to tap into this large growing market. While Ni-MH battery companies have had limited success thus far, some LIB companies are expecting 100 % growth in sales in the next year and predict the market for LIB e-bikes will grow to 20 % of total annual e-bike sales in the next 5 years. Ultimately, the battery type that succeeds will depend on its performance relative to the alternative based on the following key factors:

Cost: battery cost is likely the most critical factor in battery choice, as evidenced by the market dominance of VRLA. Despite the significant advantages in energy density and lifetime of Li-ion, VRLA is much lower cost. The emphasis on cost may change as average income increases throughout China.

Cycle life: lifetime of the battery is critical because it affects users long-term operating cost. E-bike length of ownership can last 3-5 years depending on use. However, most users find they need to replace their battery after 1-2 years due to serious performance degradation (2006).

Weight: Vehicle range is one of the most critical metrics for e-bike users due to the long recharge times. Range depends on stored energy capacity, which for a given specific energy (Wh/kg), determines battery weight. Battery weight is limited by the user's physical strength, since some users require removing the battery from the bike to recharge it in their apartment/home. Weight for VRLA e-bike batteries range from 12 kg for BSEB to 26 kg for large SSEB. Users with batteries over 20 kg often roll the entire e-bike into their house/apartment if there is an elevator or find a convenient place to recharge on ground level.

If SSEBs get bigger and more powerful (depends on national and local e-bike standards), the ability to move the vehicle when power-off (e.g. parking) may be a limiting factor to battery weight. For comparison, a large 100 cc gasoline scooter weighs 95 kg. If an SSEB weighs much more than this, it may be too difficult to move when powered off. There may be a practical limit to the maximum range desired by the consumer. Surveys show that the average e-bike user in three medium to large-sized cities only commute 9.3 km/day (Weinert, Ma et al. 2006). Long-distance commutes are uncomfortable on a two-wheeler, especially in bad weather. The highest-range e-bike on the market in 2006 is quoted as 70 km.

Charging safety: charging for VRLAs is considerably more flexible and tolerant to improper recharging than Li-ion batteries in terms of risk of damage to self and property. As evidenced by the worldwide Sony battery recall of 2006, Li-ion batteries still entail risk, which is amplified as cell size increases.

Temperature effects: e-bike batteries are used over a wide range of temperatures from winter lows of -40 C in China’s northeast to summer highs of +40 C in the southwest. A battery’s performance at extreme temperatures will affect range and lifetime and is thus an important factor.

Other Factors

Volume: volume is likely a secondary factor since the weight constraint of a battery limits energy capacity before volume is constrained. Batteries for SSEBs are usually stored in the floorboard underneath the feet, or for BSEBs along one of the frame’s crossbars. The largest battery pack in a SSEB is roughly 9.3 L. Extra volume through smaller battery size may be valued slightly for extra storage space.

Speed: top speed is determined by battery power density and motor size. The power density of VRLA 230 W/kg is more than sufficient to meet the 350 W peak motor power limit of e-bikes. While national e-bike standards limit top speed to 20 kph, most BSEBs can reach 25-30 kph, and high-power SSEB can reach 35-40.
E-Bike Battery Performance And Price

Advances in VRLA technology over the past decade have made e-bikes affordable, efficient, and practical (Weinert, Ma et al. 2006). Li-ion technology has also improved to a point such that Li-ion e-bikes are now marketed in China. The technical performance and price of VRLA and Li-ion batteries from Chinese manufacturers are compared in this section.

VRLA PERFORMANCE AND PRICE

The following table compares the key performance characteristics and price of VRLA (AGM type) batteries from several manufacturers for two popular e-bike battery module sizes: 20 and 12 Ah. VRLA costs for 12 V-12 Ah modules from three Chinese and one Japanese brand are also compared in Table 2.

To verify performance, we obtained 12 V-12 Ah modules from 4 large e-bike battery suppliers and measured their performance using an Arbin battery testing apparatus. Current and power levels for these tests were chosen based on the typical demands of an electric bike. Table 3 shows the results of the tests. The discharge characteristics are given in amp-hrs (Ah) and Watt-hours (Wh) per kg and the maximum power (W/kg) at 9.6 V.

The results from the tests exceed the manufacturers stated claims on energy density and were considered to be good for a VRLA of such small cell size.

Cycle life

Since cycle-life testing requires over a year, the authors relied on data provided by manufacturers and warranty data. Manufacturers report cycle life between 400-550 cycles, though independent testing of 4 brands by an anonymous manufacturer revealed cycle life of 300-400 cycles. This translates into a typical 1 to 1.5 year warranty, provided by most e-bike manufacturers.

Defect Rate

The industry average defect ratio for e-bikes is 5 % while only 0.10 % for other types of LABs. The main reason for this large difference is the extreme variation in charging and discharging experienced in e-bikes compared to other applications. There was a noticeable difference in the defect rate of foreign brands compared to Chinese brand LABs. According to interviews with various battery companies (1 so far), improving the lifetime and stability of the battery is the key area of research.

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4. Comparative study of battery performance from large e-bike battery suppliers, conducted by one battery manufacturer, 2006
Table 4 compares the Li-ion battery performance and price from various Chinese and international manufacturers. Due to the limited amount of companies making Li-ion e-bike batteries, cost data are presented for only three companies. The stated cycle life of LIBs from 3 manufacturers is 600-800 cycles. The actual warranty on their batteries is 1 year.

**Battery Transitions In The E-Bike Market**

The transition from VRLA to Li-ion batteries in e-bikes is progressing in China, based on interviews with LIB companies. The pace and extent of this transition is still uncertain, since the e-bike market is currently very cost-conscious. The following section uses the battery performance and cost data and battery choice criteria from the previous sections to compare e-bikes using VRLA versus Li-ion.

**COMPARISON OF KEY FACTORS FOR VRLA AND LI-ION**

The characteristics of VRLA and Li-ion batteries are compared in Table 5. The batteries are sized for an average 48 V SSEB with 60 km range (0.90 kWh) and 350 W motor. This type of e-bike was chosen since it is a popular model for a 3-person family.

It sets a practical upper bound to maximum battery size in an e-bike, and is comparable in performance to a 50 cc gasoline scooter. Battery characteristics assumed are list in the table. An e-bike energy consumption of 0.014 kWh/km, and average user travel distance of 15 km/day was assumed in making the battery comparisons. The effect of a smaller battery weight on energy consumption was neglected.

These results suggest that the cost differential between the battery types dominates all other factors. The added lifetime from the more durable Ni-MH and Li-ion is likely not valued very high since the life of an e-bike is not much greater than 3-4 years. The 18 kg mass difference between Pb-acid and Li-ion, however, is significant since a 26 kg battery is likely unmanageable for the majority of e-bike users. If those users only option to recharge is to carry the battery indoors, they may be inclined to use Li-ion.

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5. Cost for Li-ion: Zhengke Li-ion battery e-bike (anonymous source)
JAPAN AND EUROPE
The size of the e-bike market in Japan and Europe is 200,000/yr and 100,000/yr, respectively. This is the same production rate reported in 2002 for these two countries indicating a stagnant market. Electric bikes in these markets are fairly different from Chinese e-bikes in that these bikes are typically the pedal-assist type or "pedelec". The user typically pedals but is assisted by a small electric motor when extra power is desired (e.g. acceleration, uphill climbs). Most pedelec e-bikes use Ni-MH or Li-ion batteries. Battery capacity ranges from 0.2-0.6 kWh, motor size ranges from 150-250 W, and prices range from $700-1,500.

Evaluating the Potential Shift from E-bikes to EVs
Automakers have attempted to mass market battery electric cars several times in last 50 years but have failed each time. Battery cost, energy density, and lack of recharging infrastructure remain still remain large barriers to commercialization (Future-Drive 1995). In this section, the feasibility of transitioning to EVs in China by leveraging the growing e-bike battery market is considered. To evaluate this possibility, important similarities and differences between e-bikes and electric vehicles are identified and discussed as to how they help or impede a transition to EVs. Other important drivers that may affect the transition are also considered.

KEY DIFFERENCES
EV's have a high "vehicle mass: passenger mass" ratio and thus require high power (30-100 kW) from the electric motor. This ratio is the key difference between e-bikes and cars, as seen in table 6 for various sizes of electric two-wheel and four-wheel vehicles using different battery technology.

KEY SIMILARITIES
Both applications require high energy density, long life, and deep-cycle ability. As outlined in a previous section, the process of making VRLA and Li-ion batteries for e-bikes is very similar to making EV batteries. Cell size is the biggest difference between the two applications. Hence, production experience with e-bike batteries will transfer to EV batteries.

IMPORTANT DRIVERS FOR THE TRANSITION
A transition from batteries in e-bikes to batteries in personal vehicles in China will depend on a number of key factors/drivers, listed below:

Technological learning: the e-bike battery market is fiercely competitive (300 companies) which is a driving force behind technological progress on batteries. There are three categories of learning associated with technology development: research and development (R&D), manufacturing, and in-service use. The e-bike battery market is accelerating learning in all three categories.

R&D: Breakthroughs in battery material or design which enable significantly higher specific energy, power, lifetime, or lower cost

### Table 5: Comparison of Battery Types (with Assumptions)

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>VRLA</th>
<th>Li-ion and 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($)</td>
<td>75</td>
<td>424</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>26</td>
<td>8</td>
</tr>
<tr>
<td>Lifetime (yrs)</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Volume (L)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Max Theoretical Power (kW)</td>
<td>6.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Recharging Safety</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Temperature effects</td>
<td>moderate</td>
<td>high</td>
</tr>
</tbody>
</table>

1. Data for VRLA come from Chinese battery measurements and product brochures.

### Table 6: Battery Characteristics for Various Electric Vehicle Types

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Brand</th>
<th>Battery Type</th>
<th>Battery Weight (kg)</th>
<th>Battery Capacity (kWh)</th>
<th>Vehicle Weight (kg)</th>
<th>Range (km)</th>
<th>Ratio of battery to vehicle weight</th>
<th>Vehicle mass / passenger load</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSEB</td>
<td>Luyuan</td>
<td>VRLA</td>
<td>12</td>
<td>0.43</td>
<td>49</td>
<td>31</td>
<td>0.24</td>
<td>0.65</td>
</tr>
<tr>
<td>SSEB</td>
<td>Luyuan</td>
<td>VRLA</td>
<td>16</td>
<td>0.50</td>
<td>56</td>
<td>36</td>
<td>0.29</td>
<td>0.75</td>
</tr>
<tr>
<td>SSEB</td>
<td>Luyuan</td>
<td>VRLA</td>
<td>26</td>
<td>0.82</td>
<td>95</td>
<td>58</td>
<td>0.27</td>
<td>1.27</td>
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<tr>
<td>BSEB</td>
<td>Lantian</td>
<td>Li-ion</td>
<td>3</td>
<td>0.36</td>
<td>26</td>
<td>26</td>
<td>0.13</td>
<td>0.35</td>
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<tr>
<td>BSEB</td>
<td>Panasonic</td>
<td>Li-ion</td>
<td>2</td>
<td>0.21</td>
<td>25</td>
<td>15</td>
<td>0.09</td>
<td>0.33</td>
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<tr>
<td>4WV</td>
<td>Reva</td>
<td>Pb-acid</td>
<td>274</td>
<td>9.6</td>
<td>750</td>
<td>80</td>
<td>0.37</td>
<td>10</td>
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<tr>
<td>4WV</td>
<td>Ford Think City</td>
<td>Ni-Cd</td>
<td>245</td>
<td>100 Ah</td>
<td>927</td>
<td>104</td>
<td>0.26</td>
<td>12.4</td>
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<tr>
<td>4WV</td>
<td>Toyota e-Com</td>
<td>Li-ion</td>
<td>39</td>
<td>4.3</td>
<td>310</td>
<td>100</td>
<td>0.13</td>
<td>4.1</td>
</tr>
</tbody>
</table>

1. Assumes one 75 kg passenger for each vehicle.
Manufacturing: learning how to assemble batteries cheaper and with higher quality

Operational: learning how batteries operate in ‘real-world’ use

Strong demand for Li-ion batteries in the consumer electronics sector will help EV batteries move down the cost/experience curve (Anderman 2003). Battery production, whether for electronics or e-bikes, achieves learning in the first two categories because the materials and manufacturing process for large and small Li-ion cells are similar.

Only e-bikes, however, will drive the operational learning progress for EV-type battery technology. The important areas of VRLA and Li-ion technology for which this type of learning is the most useful include safe charging and discharging of Li-ion batteries; cell degradation over time; operation in extreme environments (low and high temperatures); and cell variability within a battery pack and its effects on lifetime. Using deep cycle VRLA and Li-ion batteries in e-bikes provides developers invaluable experience on how batteries fail in real-life environments.

Vehicle Size: batteries are better suited for smaller vehicles, as evidenced in the Table 6. Policy changes or high fuel prices could cause the market for smaller more efficient vehicles to grow. There has been some development underway at Tongji and Wuhan University of Technology on producing a light compact electric car.

Vehicle Powertrain: hybrid electric vehicles sales have been steadily increasing since the early 00’s and plans for plug-in electric vehicles have been announced by at least one major car maker. Lead-acid battery electric vehicles sales are still low even for small, low speed neighbourhood electric vehicles. The advanced batteries (Ni-MH or Li-ion) (Razelli 2003) replace the lead-acid batteries in full-function electric vehicles and full-hybrids using high voltage and high power electric motors. This is a similar transition to that which could occur in e-bikes and e-scooters.

Automotive SLI/accessory batteries could switch from Pb-acid VRLA to Ni-MH (Bullock 2003) or LIB as electrical demands in cars continue to increase. Table 7 compares the power system requirements of an e-bike vs. other larger electric vehicles.

Table 7: Electric Vehicle Comparisons

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total battery pack capacity (kWh)</td>
<td>0.4-0.6</td>
<td>0.8-1.0</td>
<td>16</td>
<td>5-1.5</td>
<td>5-10</td>
</tr>
<tr>
<td>Maximum current</td>
<td>15</td>
<td>20-30</td>
<td>100-200</td>
<td>200-300</td>
<td>200-300</td>
</tr>
<tr>
<td>Voltage</td>
<td>36</td>
<td>48</td>
<td>100-200</td>
<td>150-300</td>
<td>150-300</td>
</tr>
<tr>
<td>Modules/pack (typical)</td>
<td>3</td>
<td>4</td>
<td>10-20</td>
<td>15-30</td>
<td>15-30</td>
</tr>
<tr>
<td>Cells in series</td>
<td>18</td>
<td>24</td>
<td>50-100</td>
<td>75-150</td>
<td>75-150</td>
</tr>
<tr>
<td>Peak motor power (kW)</td>
<td>0.24</td>
<td>.50-1</td>
<td>51</td>
<td>20-50</td>
<td>50-75</td>
</tr>
<tr>
<td>(18 avg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum depth of discharge (%)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>3-5</td>
<td>80</td>
</tr>
</tbody>
</table>

¹. Newly designed Chinese concept EV: equipped with 24 12V55Ah LAB battery

Obstacles

There are many challenges arising from the differences in e-bike and EV batteries.

The automotive market requires larger number of cells per battery and longer life (Anderman 2006). Therefore, the e-bike market may be a more forgiving market in the near-term while the technology is still developing. Experience with computer batteries is not relevant for vehicle applications.

Cost: The current high cost of batteries relative to transmission/engine drivelines is the major barrier to EV commercialization. Speculating on the future cost of batteries is difficult since it is a function of cumulative production volume, design, material composition, and raw material price. This is particularly difficult for a new technology like LIB, but it is not without uncertainty even for a developed technology like VRLA. Production volumes per company are expected to rise as VRLA demand grows and the industry consolidates to fewer companies. Raw materials cost is also variable. Lead price increased from $ 500-$ 600/ton (2006$) in 2002 to $ 1,000-1,600/ton in 2006 and was $ 1,624 as of January 2007 (2006). To further complicate matters, a battery in five years will likely have better performance than a battery today. To illustrate this, the historic cost of one manufacturer’s price history versus production volume for VRLA is shown in Table 8.

Li-ion battery technology is still relatively new (12 years) so there are potentially many opportunities for cost reductions. Material substitution could make a large impact since 75 % of the total battery cost is due to materials (Gaines and Cuenca 2000). Research and development efforts are focused on using more inexpensive and chemically stable materials.

Infrastructure: one reason why electric bikes in China are so popular is that their batteries are portable. This greatly expands the network of available charging stations to anywhere with a 120 V AC outlet (i.e. every residence and business in the country). The ubiquity of charging points for e-bikes eliminates a key barrier that has plagued past attempts at transitioning to alternative fuel vehicles: fueling infrastructure. As seen in Table 6, batteries for EVs are much larger than for e-bikes, even if using the lightest weight Li-ion technology. To recharge an EV thus requires the user to have daily access to a high voltage charging station. In a country where 50 % of people live in multi-level residences in dense urban areas, providing uni-
versal access to recharging facilities is likely to be extremely challenging.

Cell Variability: VRLA batteries exhibit considerable scatter in performance (i.e. no two modules have exactly the same electrical characteristics). This results from slight variations in the properties of materials and the electrodes used to assemble the cells due to the imprecise, labor-intensive manufacturing process (Rossinot, Lefrou et al. 2003). When connecting several modules in series as in the case of a 36 V (3 module) or 48 V (4 module) e-bike battery pack, there is risk of significant variability in the module voltage. This causes accelerated aging since the “weakest” module of the pack ages more rapidly (Rossinot, Lefrou et al. 2003).

Because EV battery packs are much larger than e-bike packs, the number of cells connected in series increases from 18-24 to > 100, as shown in Table 7. The problem of cell variability is thus exacerbated in EVs. This problem could be reduced if battery quality is improved through better manufacturing or design.

Safety: For Li-ion batteries, safety risks such as battery overheating, combustion, and explosive disassembly increase with the amount of energy contained within the cell/battery pack. EVs battery cells are larger than e-bike cells. Another safety concern is with the high voltages of EVs (300 V vs. 36-48 V). This creates problem of user/emergency responder/technician safety.

Conclusions

There has been a rapid transition to electric bikes and scooters in China with the market reaching nearly 16 million/year in 2006. This e-bike growth has been in part due to improvements in rechargeable valve-regulated lead acid (VRLA) battery technology in China. Further improvements in this technology and a transition from VRLA (the dominant e-bike battery type) to lithium-ion batteries (LIB) could have a large impact on the future market growth of electric vehicle transportation in China and abroad.

VRLA and Li-ion battery technology for e-bikes has been assessed. For VRLA, a specific energy of 34 Wh/kg and a cost of $ 88/kWh were determined for a number of international brands. Li-ion batteries in China on average have specific energy of 106 Wh/kg and cost of $ 590/kWh. Battery technology will likely progress given the size and growth of the battery market for e-bikes. A widespread shift from VRLA to Li-ion batteries seems improbable for the mass market given the cost premium relative to the performance advantages of LIB.

E-bike and EV battery similarities suggest that R&D, manufacturing, and operational experience gained in the e-bike battery market will transfer to EV batteries for small, 4-wheel electric cars. Costs will decrease with cumulative production volume. However, there are some major obstacles facing EVs that will not be easy to overcome in China. The largest is the issue of recharging infrastructure, which will need to be built since EV batteries are not portable like e-bike batteries. Even with advancements in Li-ion specific energy, battery packs will be too heavy to remove from the vehicle to a charging station in or near the residence of the EV owner. Cell variability, safety issues related to high-voltage and unstable battery chemistry in Li-ion are other obstacles.

References


Table 8: Historic battery price vs. production volume of one battery company

<table>
<thead>
<tr>
<th></th>
<th>2002</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price ($/kWh) (12V12Ah module)</td>
<td>71</td>
<td>87</td>
</tr>
<tr>
<td>Assembly lines</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Production Volume (modules/year)</td>
<td>16,000</td>
<td>80,000</td>
</tr>
<tr>
<td>Lifetime (guaranteed) (months)</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Lead price ($/ton in 2006$)</td>
<td>$550</td>
<td>$1500</td>
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</table>
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