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Lead-acid and lithium-ion batteries for the Chinese electric bike market and implications on future technology advancement

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Abstract

China has been experiencing a rapid increase in battery-powered personal transportation since the late 1990s due to the strong growth of the electric bike and scooter (i.e. e-bike) market. Annual sales in China reached 17 million bikes year^{-1} in 2006. E-bike growth has been in part due to improvements in rechargeable valve-regulated lead-acid (VRLA) battery technology, the primary battery type for e-bikes. Further improvements in technology and a transition from VRLA to lithium-ion (Li-ion) batteries will impact the future market growth of this transportation mode in China and abroad.

Battery performance and cost for these two types are compared to assess the feasibility of a shift from VRLA to Li-ion battery e-bikes. The requirements for batteries used in e-bikes are assessed. A widespread shift from VRLA to Li-ion batteries seems improbable in the near future for the mass market given the cost premium relative to the performance advantages of Li-ion batteries. As both battery technologies gain more real-world use in e-bike applications, both will improve. Cell variability is a key problematic area to be addressed with VRLA technology. For Li-ion technology, safety and cost are the key problem areas which are being addressed through the use of new cathode materials.

Keywords: Battery; Electric bike; Electric scooter; Valve-regulated lead-acid; Lithium-ion

1. Introduction

The Chinese electric bike market has expanded more rapidly than any other vehicle mode in the last 7 years, from nearly 40,000 in 1998, to an estimated 15–18 million in 2006 [1,2]. 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). These two types (referred collectively henceforth as "e-bikes"), are shown in Fig. 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. National and many local governments promote them 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 bicycle mode share proportion.

Electric bikes have been by far the most successful battery electric vehicle application in history with estimated cumulative production of ∼30 million by 2007 [3]. 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 scoot-

Abbreviations: VRLA, valve-regulated lead-acid; SSEB, scooter-style electric bike; BSEB, bicycle-style electric bike; AGM, absorptive glass mat; FLA, flooded lead acid; LAB, lead-acid battery; SLI, starting, lighting and ignition

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Fig. 1. Bicycle style and scooter-style electric bikes.

ers in price and performance [4]. E-bikes using VRLA achieve low cost ($150–300) and adequate range (30–70 km/8 h charge). The power system characteristics of e-bikes are shown in Table 1. Because most e-bikes use either VRLA or Li-ion, this analysis will focus on these two battery types.

1.1. Motivation

Urbanization and income levels are both rising rapidly in China. As a result, the low and middle classes are demanding faster, more comfortable transportation options. Survey data from three major cities in China indicate that today's bicycle users (450 million) will most likely purchase an e-bike as their next mode of transport [5]. This mode shift choice has far-reaching impacts around the world in terms of battery technology development and the future market of electric two-wheelers.

This market development has important implications on the environment and public health. E-bikes are an extremely energy efficient (∼50 mile kWh^{-1}) mode of personal transportation with zero tail-pipe emissions. Life-cycle carbon emissions per kilometre travelled of an e-bike are roughly one-fifth that of a gasoline-fuelled car [6]. E-bikes are also having positive effects in cities battling poor air quality by displacing gasoline-powered scooters.

1.2. Methodology

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 Pb-acid and Li-ion batteries. Batteries from some of these manufacturers have been laboratory-tested.

Table 1
Electric two-wheeler power system characteristics

Specifications	Bicycle-style e-bike	Scooter-style e-bike
Total battery pack capacity (kWh)	0.4–0.6	0.8–1.0
Maximum current	15	20–30
Voltage	36	48
Modules/pack (typical)	3	4
Cells in series	18	24
Peak motor power (kW)	0.24	0.50–1
Maximum depth of discharge (%)	80	80

2. 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^{-1}) 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 (1–2 kWh for large electric scooters).

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 are used to provide high bursts of power output to start an engine (∼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 2 summarizes these battery applications and their requirements.

3. 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. Estimates on the production volume capacity (kWh) of Pb-acid batteries range from 35 to 67 million kWh $year^{-1}$, produced by more than 2000 companies [3,7]. Three hundred of these companies specialize in e-bike batteries with an estimated annual production between of 3.5 and 9 million kWh $year^{-1}$ in 2005. Calculations based on the annual e-bike sales in 2006 and assumed after-market sales to the existing e-bike population reveal a much higher annual production between 15 and 20 million kWh $year^{-1}$ [8]. Fig. 2 shows the proportions of different battery types in China.

Table 2
Battery applications [28]

Application	Function	Battery size	Technology	Requirements
Electronics	Portable power	10^1 to 10^2 Wh	Li-ion, Ni-MH	Low weight and volume, high energy
Energy Industrial	Remote-area power supply Back-up power	10^3 to 10^5 Wh [29]	FLA, VRLA	Low maintenance, high reliability, long life
Transportation	Motive power (hybrid)	10^2 to 10^3 Wh	Ni-MH, Li-ion	High specific power
	Motive power (battery only)	10^2 to 10^3 Wh	VRLA, Ni-MH, Li-ion	High specific energy, low cost
	Auxiliary power (SLI)	10^2 Wh	FLA, VRLA	Low cost, high reliability
	Traction	10^3 Wh	FLA, VRLA	Abuse tolerant, long life, low cost

VRLA batteries were first introduced into UPS applications in America and Europe in the 1970s because of their low maintenance requirements and high reliability over traditional flooded lead-acid [9]. The rapid growth in telecommunication and computer networks throughout the world during the 1980s created a huge market for this battery type. The VRLA industry finally spread to China in response to their telecommunications boom of the 1990s [10]. Prior to the 1990s, the Chinese battery industry produced mainly flooded Pb-acid batteries for agriculture and transport (e.g. trucks and train infrastructure). Between 1990 and 1996, sales of VRLA batteries grew from 60,000 to 730,000 kWh, primarily for telecommunications applications. In the late 1990s, production of small VRLA and flooded SLI batteries grew in response to the growing automobile, gasoline scooter, and electric bike markets [11].

One of the main problems with China's Pb-acid battery industry is that it is difficult for government to regulate production, quality, and environmental impacts. This is in part due to the large number of relatively small manufacturers spread throughout the country. This high industry decentralization results in lower quality batteries entering the market and batteries containing toxic performance enhancing materials such as cadmium, and lead waste issues. In 2006, 23% of the e-bike battery companies inspected did not pass the minimum quality standards set by the national inspection bureau [7]. It is expected that considerable consolidation within the industry will occur, as occurred in the European battery industry during the 1990s [11,12].

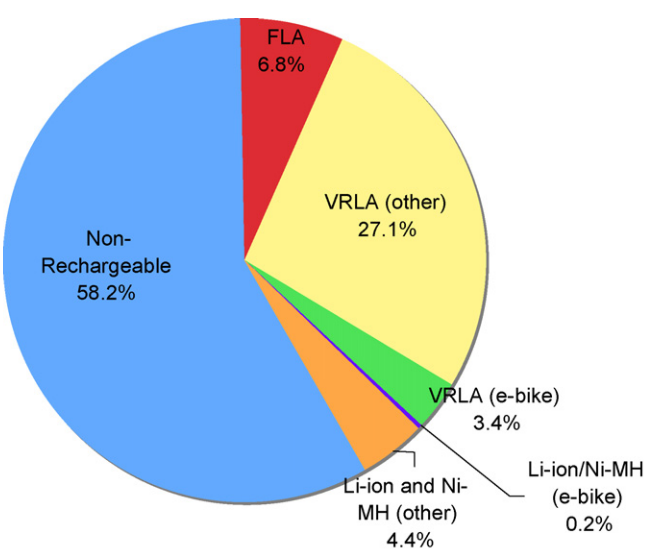

Fig. 2. The China battery market by battery type.

The advanced battery market in China makes up 15% of the total market, which includes batteries using lithium or nickel compounds. These companies primarily produce batteries for consumer electronics applications used throughout the world. The first Li-ion battery was commercialized by Sony in 1991 in Japan for use in consumer electronics. 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.

3.1. 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 [11]. The process for making large modules is roughly the same as making small modules. Manufacturing is labor 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.) [13].

3.2. Li-ion production

Li-ion batteries, whether for electric vehicles, electric bikes, and consumer electronics, are all produced using similar processes [14]. Hence, a single manufacturer can produce battery sizes for a wide range of applications, from portable consumer electronics to EVs [15]. Li-ion batteries can be designed for high power or high energy depending on cell size, thickness of the electrode, and relative quantities of material used [14]. 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 second largest producer of lithium in the world and in 2004 produced 18,000 metric tonnes [16,17].

4. 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.

4.1. VRLA

In 2005, it is estimated that 95% of e-bikes produced in China used VRLA; the rest use Li-ion, Ni-MH, or NiCd though the majority of these are exported [1]. 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 absorptive 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% [18]. 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.

4.2. Lithium-ion

Li-ion battery packs for e-bikes range from 24 to 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 in these regions are two orders of magnitude lower than in China.

4.3. E-bike battery requirements

VRLA is the current dominant technology in e-bikes. Li-ion and Ni-MH battery manufacturers are trying to tap into this large growing market. Some Li-ion battery companies are expecting 100% growth in sales in the next year and predict the market for Li-ion battery 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 several key criteria, described below. These criteria are compared for VRLA and Li-ion batteries in Section 5.

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 [19].

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 ($Wh\,kg^{-1}$), determines battery weight. Weight for VRLA e-bike batteries typically range from 12 kg for BSEB to 26 kg for large SSEB. There are practical battery weight limitations based on the user's physical strength, since some users require removing the battery from the bike to recharge it in their apartment/home/office. Many users however 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. In terms of practical limitations on consumer for demand range, surveys of e-bike users in three medium to large-sized cities show that average commute distance is 9.3 km day^{-1} [4]. However, there are high-range e-bikes on the market that can achieve range of up to 80 km $charge^{-1}$.

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 batteries performance at extreme temperatures will affect range and lifetime and is thus an important factor.

4.3.1. 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 $W\,kg^{-1}$ 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 $km\,h^{-1}$, most BSEBs can reach 25–30 $km\,h^{-1}$, and high-power SSEB can reach 35–40.

Charge time: Since most people charge their battery overnight when electricity is cheapest, the maximum acceptable charge time is likely 8 h. Full battery capacity should be restored to full charge by an 8-h charge regime using 220 V ac.

5. E-bike battery performance and price

Advances in VRLA technology over the past decade have made e-bikes affordable, efficient, and practical [4]. Li-ion technology has also improved to a point such that Li-ion e-bikes are now marketed in China, in addition to being exported throughout the world. The technical performance and price of VRLA and Li-ion batteries from Chinese manufacturers are compared in this section.

5.1. VRLA battery performance and price

The key performance characteristics and price of VRLA (AGM type) batteries from several manufacturers for two popu-

Table 3
Twenty and 12 Ah VRLA module characteristics of various manufacturers[a]

Manufacturer	Capacity (Ah) (2 h)[b]	Weight (kg)	Volume (L)	Specific energy ($Wh\,kg^{-1}$)	Energy density ($Wh\,L^{-1}$)	Cost ($\$\,kWh^{-1}$)
Ritar	12	4.4	1.39	33	104	86.4
Tian Neng	12	4.1	1.39	35	104	80.5
Chaowei	10	4.1	1.39	29	86	81.9
Panasonic	12	3.8	1.39	38	104	104.3
Sunbright	10	4.1	1.39	29	86	
Huafu	12	4.2	1.39	34	104	
Average				**33**	**97**	**$88**
Ritar	20	7.2	2.37	33	101	
Chaowei	20	10	3.63	24	66	
Panasonic	20	6.6	2.30	36	104	
Sunbright	20	7.0	2.31	34	104	
Huafu	20	6.8	2.40	35	100	
Average				**33**	**95**	

[a] Information obtained from company websites. Price data is the purchase price from a retailer.
[b] A "2 h" rate is a commonly used metric for testing battery capacity. It represents the discharge rate used to completely discharging the battery in 2 h.

lar e-bike battery module sizes (20 and 12 Ah) are compared in Table 1. VRLA costs for 12 V to 12 Ah modules from three Chinese and one Japanese brand are compared in Table 3. Note that the batteries tested are specifically designed for motive power, not SLI applications, which have different characteristics when deep-discharged.

To verify performance, we obtained 12 V to 12 Ah modules from four large e-bike battery suppliers and measured their performance using an Arbin BT2043 battery testing device. Current and power levels for these tests were chosen based on the typical demands of an electric bike. Table 4 shows the results of the tests. The discharge characteristics are given in Ah, $Wh\,kg^{-1}$, $W\,kg^{-1}$ at 9.6 V. The results from the tests exceed the manufacturers stated claims on energy density and are considered quite good for VRLAs of such small cell size.

5.1.1. 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 and 550 cycles, though independent testing of four brands by an anonymous manufacturer revealed cycle life of 300–400 cycles. This corresponds with typical 1–1.5 year warranties provided by most e-bike manufacturers.

5.1.2. Defect rate

The industry average defect ratio for e-bike batteries is 5% while only 0.10% for other types of LABs [20]. 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 one battery company, improving battery lifetime and stability is the key area of research.

5.2. Lithium-ion performance and price

Li-ion battery performance and price from various Chinese and international manufactures is compared in Table 5. Prices range from \$510 to \$760 kWh^{-1}. Due to the limited amount of companies making Li-ion e-bike batteries, price data is presented from only three companies. Data from another Chinese Li-ion battery manufacturer quotes *cost* between \$300 and \$600 kWh^{-1} (retail price is not provided) [21]. The stated cycle life of Li-ion batteries from three manufacturers is 600–800 cycles. The actual warranty on their batteries is 2 years.

6. 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 Li-ion battery 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.

Table 4
Performance of 12 V to 12 Ah VRLA battery modules from four battery manufacturers (*C*/2.4 discharge rate)

Company	Mass (kg)	Capacity (Ah)	Specific energy ($Wh\,kg^{-1}$)	Resistance (mΩ)	Max. power at 9.6 V ($W\,kg^{-1}$)
1	4.24	12.0	34.2	20	272
2	4.05	12.2	36.8	22	258
3	4.27	12.1	34.3	27	200
4	4.00	11.5	35.0	30	192
Average	**4.14**	**12.0**	**35.1**	**25**	**231**

Table 5
Characteristics of Li-ion modules from various manufacturers

Manufacturer	Capacity (Ah) (2 h)	Weight (kg)	Volume (L)	Specific energy ($Wh\,kg^{-1}$)	Energy density ($Wh\,L^{-1}$)	Power density ($W\,kg^{-1}$)	Price ($\$\,kWh^{-1}$)
Xingheng, high power	15	0.88	0.43	63	128	1261	
Xingheng, high power	7.5	0.41	0.16	68	173	1805	
Average, high power					151	1533	
Xingheng, high energy	30	1.0	0.45	111	249	111	510
Xingheng, high energy	10	0.37	0.15	100	241	200	527
Lantian	60	1.8	0.78	123	286	Unavail.	Unavail.
Lantian	18	0.6	0.31	111	215	Unavail.	Unavail.
Lantian	4.7	0.14	0.052	124	333	Unavail.	Unavail.
Citic Guoan MGL	50	1.95	0.95	97	201	Unavail.	Unavail.
Citic Guoan MGL	30	1.1	0.66	104	173	Unavail.	Unavail.
Citic Guoan MGL	10	0.47	0.19	81	198	Unavail.	Unavail.
Zhengke	11	Unavail.	Unavail.				505
Panasonic	Unavail.	Unavail.	Unavail.				761
Average, high energy				**106**	**237**	**156**	**$586**

6.1. Comparison of key factors for VRLA and Li-ion

The characteristics of VRLA and Li-ion batteries are compared in Table 6. 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 three-person family. It sets a practical upper bound to maximum battery size in an e-bike, and is comparable in performance to a 50 cm^3 gasoline scooter. Battery characteristics assumptions are also listed in the table. An e-bike energy consumption of 0.014 $kWh\,km^{-1}$, and average user travel distance of 15 $km\,day^{-1}$ 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.

Table 6
Comparison of battery types (with assumptions)

Results	VRLA	Li-ion [30]
Cost ($)	75	424
Mass (kg)	26	8
Lifetime (years)	3	9
Volume (L)	10	5
Max theoretical power (kW)	6.2	2.9
Recharging safety	High	Low
Temperature effects	Moderate	High
Assumptions	**VRLA[a]**	**Li-ion**
Specific energy ($Wh\,kg^{-1}$)	35	110
Energy density ($Wh\,L^{-1}$)	86	170
Power density ($W\,kg^{-1}$)	240	350
Cost ($\$\,kWh^{-1}$)	83	505[b]
Cycle life	300	800

[a] Data for VRLA come from Chinese battery measurements and product brochures.
[b] Zhengke Li-ion battery e-bike (anonymous source).

6.2. Japan and Europe

After China, the next largest e-bike market is Japan—with annual sales of 270,000 $bikes\,year^{-1}$ in 2006 and 13% average annual growth since 2000 [22]. In Europe, the market is estimated at 190,000 $bikes\,year^{-1}$ in 2006 [23]. Electric bikes in these markets are 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 to 0.6 kWh, motor size ranges from 150 to 250 W, and prices range from $700 to $2000.

7. E-bike market growth and battery technology advancement

The growing e-bike market will necessarily lead to further advancements in battery technology and a gradual transition to more advanced battery technologies. In turn, this battery advancement will expand the market for e-bikes in China and throughout the world, especially in developing countries with high two-wheeler use. This section describes the importance of technology learning to the advancement of battery technology, and the key areas where this learning is most important.

The principal reason for anticipated improvements in battery performance and cost is due to technological learning effects. 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.

Li-ion 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 cells are similar

[24]. Only e-bike battery production, however, will drive the operational learning progress for large-format battery cell technology. The key areas of technology improvements for which this type of learning will have the most impact are safe charging and discharging, cell degradation over time, operation in extreme environments (low and high temperatures), and cell variability within a battery pack and its effects on lifetime. Cell variability is a key issue with VRLA cells. Safety and cost are the key issues with Li-ion cells. These issues are explained in the following sub-sections.

7.1. 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 [25]. When connecting several modules in series as in the case of a 36 V (three module) or 48 V (four module) e-bike battery pack, there is often significant variability in the module voltage. This causes accelerated aging since the "weakest" module of the pack ages more rapidly [25].

7.2. 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. $LiCoO_2$ is commonly used material for small cell Li-ion batteries, but considered unsafe for large-format batteries [21]. New cathode materials such as $LiFePO_4$ are being introduced into Li-ion batteries for e-bikes, resulting in significantly safety improvements [26]. Hot-box heating and overcharge testing reveal safety advantages of $LiFePO_4$ over both $LiMn_2O_4$ and $LiMn_2O_4$ [27].

7.3. Cost

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 [14]. Research and development efforts are focused on using more inexpensive and chemically stable materials such as $LiFePO_4$ and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ for the cathode. Table 7 presents the cost, energy density, and cycle-life differences between the commonly used $LiCoO_2$ cathode and these two alternative materials. For $LiFePO_4$, energy density is sacrificed for lower cost and longer life, along with the safety advantages mentioned above.

Table 7
Performance characteristic of various cathode materials for Li-ion batteries [21]

Cathode material	$LiCoO_2$	$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$	$LiFePO_4$
Energy density (Wh kg^{-1})	180	170	130
Cycle life (cycles)	400	400	1000
Price (US $ kg^{-1})	30	22	12

8. Conclusions

There has been a rapid transition to electric bikes and scooters in China with the market reaching nearly 16 million year^{-1} 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 growth in the market and a transition from VRLA to lithium-ion batteries will in turn lead to greater improvements in performance and cost.

VRLA and Li-ion battery technology for e-bikes has been assessed. For VRLA, a specific energy of 34 Wh kg^{-1} and a cost of $88 kWh^{-1} were determined for a number of international brands. Li-ion batteries in China on average have specific energy of 106 Wh kg^{-1} and cost of $590 kWh^{-1}. 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 Li-ion batteries. As both battery technologies gain more real-world use in e-bike applications, both will improve. Cell variability is a key problematic area to be addressed with VRLA technology. For Li-ion technology, safety and cost are the key problem areas, which are already being addressed through the use of new materials such as $LiFePO_4$.

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