Lead-Acid Batteries

Impact on future tin use

Technical Report 2017

Lead-Acid Batteries

Impact on future tin use

We are grateful Mark Stevenson, Global Lead Technologies, for expert contributions in editing of this report.

Contents

Executive Summary

This ITRI report has reviewed use of tin in lead-acid batteries, concluding that current estimated 2016 use of 28,100 tpa may grow at around 2.5% to 36,000 tpa by 2025, after which there is a high risk of substitution by lithium-ion and other technologies. Loss of an important current market in e-bikes in China will be compensated by moves towards high performance tin-containing products for new hybrid vehicles. Substitution will only impact by around 10% to 2025 but may then become significant, especially if the EU bans lead-acid battery use in electric vehicles.

Lead-acid battery markets will grow by 2-4% to 2025

As well as fundamental economic growth for existing applications, new markets for energy storage in rechargeable batteries are driven strongly by growth in renewable energy, the need for reduced transport emissions and the rapid increase in communications technologies. Lead-acid batteries remain the lowest cost and most widely used solution but technology is changing rapidly towards lithium-ion and other new solutions, including a set of post-lithium technologies and ultimately fuel cell batteries. Overall battery markets are set to grow at 7.7% by value to 2020, with lead-acid market growth at a slower 2-4% to 2025.

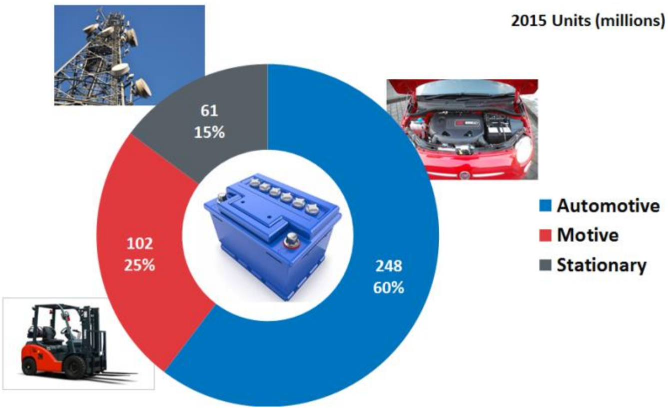
Tin is added to battery grids and other components to improve performance

Tin is added at up to 1.6% in positive lead-calcium battery grids to improve casting and cycling performance in high end AGM/VRLA products, especially in automotive batteries. Up to 0.4% tin is typically added to the negative grid. These replace lead-antimony alloys containing 0.2% tin that are still widely used in flooded products, especially stationary batteries. Up to 2% tin is contained in lead-tin alloy posts & straps connecting the grids, and in some cases up to 40% tin is used in solder joining components. A tin sulphate additive can be used to mitigate corrosion.

Tin is used in advanced products but there are also some low tin alternatives

More recently carbon has been added to the lead oxide pastes to boost performance in a new generation of high performance ‘advanced lead-carbon’ products that are more competitive with newer technologies, using higher tin content. On the other hand Thin Plate Pure Lead (TPPL) products use only a very small tin addition, sometimes with silver. These products are more expensive but have a better temperature range, longer life and faster charge. New Bipolar products under development replace the metal grid entirely with conductive ceramic, carbon foam or polymer plate to reduce weight and lead content. However, TPPL and Bipolar currently represent less than 1% of the world market.

Global tin use has been estimated at 27,500 tpa in 2015



Global use sectors include Automotive Starting, Lighting, Ignition (SLI) (248 million units 2015, 60%), Motive, including for example forklift trucks (102 million units 2015, 25%) and Stationary (or 'Industrial') for telecoms, Power supply backup (UPS) and similar (61 million units 2015, 15%). ITRI Survey data in China gathered 2016 data on tin content of grid alloys used in different applications, showing that while automotive and motive sectors, including e-bikes, used tin at typical levels, the largest surveyed sector Stationary still used only antimony alloys with 0.1-0.3% tin. These data have been combined with other data to estimate that global use of tin has risen from 23,700 tpa in 2013 to 28,100 tpa in 2016. Tin use in China grew rapidly from 2011 following a government directive to switch to tin but has plateaued in 2015/2016.

Use in China e-bikes will decline but shift to high performance vehicles will benefit tin

E-bikes in China have been a dominant tin use sector there but this market has now saturated and is expected to decline sharply to 2025. Tricycles and Low Speed Electric Vehicles (LSEV) will grow fast to partially compensate. Tin use globally will be boosted by an ongoing shift to high performance automotive products, notably stop-start 'mild hybrid' vehicles, to be used in 50% of all global vehicle stock and all new cars produced in Europe and Japan by 2020. By 2025 one in ten vehicles will be 48V, increasing tin use from the current 12V systems.

There will be some benefit from renewable energy storage but other technologies dominate

Solar power systems represent a new opportunity in the Stationary sector, where price parity for residential solar systems vs grid supplied energy will be reached in Germany, Australia and elsewhere shortly. Currently 75% of such systems in China use lead-acid batteries, although tin use per unit is much lower and technology competition in this sector is much greater and likely to grow fast. The simultaneous evolution of renewables, electric vehicle and new utility storage systems is already creating new infrastructures for energy including localised 'micro-networks' organised on a community basis. The market for large scale Battery Energy Storage Systems (BESS) to support such a trend is set to grow fast but lead-acid has only a minor market share in most current development projects.

Lithium-ion technology is the most immediate threat but will take time

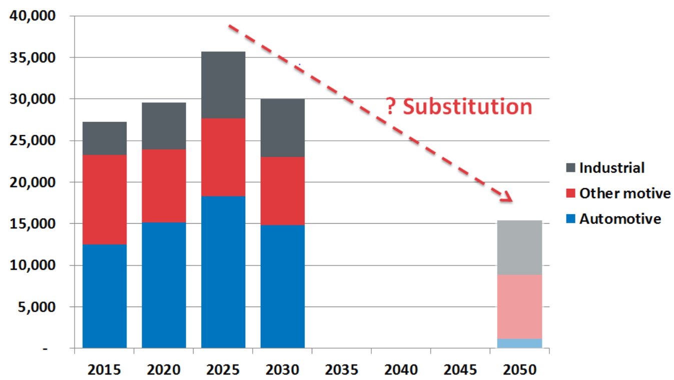
Lithium-ion technology is the most immediate threat to lead-acid battery use, especially now that costs have fallen faster than expected, with some claiming that cost parity with lead-acid is being approached on a total cost of ownership basis. Performance is superior to lead-acid in most applications. High profile large scale lithium-ion production investments are underway including Tesla 'giga-factories' but there are a number of obstacles including lithium supply, technology risk, safety and recycling that will delay full market implementation. Industry experts are more sceptical, especially on replacement of SLI in the automotive sector, and in any case substitution of lead-acid will be limited to 10% by 2025.

There is a significant long-term risk of substitution after 2025 in electric vehicles

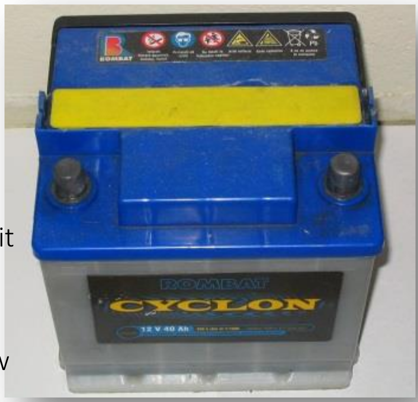
However, full implementation of 'zero-emission' PEV and EV electric vehicles by 2050 represents a significant long-term substitution risk to lead-acid battery in its largest use sector. The automotive industry argues that it will have no effect because 12V lead-acid batteries will continue to be used in auxiliary function alongside larger lithium-ion motive batteries. However, the EU is already considering a lead ban once alternatives have sufficient field experience and superior performance arguments for lithium-ion may prevail.

Tin use may grow at 2.5% to a peak of 36,000 tpa in 2025

Combining these threats and opportunities, a model has been used to forecast future refined tin use in lead-acid batteries, estimating a growth of around 2.5% to a peak use of 36,000 tpa by 2025, after which there is a significant risk that substitution will reduce use to 15,000 tpa by 2050.



Background

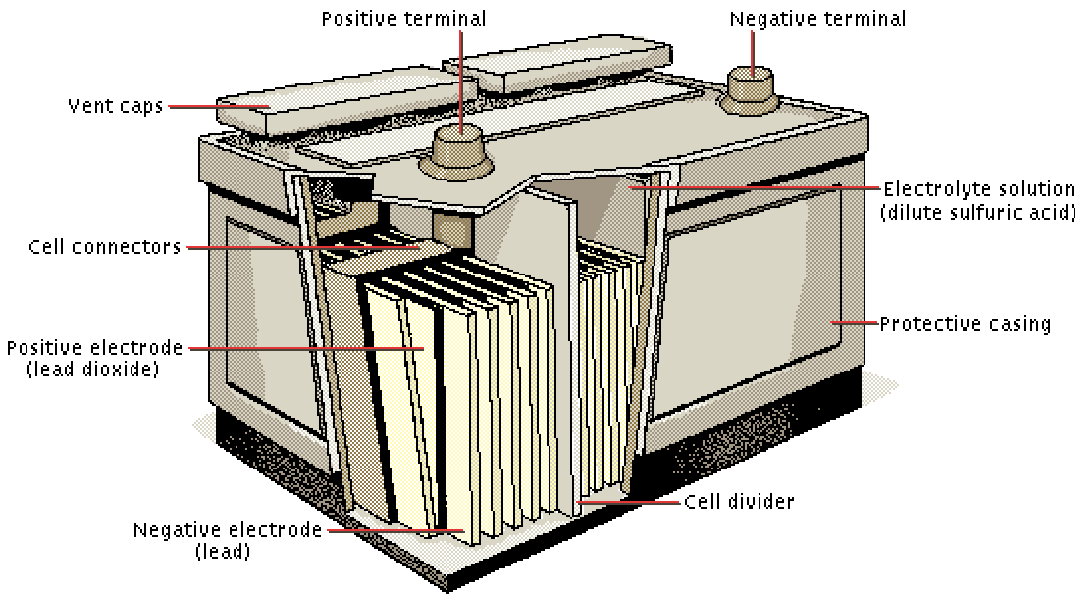


Lead-acid batteries were invented by French physicist Gaston Planté in 1859 and have a long and successful history as a basic commodity for rechargeable electrical energy storage. The basic technical principle is simple and robust and can be relatively easily manufactured at low cost.

A large mass means that the energy-to-weight ratio is low, but it can supply large surge currents, so has a high power-to-weight ratio, useful in, for example, automotive starting (Starting Lighting Ignition - SLI). Even when this is not important their low cost means that they are still used even when other battery types may have better energy densities, for example in backup supplies for mobile phone towers, hospitals and off-grid remote storage.

Metallic positive and negative grids are formed into plates, with addition of a pressed lead-oxide paste, often referred to as the 'active material'. The electrolyte is sulphuric acid and can require refilling due to evaporation and water loss if antimony containing electrodes are used. The automotive industry in particular has driven a move to 'maintenance-free' products that replace lead-antimony with lead-calcium grid alloys and, since the 1970s, a sealed or 'valve regulated' (VRLA) design has been in use, allowing true 'maintenance-free' use.

Some batteries for 'deep-cycle' applications in confined spaces such as forklifts or marine engine starting have a series of tubular lead oxide positive electrodes instead of flat plates to increase surface area. They allow higher currents for more power density, but have a lower energy density. Lead-antimony alloys are used because cycling properties in these applications are superior to lead-



calcium products.

In all battery types the plates are joined by “busbars” made of various alloys, often referred to as the strap, COS (cast on strap), or connector. These are lead-based alloys but the same alloy as the grids, to aid welding. Lead alloy posts or terminals are connected to the straps to complete the electrical connection and are generally high in antimony to give good hardness. It has been reported that lead-tin solder is used in China to join components, but it is not widely used except in small VRLA products.

The chemical reaction at the negative plate during discharge is conversion of lead metal to lead sulphate and at the positive conversion of lead oxide to lead sulphate, meaning that at full discharge both plates are primarily lead sulphate. Charge is carried by electrons from the negative to positive plates. These reactions reverse on charging. Voltage sensitive additives in the electrolyte can be used to control access to the electrodes of water molecules and metal ions from corrosion, improving lifetime[1].

Theoretical charge capacity of a 2V cell is 167 WH/kg, but in practice this is only 30-40 WH/kg since the mass of water and other constituents has to be accounted for.

Theoretical voltage of 6 cells used in most conventional products is thus 12V, varying in practice depending on the charge state and design. 24V, 36V and 48V products are also available. 48V are of particular interest for mild hybrid vehicles to deal with increased storage requirements from, for example, brake regeneration systems. These may well be two paired 24V units, as it has been previously shown that there is otherwise too much heat generated.

Capacity is not a fixed quantity but, because it takes time for the interface charge to diffuse through the electrolyte and electrode materials, varies according to how fast or slow the battery is charged or discharged, using a relationship defined in Peukerts Law. Although the battery can be discharged very fast it takes much longer to charge, because lead sulphate build-up on the negative electrode inhibits charging electron flow. Battery lifetime can be increased by using an optimal charge-discharge procedure and it is better to keep the battery charged in winter to prevent freezing of the electrolyte.

Insufficient voltage through lack of use or insufficient recharge causes sulphate precipitation – ‘sulphation’ - that may only be partially reversible. In some Chinese products at least tin sulphate is added to the electrolyte to inhibit sulphation, but it is not a common practice. Excessive voltage leads to corrosion and potentially gassing from oxygen and hydrogen. In modern valve-regulated batteries (VRLA) recombination of the hydrogen and oxygen takes place, minimising water loss. Any excess gas is released through one-way valves.

Lead oxide pastes contain additives such as barium sulphate (‘blanc fixe’) in the negative plate to act as seed crystals for the conversion reactions and lignosulphonate/carbon black to form the crystals into better performing needle-like dendrites. Sulphonated naphthalene can be used instead of lignosulphonate as a more effective dispersant. Newer advanced ‘lead-carbon’ products use specialised carbons to improve performance.

Separators between the electrodes are necessary to prevent shorting by various mechanisms including inter-electrode dendrite formation. These can be made from a variety of materials, the most common and widely used is a polyethylene (PE) type. Newer types include an absorbed glass mat (AGM), being glass fibre wetted with electrolyte, allowing operation in any position and preventing ‘stratification’ in which lead sulphate crystals can fall to the bottom of the cell, leaving primarily water at the top. They do have slightly higher acid content that can lead to shorter life. Intermediate ‘Enhanced Flooded Battery (EFB)’ automotive types use a porous plastic ‘scrim’ to support positive paste on the grid under charge-discharge and enhance electrolyte mixing during driving. This can double cyclic stability of conventional flooded batteries, enhance starting power and provide basic start-stop functionality in mild hybrid vehicles but doesn’t match performance of AGM products.

Gel electrolytes are made by adding silica into the electrolyte to make a semi-stiff paste. This decreases evaporation and spillage but does inhibit movement of ions, making them more suitable for lower current applications such as grid storage. Their lower freezing points and higher boiling point means that they can be used in more extreme conditions.

Battery types are generally defined by their different design and use, typically SLI (Starting, Lighting, Ignition), Motive and Stationary.

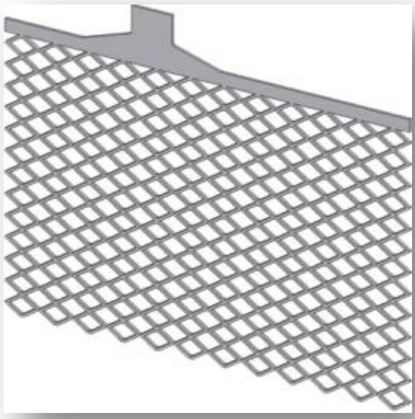
SLI batteries are generally not designed for deep discharge, having thinner plates for maximum surface area that are less resistant to discharge stresses. Deep cycle batteries, on the other hand, for Stationary (‘Industrial’) and Motive applications generally have thicker plates and a lower peak current. Intermediate type batteries compromise between the two and are used in marine or motorhome ‘leisure’ applications.

Thin Plate Pure Lead (TPPL) products use 1 mm thick rolled plates of 99.99% pure lead and usually a small amount of tin and/or silver, to improve performance, especially for outdoor applications and extreme environments such as marine. They are produced in ‘flat plate’ and ‘coiled’ or ‘spiral wound’ designs with AGM (Absorbed Glass Mat) separator technology. Application temperature range is extended from the conventional -15 to 50^{o}C to -65 to 80^{o}C, which is particularly useful for low temperature applications[2][3].They are more expensive but lifetime is claimed to be at least doubled with better cold start and faster charge[4]. Current commercial use is reported to be less than 1% of the global market[5].

Products

Product Definition

Early battery plates were pure lead, but in 1881 these were replaced by stronger lead-antimony alloys with 8-12% antimony. However, the high antimony content was found to cause higher hydrogen evolution and thus maintenance and these have been slowly replaced over time with lead-calcium or lead-antimony grids with reduced antimony content (4-6%). Further refinement to the lead-antimony alloy was the introduction of selenium to the alloys resulting in further possible antimony reduction to 1.6-2.5%.



Today's antimony-containing battery alloys typically have 1.6-2.5% antimony, with the higher end of the range used in hotter climates like Asia [6]. There are still some products with the 'conventional' 3-6% Sb. In Asia the most common antimonial SLI battery has 1.6-3% Sb. These alloys can include 0.05-0.20 % tin[7] and other grain refining additives, as alloys with less than 3% Sb are much harder to cast and susceptible to cracking. Being softer they take longer to age harden.

There is a continuous trend away from antimony alloys towards lead-calcium products driven mainly by the presence of higher under-hood temperatures in vehicle design and the need for maintenance-free products[8]. Some industrial products and VRLA batteries have used them for many years in both plates. Due to elevated temperature operating conditions some regions such as Asia use them in 'hybrid' design where the positive plate is a 1.8% Sb alloy and the negative is a Calcium alloy[6][5].

Early versions of the lead-calcium technology were found to suffer from Premature Capacity Loss (PCL) meaning that the battery would not recover sufficiently from continuous discharging. It was found that antimony was vital for cycling and PCL became known as the 'antimony-free' effect. Tin was added to the positive plate to correct this problem. A small amount of aluminium (0.01-0.03%) is also added as an antioxidant for calcium and in part tin[7]. Other additives improve various properties, including silver which is alloyed to enhance corrosion resistance and limit positive plate growth.

Some impurities, especially Se, Ni & Te but also Sb and As, enhance corrosion, whilst others, notably Bi[7] and Zn[9] can enhance properties. It has been suggested that the combination of bismuth and tin could be particularly beneficial[10].

The importance of impurities means that lead-calcium alloy specifications often restrict Sb and As to 0.001% max and can be easily breached. Even small tin additions can have an impact and so high purity tin is often used[7].

The toxic element cadmium was used in China before a government directive in 2012 forced its substitution in 2013, significantly benefiting tin use. Lead-cadmium-antimony alloys are both metallurgically and electrochemically superior to lead-calcium products, but during recycling the cadmium enters all aspects of the recycling loop, including waste water, slag and air. All motive applications in China now use lead-calcium-tin, as well as a significant proportion of SLI and industrial batteries[11].

Tin needs to be added at above 0.05% to be effective[7] and is lost to the dross during grid casting operations. The amount of tin used is related to the calcium content. It is used in the positive grid at up to 1.6%, typically 0.8-1.2%, particularly for VRLA and lead-carbon advanced batteries, and 0.2-0.4% in the negative grid [6]. Average tin contents of battery grids from ITRI 2015 survey of the top six China producers are shown in Figure 1 below. Stationary products in this sample are antimony alloys with much lower tin contents.

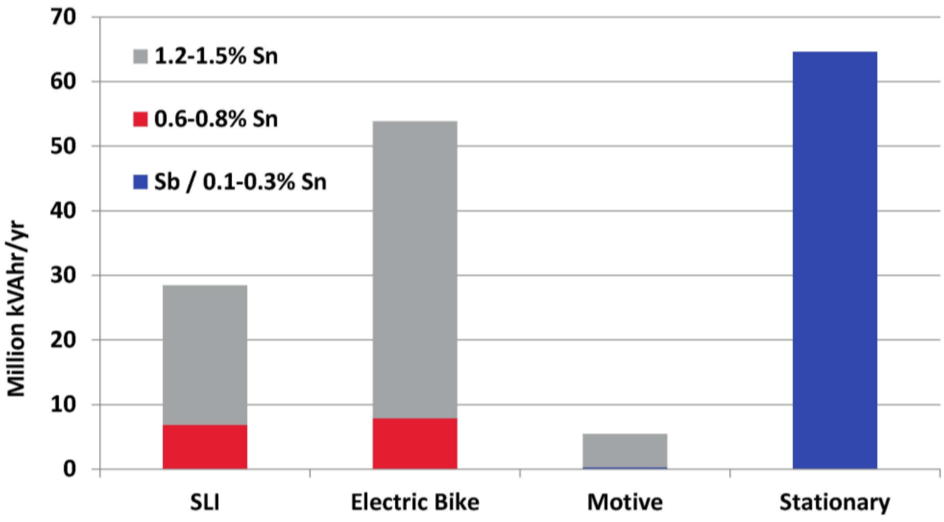


Figure 1 - Tin content of battery grids, top six ITRI surveyed companies China 2015[12]

Tin use in posts and straps appears to vary, perhaps reflecting a wide variation in tin content of lead and lead-calcium alloy specifications used in practice[5]. Chinese producer Tianneng has published a figure of 0.5-0.8% (~6g Sn per KVAh) [11]. However much higher levels of either 0.8-2.5%, 2% or 2-3% tin (~21g Sn per KVAh) have also been reported in high end VRLA Gel or VRLA AGM batteries[8][13] with lead-calcium-tin grids. All Advanced batteries with carbon in the negative active material use 2% tin in lead-tin alloys for posts and straps [8]. Posts and straps can represent around 20% of lead alloy weight[8].

Application of 25-40% Sn leaded solder would mean 3-5g solder use per battery, representing an extra 1.2-1.3g Sn per kVAh[13][11], though, as above, use is mainly only for smaller VRLA products.

Use of stannous sulphate (~8g Sn per KVAh) to inhibit sulphation has been reported in China but it is uncommon [11].

Lead makes up around 60% of a typical automotive battery weight. 'Average' car battery weights vary widely between 'lightweight' (7kg) and 'standard' (23kg) types[14]. For a compact passenger car estimates similarly vary between 8kg[5] and 19-20kg[15]. Heavy vehicles average 1.7 units per vehicle, with average battery weight of 45kg[16]. Around 55% of the lead weight is due to the positive and negative oxide and sulphate active masses. AFB and AGM battery types use around 17% more lead and hence tin[17].

Using this data, assuming average battery weight of 18kg[14] lead alloy weight of 5kg, high end VRLA AGM automotive products, without tin sulphate, could contain a total of 47g tin per KVAh.

Product Advantage

The use of tin to improve properties has been known for many years. In 1995 the ALABC published results of a study of adding tin and silver up to 5% on performance of lead-acid batteries for electric vehicles, showing potential for improved cycling performance, reduced corrosion, and improved heat resistance[18]. Tin content of alloys more than doubled in the next five years to 2000 from an average of around 0.25% to 0.5%[19] and has now further increased to typically 0.7 to 1.6% as above. Panasonic recently patented use of up to 2.3% tin in the positive grid to reduce corrosion[20].

The benefits of tin addition are especially emphasised more recently as market trends for improved performance and cleaner materials push towards lead-calcium alloys and the high performance, low maintenance VRLA products where tin is used.

The specific beneficial properties of tin are[19]:

- Improves mechanical properties of lead-calcium alloys
- Changes the hardening process from Pb_3Ca to Sn_3Ca, a more stable and heat resistant form
- Alloys are more stable allowing rolling without recrystallisation
- Alloys are more corrosion resistant
- Increases conductivity of the corrosion layer at the end of discharge
- Transforms the PbO passivation layer into an electrically conductive layer (at > 1.2% tin)
- Disseminates in the PbO layer lattice by semiconductor doping
- Improves fluidity and ability of grids to be bonded to straps

Tin is critical in lead-calcium alloys grids to overcome the ‘antimony-free’ effect, as above, allowing deep discharge cycling. Sealed VRLA AGM products use higher tin content in the positive grid to improve recharge[8].

It is used at lower levels in some lead-antimony alloys as a grain refiner to improve castability.

Use of a small amount of tin in Thin Plate Pure Lead (TPPL) products counters a tendency to develop a resistive layer at the grid to active material interface. This resistive layer can also cause the battery to have difficulty in recovering from deep discharges[4]. In general TPPL products have a much lower corrosion rate than calcium or antimony alloys.

Cost is an issue and this may limit tin use in some cases, although only by relatively small amounts.

Tin can be lost from the alloys during production due to drossing, especially at high temperatures and stirring rates.

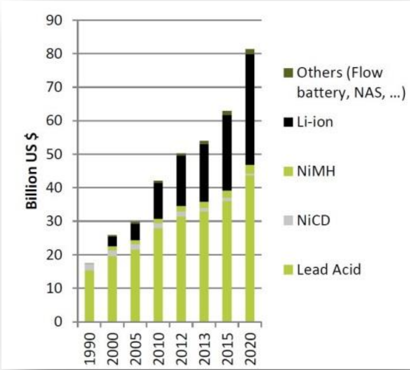
Recycling is an important way that the lead industry justifies the continued use of lead in this, its largest use sector - the industry reports that 99% of products are recycled[16]. Tin is also an important element in the recycling chain. Levels in recycled bullion lead are often high, requiring basic refining procedures for its removal such as the introduction of oxygen. The resultant "dross" is often now upgraded to a level where it can be recovered through vacuum distillation. Importantly the recycled tin needs to be of high purity if it is reused in Ca alloys. Tin is also lost from the recycling process itself as the major of the element reports to the slag. Levels in the slag range from 0.7 to 1.5% tin and industry estimates around 15,000 tonnes per annum is lost.[7]

Overall it is estimated that 20-30,000 tpa tin may be ejected or lost in production and recycling worldwide. [7].

Market

Market Size

The global battery market was worth $83 billion in 2015[21] and estimated to grow at 4.15% to 2021[22]. Secondary (rechargeable) batteries were expected to account for 82.6% of demand by 2016, representing the fastest growth at 7.7% annually[21] to $120 billion in 2019, driven by consumer sectors such as mobile phones and tablets. Some primary (nonrechargeable batteries) are still used in watches, electronic keys, sensors, beacons and some military devices for example, but the sector is in decline[23].



China is the major producer and market for batteries, driven by massive rising output from manufacturing and rise in consumer spending, with additional positive pressure from government energy regulation. India is also forecast for strong growth. Expected demand boosts in the US and Europe are linked to the introduction of hybrid and electric vehicles through 2019, as well as larger scale utility and energy storage projects[21].

The sector is characterised by high R&D costs for new technologies such as lithium-ion, competitive pressures from incumbent suppliers, lengthy testing to meet regulatory requirements and the difficulty of bringing new technologies to market. Several start-ups and even some major companies have been impacted by development issues, for example, delays in introduction of electric vehicles[24].

Lead-Acid Batteries

Major market sectors for lead-acid batteries are SLI for cars and commercial vehicles (248 million pa, 60%), Motive including e-bikes, forklift and other vehicles (102 million pa, 25%) and Stationary industrial uses including UPS, telecom and grid storage for alternative energy (61 million pa, 15%). Total units pa can be estimated at 411 million in 2016[25]. The market is expected to grow at 4% to 2020[26].

Energy demand for lead-acid batteries globally was 478 million KVAh in 2014, up 5.7% from 2013[27], with the market worth $47.88 billion[28]. China demand grew by 12.4% in 2013 to a total of 213 million KVAh in 2014 (45%).

China is the major producing and using region, producing 42% of global demand in 2014, with 27% produced in US. Market growth in China was reported to be 12.4% in 2014 compared to growth in the rest of the world of around 2%[27], with total value of $15 billion[13]. Although a slower growth rate CAGR of 5.6% was expected for the period 2014-19, with longer term growth likely to align with global growth at 2-3%[27], actual growth 2013-2016 was lower at 3-5%. China exports have been growing steadily at around 4% pa since 2009, totalling $2.57 billion in 2015[13].

Product mix in China is distorted by the high number of Motive batteries used in e-bikes. 2015 data was SLI (100 million pa, 44%), Motive (90 million, 40%) and Industrial (37.5 million, 17%[11]).

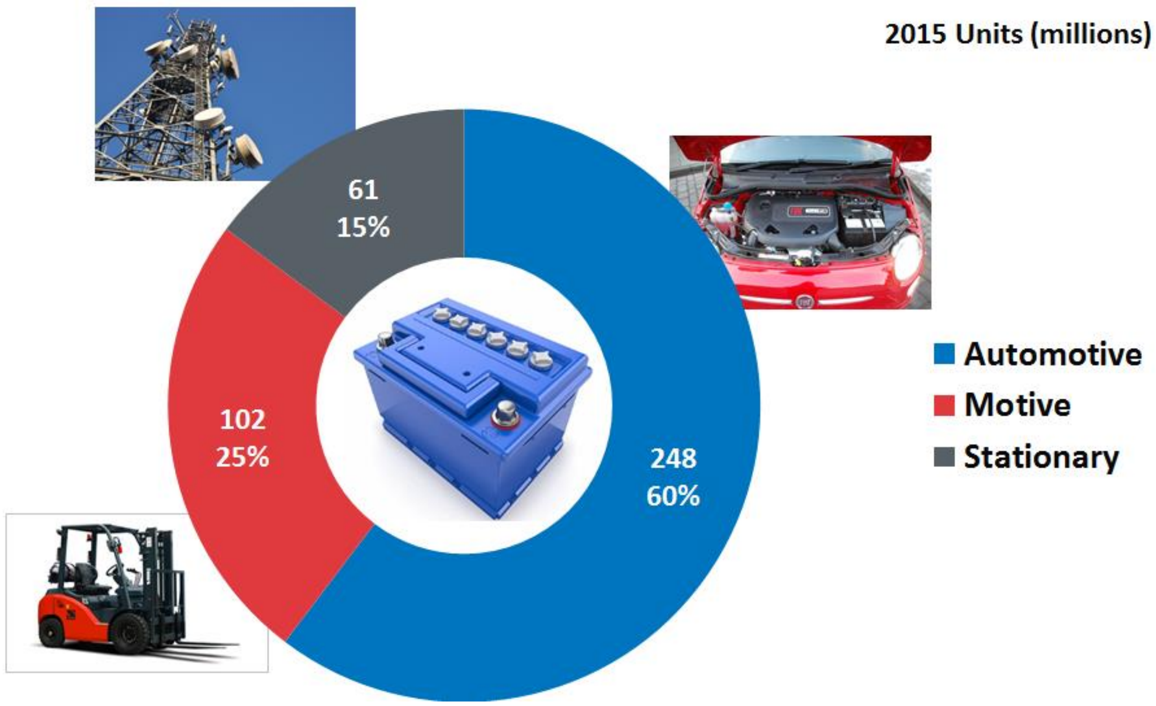


Figure 2 - Global Unit Sales 2015 Estimates Lead-Acid Batteries (millions)[29][30][31][32]

As shown in Figure 3 below, China's tin use was growing fast under new regulation requiring a switch back from cheaper antimony-cadmium to calcium-tin alloys by 2013. However use is already slowing due to competition from lithium-ion in e-bikes, slowing of upstream automotive & electric tricycle markets and environmental regulation from the government that is pressuring smaller producers particularly. Further the government announced a 4% tax on lead products in 2016[33]. Competition is fierce and even larger companies such as global leader Johnson Controls are continuing to lose market share.

The Asia-Pacific market valued at $14[24] or $19 billion[28] in 2014, dominates the lead-acid battery market with 34.2% share of use, and this is expected to continue. As well as a general increase in automotive markets[34], especially in China, Indonesia, Malaysia, Vietnam, Thailand, Mexico and India[35], there are significant growth predictions for new markets in Electric & Hybrid Vehicles, UPS for Telecoms and Industrial sectors as well as grid-scale Energy Storage for PV, Wind and other alternative energies. Overall the global market is expected to reach $76.44 billion by 2022[31].

Europe was the second largest market in 2014, accounting for 24.8% of global share. Growing investment in green transport and industrial materials handling options, as well as solar systems in UK, Germany and Netherlands, will boost growth[31].

Older-type flooded lead-acid batteries accounted for 65% of global share in 2014 [28].

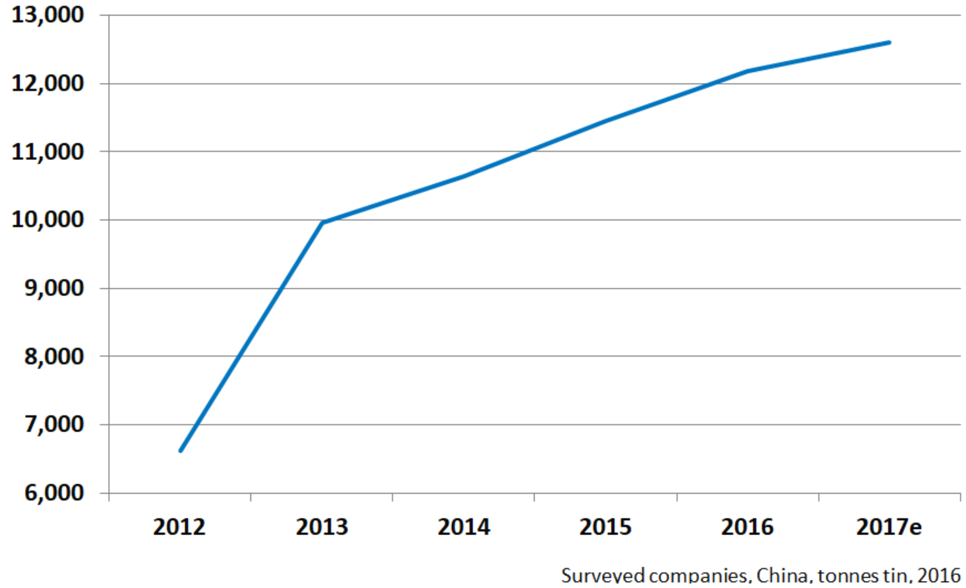


Figure 3 - Tin use by China top six lead-acid battery manufacturers, tonnes pa 2016[37]

Consumption of lead in lead-acid batteries was 9.8 million tpa in 2014[36]. Antimony content in the world recycled lead circuit can be used to estimate 2013 antimony alloy production at 1.2 million tpa with associated tin use of 1,175 tpa. Assuming that half of lead is used in electrode paste rather than grids, calcium alloy production, calculated by deduction from total lead use, was thus 3.5 million tpa (75%). Accounting for an estimated 5% hybrid electrode Sb/Ca units, positive grids used 17,053 tpa tin and negative 3,590 tpa. tin. Adding an estimated 385 tpa from solder and excluding tin sulphate use, total tin 2013 use estimate was 21,800 tpa[37].

ITRI tin use survey data estimated 2013 China production used 9,955 tpa refined tin use[11] China had an estimated 42% production share[11] in 2014, deriving a reasonably close 2013 global estimate of 23,700 tpa tin.

ITRI survey data from 2017[38] could similarly estimate that 2016 refined tin use had risen in China to 15,400 tpa and global tin use had risen to 28,100 tpa tin. A 2015 close estimate from another source was 13,260 tpa tin use in China[11].

SLI Batteries

Jian[11] has estimated 2015 tin use in SLI batteries in China at 5,200 tpa, based on 100 million units. This includes tin in grids, posts & straps, solder and tin sulphate electrolyte additive, although use of the sulphate is not common. ITRI 2015[12] Survey data estimated 4,147 tpa tin not including tin sulphate. There is currently no direct data available for tin use outside China. European 2014 production was 70 million vehicles[39].

Analysts forecast growth of the global automotive lead-acid battery market CAGR at 2.92% in terms of units over the period 2014-19. China growth in SLI will be 9-15% over the next few years[27][11]. Trends will roughly follow growth demand for passenger cars and commercial vehicles, mainly in emerging economies, primarily responsible for increasing automotive profits by nearly 50% by 2020[40]. China's vehicle production was 24 million in 2014[11] and its vehicle population will increase to 185, 364 and 607 million by 2020, 2030 and 2050 respectively[41]. Developed country demand will remain static.

Producers are following this trend by moving production to these lower cost regions where they can be closer to the auto production lines and at the same time cheaper cost[34].

Advanced (EFB/AGM) types increased share in Europe from 7.5% in 2010 to 25% in 2014, of which 71% were OEM products [30]. AGM-type production in Europe was approaching 10 million (14%)[39]. A similar trend was reported in China[13] in 2016.

The need for improved performance for Start-Stop vehicles and Regenerative Braking in so-called 'micro hybrid' or 'mild hybrid' vehicles is pushing market share towards VRLA and especially advanced products, favouring tin. Stop-Start batteries were used in 35 million vehicles globally in 2016 – nearly 40% of the estimated 89 million global car production in 2015[42]. Between two-thirds and three quarters of all new registrations in Europe and Japan in 2016 were estimated to be stop-start and one-tenth in the US[42]. Major producer Johnson Controls expects to make 50 million Stop-Start products in 2020 from 17 million in 2015, estimating that by 2020 all new cars in Europe and Japan will use the technology[42]. In China demand for Stop-Start and Pb-C products will increase by CAGR 30-40% in the short term[27].

A trend towards 48V products from 12V could boost tin use. This is partly driven by the need for more electrical power to run the increasing number of motors and other electrical components but also for use in mild hybrids[43]. The first production vehicle to use 48V is the SQ7 Audi luxury sports vehicle and it has been estimated that by 2025 one in every ten cars sold globally will be 48V[44]. The Advanced Lead-Acid Battery Consortium showcased a 48V vehicle in 2014[44].

Motive Batteries

The major market is forklift trucks but there are a large number of other applications including golf carts, people movers, sweeper trucks, access platforms, boats and mobility aids.

Jian[11] estimated 2015 tin use in Motive batteries in China at 5,310 tpa, based on 90 million units, 88% of estimated global use. This includes tin in grids, posts & straps, solder and tin sulphate electrolyte additive. ITRI 2016 Tin Use Survey[12] data estimated 2015 tin use somewhat higher at 6,532 tpa, not including tin sulphate. There is currently no data available for tin use outside China.

The global market to power electric vehicles and other conveyances is predicted to rise to $47 billion in 2017, 50% higher than 2013[45].

Lead-acid batteries have a high use in this market on account of their low cost, reliability and well-established supply chain[28]. Flooded lead-acid batteries had a market share of 49% in 2013 expected to fall to 39% in 2017, because of their maintenance requirements. However their low cost and widespread use in industrial trucks and golf carts means that they will retain significant share in the near future against EFB/AGM and VRLA types [45].

Electric vehicles are seen to be ‘greener’ than fossil fuels in markets such as industrial materials and mining[45] and around 60%+ of materials handling applications using forklifts and similar were electric[46] in 2013. China and India markets are expanding with their increasing prevalence as trading and transit hubs for logistic transport[31].

The ‘club car’ market, including for example golf carts, sight-seeing and campus vehicles, is expanding, especially in the US and China[47].

Lead-acid batteries have been used for most of the small number of commercial Plug-In or Fully Electric cars (PEV or EV) produced to date, (~1.2 million globally[48]), with notable exceptions[49], but are not thought to have the high performance or range required for future designs. Most of the current development projects are dominated by lithium-ion technologies.

Electric buses are used mainly in China, with an estimated 173,000 in use in 2015 and 200,000 planned for 2020. A few tens of buses are used in the Netherlands, Sweden and Japan[50].

E-bikes are the largest market sector in China, with 30 million units produced in 2013[41], and estimates for total of 190-230 million in use[50][51], representing more than half of all bicycles there. These have been boosted by banning of conventional motorcycles in cities on pollution concerns[50]. Sales were forecast at 35 million in 2016 and 40 million by 2023[52], with revenues set to increase from $15.7 billion in 2016 to $24.4 billion in 2025[53]. Each e-bike on average represents about 1 KVAh [11] and contains 10.3-14.7 kg of lead[41], although there is significant variation of voltage and hence size from the basic 12V to 36V. Some 48V or even 83V products are used.

However, lead-acid battery use in e-bikes has already started to be impacted by lithium-ion battery substitution and in 2015 demand for lead-acid fell by 0.8% and is expected to see negative annual growth of above 15% over the next few years[27]. China lithium-ion e-bike production in 2014 reached 1.7 million units, a 36% increase, accounting for 50% of exports[51]. It is thought unlikely that lead-acid will be used significantly outside China in the future, additionally so now that designs are trending away from pedal-assisted types towards throttle-controlled scooter types that require higher performance[54].

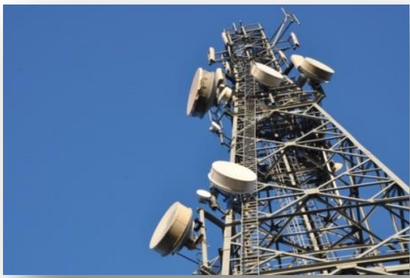
There is also a market saturation of e-bikes inside China and they have been banned in some cities. Public transport systems have also improved. Navigant Research had predicted sales of e-bikes in China would rise to 43 million in 2018 [53] but this is now unlikely. During the first half of 2014 e-bike production of the top 50 e-bike producers fell by 2%, in contrast to previous average 30% growth rates[51]. Battery production fell by 5% in 2015[13]

Growth markets for e-bikes are in European cities where there is a shift away from cars to bikes, with e-bike sales growing to 907,000 in 2013[55]. The Paris Declaration on Electro-Mobility sets a global stock target of more than 400 million two and three-wheelers by 2030, corresponding to 70% of 2030 sales of this type of transport[50]. UK e-bikes use either lithium-ion or lithium-polymer batteries[56]. E-bikes are more environmentally friendly and can be faster than cars in bad traffic. In Netherlands and Belgium almost a fifth of all bikes sold are e-bikes. In Japan their popularity is also rising after the 2011 tsunami made car travel difficult and where older people find them more convenient and cheaper. In the US there is more resistance and a ban in place in New York[51].

Demand from electric tricycles in China has been increasing rapidly, as evidenced by over 15 million electric tricycles owned in 2013. Production surpassed 7 million in 2014, with the output growth rate reaching about 20% annually[11]. All e-bike and e-tricycle batteries in China are VRLA and use tin[8].

'Short Range' or 'Low Speed Electric Vehicles (LSEV)', also known as 'quadricycles', 'electric micro-cars' or 'sub-compact electric vehicles' are a new and fast growing market, especially in China. Their speed is limited to around 70 km/h but they are a convenient and safe way to travel short distances. After an initial ban the Chinese government is moving towards regulation in 2016 as the concept is in line with new energy policies for cities. The China market is still small – total ownership of 600,000 vehicles in 2015[50] – but expected to grow fast at 25-30%[27][13] as its expands from smaller to larger cities, and could reach 150 million[11], with annual production at 2 million by 2020[50]. The China government was expected to issue regulatory standards for LSEVs in 2016.

Stationary Batteries



This sector has a number of static applications, generally referred to as 'Stationary', 'Industrial' or 'Fixed'. These are mainly standby uses, providing backup in case of electrical failure, notably as data systems UPS and telecoms but also in many other sectors such as hospitals. The also provide power for air conditioning and lighting in buses and trains[13] as well as security lighting.

Smaller products are of a similar size to automotive batteries, typically with a capacity lower than 24Ah. 2.1 million 'small industrial' lead-acid batteries were produced in EU-28 member states in 2013[16]. The UPS sector was valued at over $4.7 billion in 2014[28].

2016 Global share in the lead-acid product mix was estimated at 29%[36] with the market for lead-acid forecasted to grow by one analyst at 6.9% 2014-2019[57], another similarly at 6%+ 2015-2022[28], with another slightly higher at 8.6%[58].

Published data for the China market, as above[11], gives this sector a 17% share of the lead-acid market based on units. FastMarkets published an estimate of 33% in 2016[36] based on lead use and ITRI's 2015 Tin Use Survey gave a share of 42% based on KVAh data[12]. This probably reflects the larger size and thus capacity per unit typical of this sector.

Jian[11] estimated 2015 tin use in Industrial batteries in China at 1,330 tpa, based on 37.5 million units. This includes tin in grids, posts & straps, solder and tin sulphate electrolyte additive. ITRI 2016 Tin Use Survey estimate for 2015, not including tin sulphate, was remarkably close at 1,310 tpa[12].

As shown in the chart above from the 2015 ITRI Tin Use Survey, tin is only used at low levels in battery grids in this sector in China, presumably because there is not the same pressure as in transport uses for the tin-containing higher performance products[12]. Flooded deep cycle products are widely used[59], although there is some investment in higher tin AGM products.

A 2016 forecast from China, based on data from the first half of 2016, suggested an increase of 25% for the year[13], although another analyst suggested that the market for telecoms backup would shrink slightly[27].

Growth has largely come from the telecom and UPS/data communication sectors[24] . 4G, development of wireless broadband networks, with increasing span of communications[58] towers, is important for telecoms[60] , seeing a massive growth in internet traffic[46]. A growth of data centres in Asia Pacific particularly is driving demand for UPS[31][58] , although there is also in general an increasing requirement for UPS from industry, corporate offices, hospitals, research institutions, educational institutes and residential applications in emerging economies[28], [58].

Increasing automation in the future is also likely to require more energy backup systems and deployment of vehicle charging infrastructure will also have a positive impact[58].

There are now also important developing markets in utility and alternative energy. 75% of Photovoltaic (PV) systems in China use lead-acid batteries, with 36kg of Pb used per kW-year of a

2016 installed capacity[41] of 77.4GW[61]. Even if tin content was as low as 0.2% this could equate to 2,000 tpa tin, which is higher than total estimates for all China tin use in this sector. Lead-acid batteries for photovoltaics are primarily AGM VLRA type[8].

Market Issues

Electric Vehicles

The advent of hybrid and electric vehicles will initially benefit and then significantly challenge lead-acid battery use in its major use sector.

As Figure 4 below shows, car designs are already segmented into types ranging from the standard internal combustion engine (ICE), through various degrees of hybrid technology - 'micro' / 'mild HEV', 'full hybrid (HEV)', Plug-in hybrid (P-HEV) – to fully Electric Vehicle (EV), expected to be implemented by 2020 and beyond[26].

Functions and voltages for each of the vehicle types are shown in the Figure 5 below[26].

The International Energy Authority has published similar but longer range roadmap, Figure 6, showing that pressure for use of zero-emission electric vehicles will result in the complete phase-out of ICE light vehicles by 2050[62].

These data show that until 2025 the increased use of 'stop-start', regenerative braking and similar 'mild/micro' hybrid technologies will continue to benefit tin as higher performance or 'advanced' lead-acid batteries take market share from 'standard' types that can still use lower tin content 'flooded' or 'low-maintenance' products.

However, from 2025 the share of 'full hybrid', P-EV & EV is expected to grow from around 10% to completely replace ICE technology by 2050. Governments are also beginning to set 'zero-emission vehicle' timescales to 2050. Although the ALABC are developing lead-carbon technologies to reach 'full hybrid' standards[63], it is not widely expected that lead-acid will have the performance to be competitive for these type of vehicles and instead most seem likely to use nickel-metal hydride (NiMH) or lithium-ion technologies. Lead-acid batteries were and are used for 'electric' vehicles (P-EV & EV) but lithium-ion dominates development.

The lead-acid battery industry challenges these timescales on the basis that 'mild/micro' hybrid technology gives '70% of benefits to emissions for 30% of the cost'. The development of advanced types using specialised carbon additions or bipolar designs for example, is also bolstering positioning of lead-acid, particularly in higher voltage 48V designs.

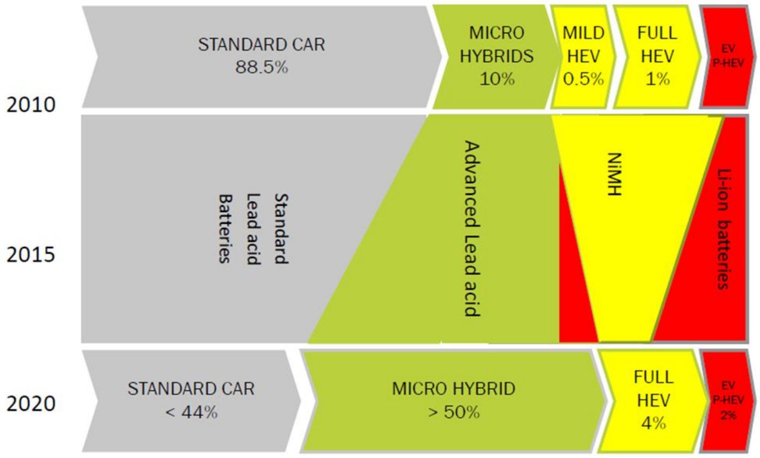


Figure 4 - Electric vehicle types[26]

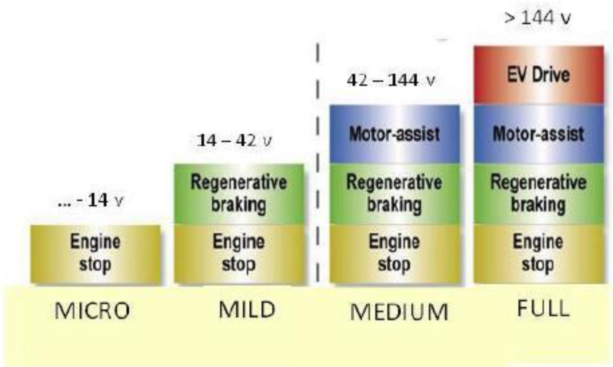


Figure 5 - Functions and voltages for hybrid and electric vehicle types[26]

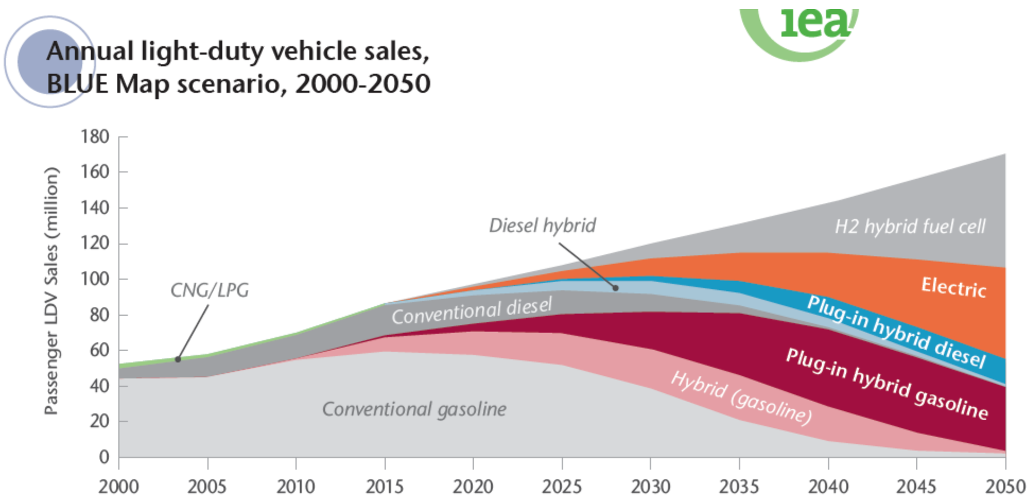


Figure 6 - IEA Roadmap for vehicle types through to 2050[62]

The automotive industry has stated that lead-acid batteries will still be used for 12V auxiliary power in hybrid and electric vehicles, as shown in Figure 7[15].

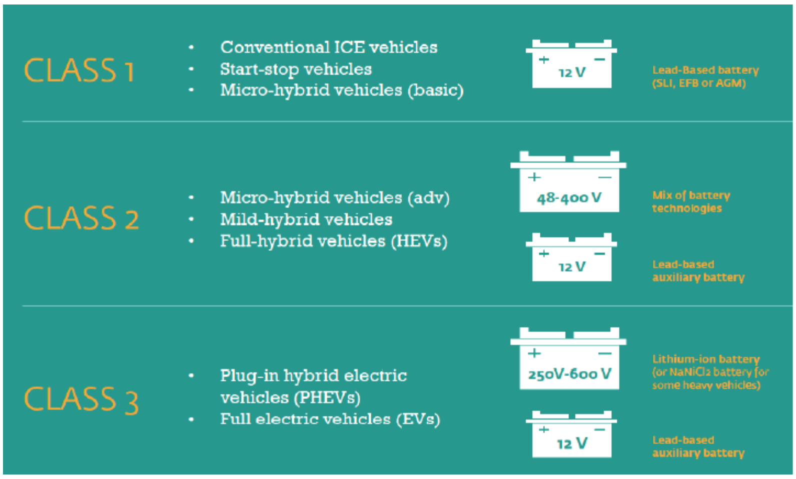


Figure 7 - Battery types for vehicle design classes[15]

Introduction of electric vehicles will be dependent on government incentives focussed on emissions as well as technology development with continued reduction of lithium-ion battery costs. Total cost of ownership calculations show a parity in Europe and China in 2021/25, excluding subsidies or incentives, but will not be achieved in the US beyond 2025 because of low fuel prices there[64]. They fit best into a low-carbon ecosystem because of better ‘well-to-wheel’ energy efficiency of renewables and their potential to integrate with solar and utility systems.

Estimates for market growth of fully electric vehicles (PHEV & EV) vary widely, but typically annual sales are forecast to reach 10 million by 2025, as shown in Figure 8[64].

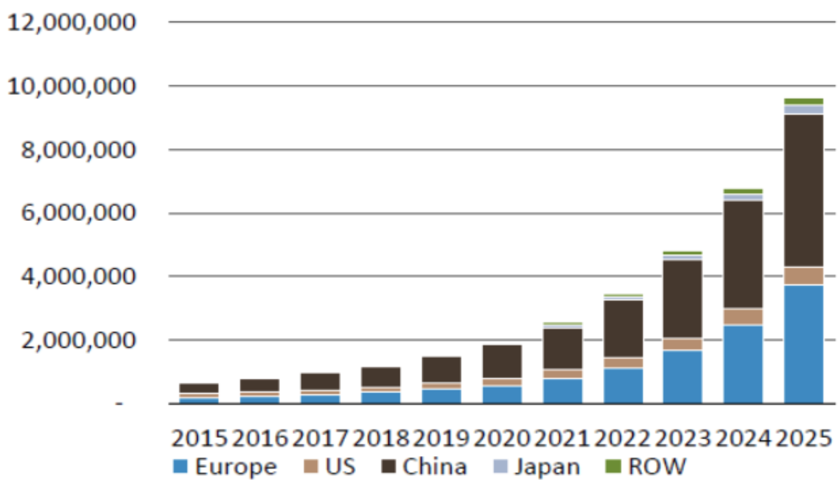


Figure 8 - PHEV & EV vehicle sales forecast to 2025[64]

There are also significant issues relating to the charging infrastructure that would be required to support large-scale implementation of electric vehicles, as well as the potential logistical, economic and physical impacts of massive multiple vehicle charging on utility supply through the grid[50],[65].

Battery Energy Storage Systems (BESS)

Battery Energy Storage Systems (BESS) are of growing interest for balancing renewable energy generation from wind, solar and other technologies, or even replacing grid supplied energy locally. They can also be used to improve cost-effectiveness of utility grid supply to industrial users by enabling lower rate purchase at off-peak, shifting use to high peak. 'Black start' installations can provide backup power in the event of grid failure.

Ten specific utility related sectors were identified in a 2010 review[66], with highest revenues earned by those that aggregated several benefits across multiple categories. Dual purposing of such systems to include, for example, UPS also improves the business case[67]. There are some risks in economic viability and some business models may fail through, for example changes in regulation, or development of alternative grid balancing strategies[68].

A number of large-scale BESS projects are in progress[69], initially focussed in the US, but financing lacks confidence with only limited track records and experience in performance, maintenance and business models. This is expected to improve with time, especially as capex falls[68]. Economics and not technology is the main driver, with several 'go-to-market' and business strategies still in development[69]. Cost is a major factor and start-ups especially are adopting an aggressive low-cost approach, for example in 2015 start-up Eos was claiming a price point of only $160/kWh for its MW-scale system[68], against a typical price range in 2014 of $300-$3,500/kW[70].

Since the emerging market for grid storage is based on mature technologies, BESS deployment is expected to grow rapidly, estimated at CAGR 7.3% 2014-2020[58]. The market for grid storage systems may be difficult to quantify, with widely varying estimates, probably depending on how much ancillary infrastructure is included. The current market was measured by one analyst at $460 million in 2015 and forecasted to grow to $6 billion value by 2025[69], another to reach $8.3 billion in 2024[71] and another $10.4 billion[72] by 2017. A different valuation estimated the current annual value at $1 billion, expected to reach $20-25 billion by 2024[68]

Corresponding battery demand for grid storage has been estimated at 15GWh annually by 2020[73].

Photovoltaic energy storage is an especially fast growing market, where, in China at least[11], lead-acid is still the preferred battery option. Solar systems and decentralised power grids are cost-effective for rural home-based use in western China, although the economic case is much less certain in the US[70].

Solar-enabled residential properties are already in some European countries approaching behind-the-meter (BTM) price parity with grid energy, ultimately enabling autonomous operation with no need for grid connection. This technology was highlighted by the launch of Tesla Powerwall in 2015. It is likely to lead to very significant changes to utility energy distribution and business models, with the creation of new 'micro-grid' or 'smart grid' networks[69]. An example is an 8-tonne 'Energy Neighbour' product, containing 192 lithium-ion cells, used in a community energy storage project in Mossham, Germany[71].

There is also a cross-industry convergence in systems development between battery, solar and utility players. With the advent of electric vehicles scenarios for integration of vehicle energy storage with home (V2H) and grid (V2G) are also being explored[69].

Residential systems use 1-10 kWh batteries, non-residential 10kWh-1MWh and utility >1MWh capacity[69].

Sodium-sulphur batteries were the most commonly used in 2010, along with alternative Energy Storage Systems (ESS), including pumped hydro systems and compressed air energy storage (CAES). Several other battery types are being evaluated now including lithium-ion, lead-acid, flow batteries, nickel-base, metal-air and others[69], [66]. Automotive companies are exploring the repurposing of used electric vehicle batteries.

ALABC have shown that advanced lead-acid batteries can in some cases operate in this application for 18-20 years, making battery replacement unnecessary[74]. Performance improvements such as adding more carbon are also used for issues relating to incomplete charging that can occur in this application. The development of grid-scale energy storage systems based on advanced UltraBattery lead-acid systems has been reviewed[67]. However, a survey of US Dept. of Energy databases in 2015 showed that less than 9% of the 454 recorded energy storage projects were lead-acid[75].

Recycling

A high recycling rate and globally established infrastructure for recycling has for some time been a strong positioning for lead-acid batteries, meeting regulatory concerns on lead use and giving competitive edge against alternatives, notably lithium-ion.

The ALABC strongly advocates that lead-acid has superior sustainability against all other battery technologies when its complete recycling is accounted for, using less energy and hence CO_2 production, and support this with work from Argonne Laboratory in 2010[63].

This is recognised by lithium-ion producers and a large number of development projects are underway aimed at optimising lithium-ion battery recycling, including from example work at Umicore, Belgium, one of the worlds most advanced metals recycling facilities.

As above, there are some technical issues with tin in the lead-acid battery recycling loop that lead to excessive losses and could be improved.

Regulation incentives

Regulation is widely seen as the key to driving new markets for batteries, especially in electric vehicles and utility storage systems. In implementing global framework directives on climate change and tackling growing concerns over health impact of vehicle emissions, governments are considering measures to incentivise transition to more energy efficient, lower emission technologies.

For example, the 2011 US Order 755 by the US Federal Energy Regulatory Commission (FERC) provided performance payments for faster, more efficient utility energy delivery, resulting in a significant increase in deployment of BESS[68]. In 2013 the California Public Utilities Commission unanimously approved a mandate that will require the state’s big three investor-owned utilities to add 1.3 gigawatts of energy storage to their grids by decade’s end[73].

China set ambitious targets for renewable energies in its landmark 2005 Renewable Energy Law, creating installed photovoltaic capacity of 3.3GW by 2011. A minimum target of 5GW was set for 2015, with longer–term targets of 20-30GW[41] annual production and capacity of 150GW by 2020, although this was were recently cut by 20% to 110GW[76] because of production overcapacity.

Government subsidies for solar installation are likely to be a significant market driver for the photovoltaic energy storage sector. There will also have to be new policies on grid energy supply to deal with the economic, pricing and legal aspects related to creation of micro-grid networks that could become local suppliers in their own right[68].

Competitive Analysis

Lithium-ion Batteries

Low cost has always been a key advantage of lead-acid batteries over its main competitor lithium-ion batteries. However, with massive investment in R&D and ramping up of production by Tesla and others, the costs of lithium-ion may be falling faster than predicted. Current published estimates are summarised in Figure 9[64]. This appears to show cost parity with lead-acid batteries (~€150/kWhr) is being approached, and in fact it is argued by some that total cost of ownership of lithium-ion is already lower[77]. Lead-acid battery industry experts are more sceptical of such data[5].

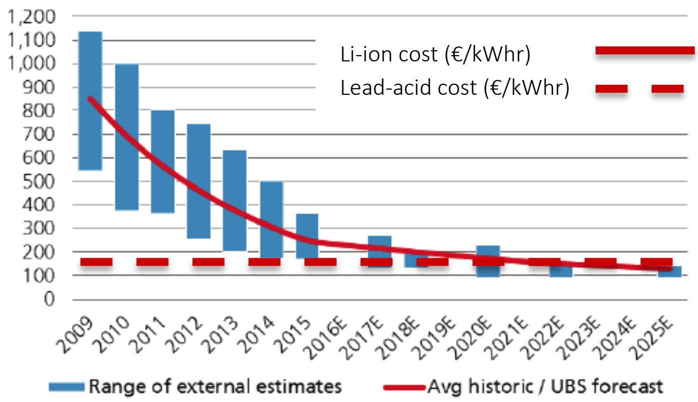


Figure 9 - Lithium-ion battery costs forecast to 2025 (€/kWhr)[64]

Pack and systems costs, along with development timescales, also have to be accounted for but in general it seems that the economic position of lead-acid batteries is being eroded quickly.

Further, as shown in Figure 10, the performance comparison strongly favours lithium-ion, with higher energy density, better charging characteristics, longer service life and completely maintenance-free.

However there are limiting factors on adoption of lithium-ion technology that will slow its introduction.

Lithium supply is a constraint, with 2015 production of 150,000 tpa required to reach a conservative 265,000 tpa by 2020 to fulfil demand forecasts[78]. There are few suppliers and the technology for large-scale conversion of lithium salts is not fully available. Prices are rising exponentially as a result.

Scale up of manufacturing will also require time and very significant investment at risk, as seen in the example of Tesla Giga-factories in the US.

Lead-acid batteries	Characteristics	Lithium-ion batteries
40 Wh/kg	Energy density	95 – 140 Wh/kg
Up to 70 %	Charging efficiency [%]	Up to 95 %
1200 cycles	Charge/discharge cycles	> 3000 cycles
Gassing and water loss occurs when charging	Emissions	Emission-free (zero gassing)
Required	Maintenance	Not required
Charging: 50 % in approx. 3 h, 90 % in approx. 6 – 7 h	Fast charging capability	Charging: 90 % in approx. 1.5 - 2 h
Negative effect on service life	Opportunity charging	No negative effect on service life

Figure 10 - Performance comparison of lead-acid batteries vs lithium-ion[79]

Safety is also a consideration, especially with recent high profile fire hazard incidents from Samsung smart phones. There are several cathode chemistries in development and use, with some already identified as unsafe[26].

Development of efficient recycling routes will also be necessary.

Market forecasts for lithium-ion battery production are shown in the Figure 11 below, predicting around demand of around 160 million kWhr by 2025[26]. Around 87 million kWhr is for use in portable electronic devices, leaving 73 million kWhr in relevant market sectors, mainly automotive. The most advanced production facilities at Tesla have estimated their production at 500,000 units by 2020[80].

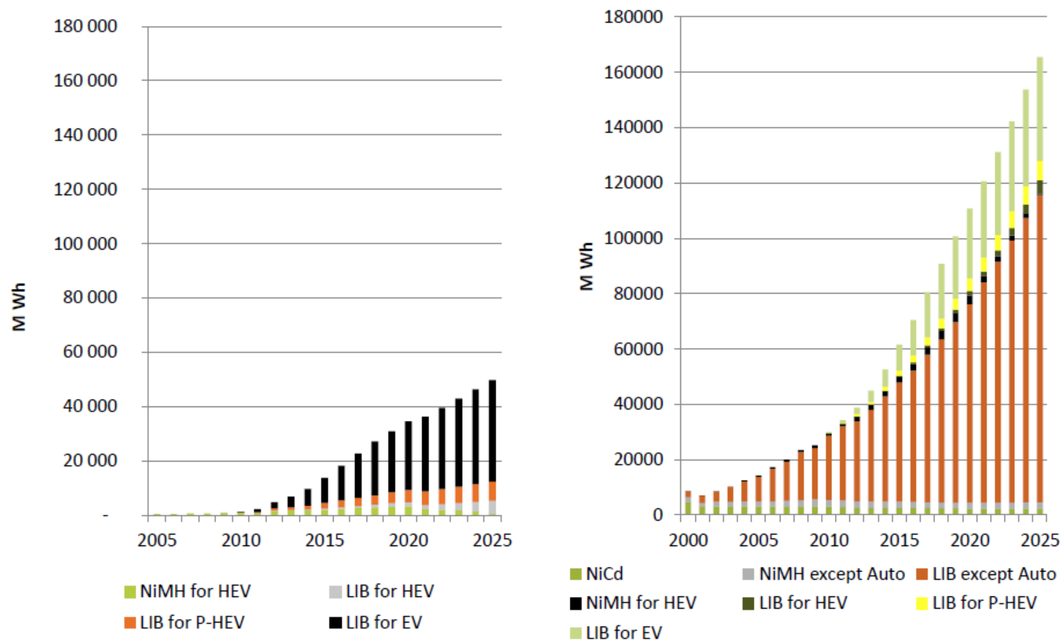


Figure 11 - Market forecasts for lithium-ion and nickel batteries to 2025[26]

Lead-acid industry experts Ecobat are however playing down medium-term substitution risks, calculating a base case of 5% substitution by 2020 and 10% by 2025[75], excluding pure EV.

Other Battery technologies

A significant number of longer term developments are looking at alternative or new battery technologies to meet the large future growth potential.

Nickel and zinc based systems are an example, with a recent published claim that nickel-zinc batteries for motive and stationary applications have the potential to penetrate 20% of the lead-acid market[81]. It was stated that they have three times more power, twice the capacity and double the lifetime of lead-acid. They are currently more expensive, but about the equivalent cost to a high-end lead-acid product.

The large-scale energy storage market is particularly attractive for new developments. For example, MIT University, US recently announced work on liquid metal batteries for grid energy storage[82]. ViZn also detailed their work on ramping up commercial production of zinc-iron flow batteries for microgrid storage. They claim a 40-50% lower lifecycle cost than lithium-ion and forecast use of 120 GW by 2025. Zinc-air batteries are also being developed for motive and consumer applications[81].

'Post-lithium' technologies are also in rapid development by researchers, including sodium-ion, magnesium-ion and even potassium-ion. Markets for such products are expected to reach $14 billion by 2024[83]. Given the difficulty of penetrating existing markets it is likely that they will initially find use in new market sectors.

SLI Batteries

The automotive industry is of the view that lead-acid batteries are the only technology capable of providing the cranking power necessary to start conventional combustion (ICE) engines. Further that all vehicle electrical systems such as lights, power management, entertainment systems are designed and standardised to be compatible with the 12V characteristics of the battery. Although it thus seems that SLI batteries at present have a strong market position, the long-term competitive position against alternative technologies, notably lithium-ion, may not be as robust as imagined.

A small number of high-end vehicles do use lithium-ion for cranking power and a new OLife technology also claims to match the cranking ability of lead-acid. A recent review of the ELV Directive exemption for lead in lead-acid batteries has concluded that for these reasons there is enough momentum for the possibility of a phaseout of SLI lead-acid batteries to be looked at again in 3-5 years[15]. The industry argues that costs involved, especially in changing vehicle charging systems, are prohibitive[5].

12V lead-acid SLI batteries are still used for auxiliary power in hybrid cars that otherwise use NiMH, NaNi (larger vehicles), or lithium-ion for motive power. This should protect the SLI market in the short term against growth in hybrid and electric vehicles. However, the same ELV Directive review concluded that in fact lead-acid may be avoidable in these cases. Although phaseout of lead-acid auxiliary batteries was not recommended in Europe on the basis that alternatives don't yet have the field experience, it seems clear that the case may become harder to defend in future reviews[15].

Market share of hybrid and electric vehicles is forecast to be around 6% in 2020[84], with conventional vehicles using fossil fuels and SLI batteries alone almost completely phased out by 2050[85],[86] under pressure from emissions regulation. In a worst case scenario all use of lead-acid batteries in the SLI sector would be phased out in the same timescale.

Stationary batteries

Lead-acid is a cheap and mature technology, with dominance at least in the China telecoms sector[57] but also more widely and in general this sector has been a growth market for lead-acid batteries. However there is also greater competition from other types[36].

New market structures from the development of BESS grid storage systems particularly have encouraged even automotive producers to enter the supply chain. New market entrants are looking for established high volume cost-effective production, as already used in the automotive industry. As lithium-ion battery production begins to be introduced for electric vehicles and prices fall even further, lead-acid may find its leading status eroded by this kind of cross-sector migration[70].

The key positioning of lead-acid as the lowest up-front cost is already being undermined by total cost of ownership arguments, especially as alternative technologies can demonstrate better lifetime performance. As an example a leading supplier of grid-storage systems, ZBB, has promoted zinc-bromide flow batteries, claiming that total cost of ownership is lower than lead-acid batteries once replacement and service costs are accounted for over a 20-year lifetime[87].

Exploitation

Key Players

The global and Chinese market for batteries has been dominated by relatively few large producers, with a significant number of much smaller players.

In 2011 the top five producers, other than GS Yuasa, were all in the US, with Johnson Controls the largest with 25% share and the others less than 10% each[32].

In 2015 estimated values of leading producers were Johnson Controls $6.6 billion, GS Yuasa $3 billion, Enersys $2.6 billion and Exide $2 billion[13]. However Exide Technologies have recently filed for bankruptcy, the second time in the last decade, the first time after losing a contract for automotive batteries to its rival Johnson Controls[88].

Johnson Controls market share had fallen to 15.7% by 2014[27] though they continue to produce 152 million units[42] and supply 36% of the automotive market[89]. The company is a leader in AGM technology with a capacity of 12.4 million units in 2015, expanding to 26.9 million units by 2020. They recently entered a joint venture with Beijing Hainachuan Automotive Parts to produce advanced lead-acid batteries for stop-start vehicles[89].

Some producers established production in China and elsewhere in Asia to reduce costs and locate close to emerging markets, especially automotive[32]. Johnson Controls generated over 80% of its revenue from slow growing markets in the US and Europe, but has expanded to Asia-Pacific, with three plants in China and plans to build two more to bring production capacity there to 30 million units by 2017.

In China there has been a significant restructuring and consolidation in the industry following environmental regulation. In ITRI 2016 surveys on tin use, just six producers occupied dominant positions[12], using 12,000 tpa tin, with the remaining 15 using only 2,000 tpa. The total number of domestic producers has decreased to 400, with strong domestic price competition and exporters subject to exchange rate fluctuations. A new 4% lead consumption tax has also impacted production[13].

More recently the advent of electric vehicles, BESS and other innovations is radically changing the supply chain, which is moving beyond traditional players to include new or potential production from previously downstream sectors such as automotive, solar cell integrators and power utility companies for example[69]. Other traditional producers such as Panasonic are reducing their investment in lead-acid technology[27].

The following table summarises available data on lead-acid battery producers.

Table 1 - Lead-acid battery producers worldwide

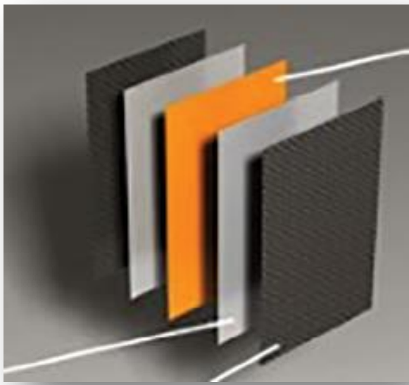
Country	Producer	Country	Producer
Global	Johnson Controls	China	Menshine
	Enersys		Chilwee
	Exide Technology		Coslight Technology International
USA	East Penn Manufacturing		Vision
	ATLASBX		Fengri Electric
	Crown Battery Manufacturing		Huabei Battery
	Axion Power International		Zhejiang Just Electric Appliance
	Concorde	Europe	Hoppecke, Germany
	Dyno Battery		FIAMM, Italy
	Hawker		Moll
	C&D Technologies		Monbat
	US Battery Manufacturing	South Korea	Sebang/Global
	Teledyne Technologies		ATLASBX
	Trojan Battery		Delkor
	Northstar		Dong Ha
China	Hubei Camel Storage Battery		Newmax
	B.B. Battery		Sungwoo
	Ruida	Oman	REEM
	Chaowei Power	UAE	Eternity
	Fengfan	Philippines	Ramcar Batteries
	Leoch International Technology	Pakistan	Exide Pakistan
	Narada Power Source		Atlas Battery
	Tianneng Power International	Myanmar	GS Batteries
	Shenzhen Senry	Taiwan	Yacht Batteries
	Shuangdeng		CSB Battery Technology
	Shandong Sacred Sun Power		Ztong Yee
	Guangdong Dynavolt		Chang Nan Battery
	Jiangsu Suzhong Battery		Kung Long Batteries
	Minhua Power Source	Thailand	Thai Storage Battery
	Yangzhou Apollo Battery		Siam Battery Industries
	Chuanxi Storage Battery		Siam BS Battery
	Shandong Longkou Battery		Siam Furukawa
	Shenyang Panasonic		Siam Choak
	Tianjin Jieshi Battery	Vietnam	Pinaco
	Zibo Torch Energy	Japan	GS Yuasa
	Narada Power Source		GS Titan
	Anxi Minhua Batteries		Hitachi
	Haerbin Coslight		Panasonic
	Wanli		Furukawa Battery
	Nandu	Canada	Rolls Battery
	Kstar	Australia	Century-Yuasa
	Wolong		Battery Energy
			Pacific Marine Battery

Country	Producer	Country	Producer
Turkey	Mutlu		Tractors & Farm Eq (TAFE)
Brazil	Moura Batteries		Amco Batteries
Venezuela	Acumuladoes Duncan CA		HBL Ltd
Colombia	Acumuladoes Duncan CA	Indonesia	Nipress
Mexico	Enerya		PT Trimitra Baterai
South Africa	FNB		PT GS Battery
	Willard		PT Yuasa Battery Ind
	Dixson Batteries		PT Tri Mega Baterindo
Uganda	Chloride Batteries	Malaysia	Tai Kwong Yokohama
Kenya	Chloride Batteries		GP Autobat
Bangladesh	Rahimafrooz		ABM
	Ejab Group		Yuasa Malaysia
India	Tudor India	Tunisia	Assad Batteries
	Amara Raja	Saudi Arabia	National Battery
	Su Kam		Acdelco
	HEB	Egypt	Chloride Batteries
	Tata		

Data: ITRI, CRU, Global Lead Technologies

Technology Development

Advanced lead-acid batteries have developed the use of carbon in the negative electrode, either as an addition to the lead paste, in EFB automotive products, or as an extra electrode in its own right, for example as a carbon foam[90],[91] with lead-tin coating eliminating corrosion and decreasing weight.



Carbon electrode products act more like a supercapacitor with up to four times increased cycle life and faster charge-discharge but can suffer from lower specific energy and fading discharge curves. Conventional lead-acid products need to be kept at full charge and so has a low ‘charge acceptance’ – they can’t accept significant energy in that state. However, these advanced products can operate at 30-70% state-of-charge (SoC) without fear of loss of performance through sulphation[1]. Others have tried to push this analogy further by, for example, using barium titanate electrodes, claiming performance superior to NiMH or even lithium-ion[1]. The Advanced Lead-Acid Battery Consortium (ALABC) claim that they can now equal, or some cases exceed, performance of NiMH and Li-ion products at far lower cost[63].

The so-called ‘UltraBattery’, developed by CSIRO, includes both a conventional negative VLRA electrode and an additional ‘supercapacitor’ carbon electrode, enabling it to handle higher power, faster charge-discharge operation and at the same time improved load smoothing over long strings of cells in large-scale applications such as energy storage from wind turbines[67].

Other advances include Bipolar Plate products where, in a chained design, the positive electrode of one 2V becomes the negative electrodes of the next. Each grid contains positive active material on one side and negative on the other. This gives a significantly more compact design, allowing for less ohmic losses, greater energy density and a lighter weight. The products have 40% volume reduction and lead content is up to 50% less. Recent enabling technology has been the development of conductive ceramic or polymer materials[24] for use as the bipolar plate between the grids. Examples are the Silicon Joule product from start-up Gridtential using silicon, or a Firefly Microcell product using carbon foam [91].

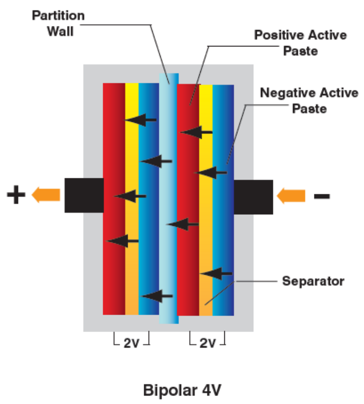


Figure 12 - Bipolar Plate design

Technology Assessment

ITRI refined tin use estimates of 27,500 tpa globally in 2015 have been estimated using more than one approach and can be considered reasonably robust, with some margin o error. More primary data from outside China is desirable and will be included in future tin use surveys as possible.

There is an industry consensus that lead-acid battery markets will remain in strong growth averaging 2-4% over the next decade to 2025, driven by several positive trends, especially in emerging economies.

The fundamentals are based on economic growth in core markets including automotive, industrial and communications where lead-acid represents the established low-cost solution. New markets in energy storage, notably hybrid vehicles, 48V vehicle power systems, low speed electric vehicles plus residential and utility power storage will add extra growth, though not without increasing competition from alternatives.

Substitution in existing markets by other technologies may be relatively modest in the medium-term, except for applications such as e-bikes where factors such as weight and range are critical and the switch to lithium-ion is already underway. The development of advanced lead-acid products, especially lead-carbon technologies, is likely to maintain competitiveness and grow markets in mild hybrid vehicles particularly.

Tin is likely to benefit additionally from the move towards higher end products in automotive markets, where tin content of alloys is higher, especially in the trend towards 48V vehicles. The trend away from flooded products more generally will also benefit tin in other markets, though there will be a more limited effect in stationary applications. There may be some gains in BESS utility storage systems, especially in emerging economies, but limited by low tin use in stationary applications and dominant competition from alternative technologies.

The largest threat to tin use in the short-term is the loss of the e-bike market in China, with a possible 15% decline over the coming years. This is proportionally a very significant sector for current tin use in China - around 60%. There will be some compensation from growth in electric tricycles and LSEVs in China.

Growth in lithium-ion production over the period in relevant markets, forecasted at 73 million kWhr annually by 2025, will only have around 10% impact on lead -acid use, forecasted to grow by 4% from the 478 million kWhr in 2015 to 708 million kWhr.

After this time, with increasing mass production of lithium-ion, growing proliferation of other energy storage technologies and development of non-metallic battery grids it is likely that substitution will accelerate towards 2050.

The most critical risk factor for lead-acid over this later period is the substitution of lead-acid in automotive use, both by lithium-ion based SLI technologies such as OLife and by lithium-ion in auxiliary function to hybrid, P-EV and EV vehicles. The threat of regulation on lead use from the EU is real once alternatives have sufficient field experience. Within the context of a government-regulated push towards 100% zero-emission vehicles by 2050, the competitive position on lead-acid will increasingly focus on sustainability issues and use may, in the worst case scenario, be phased out completely.

Modelling of these factors results in forecasted future refined tin use data shown in the Figure 13 below, showing a possible peak value of 36,000 tpa tin use in 2025.

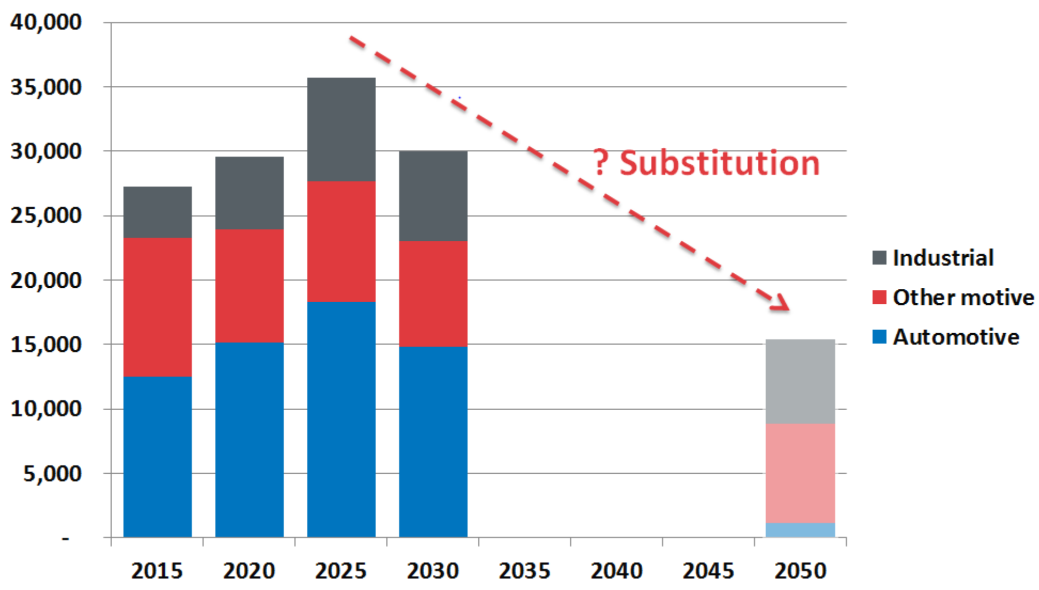


Figure 13 - Forecasted tin use in lead-acid batteries to 2050

References

[1] Battery University, “BU-202: New Lead Acid Systems.” [Online]. Available: http://batteryuniversity.com/learn/article/new_lead_acid_systems. [Accessed: 20-Jan-2016].

[2] Enersys, “Cyclon Batteries.” [Online]. Available: http://www.enersys.com/Cyclon_Batteries.aspx?langType=1033. [Accessed: 13-Apr-2016].

[3] HBL, “Lead-X Tech Manual,” 2016. [Online]. Available: http://www.hblnicad.co.uk/Brochures/LEAD-X Leaflet.pdf. [Accessed: 13-Apr-2016].

[4] P. Shumard, “Selection of Standby Batteries for Outdoor Systems,” in *Wescon IC EXPO ’97*, 1997.

[5] M. Stevenson, “Private communication.” 2017.

[6] E. Obasohan, “Lead Tin Alloys.” CRU, Private communication, 2015.

[7] M. Stevenson, “Private communication,” 2014.

[8] Prengaman, “Private communication.” 2012.

[9] W. Jing, “Gate Alloy for Low Temperature Deep Cycle Positive Electrode Plate,” WO2015196624, 2014.

[10] R. David Prengaman, “Metallurgy of recycled lead for recombinant batteries,” *J. Power Sources*, vol. 42, no. 1–2, pp. 25–33, Jan. 1993.

[11] Z. Jian, “Outlook for Tin Application in Lead-Acid Batteries,” in *2015 ITRI China International Tin Forum*, 2015, pp. 140–156.

[12] Anon, “ITRI 2016 Global Tin Use Survey.”

[13] Z.-P. Chen, “Application Prospects of Tin in Lead-acid Battery,” in *ITRI Asia Tin Summit*, 2016.

[14] Anon, “How much does an average car battery weigh?” [Online]. Available: https://www.reference.com/vehicles/much-average-car-battery-weigh-93074ba323069ac#. [Accessed: 10-Jul-2017].

[15] C.-O. Gensch, Y. Baron, and K. Moch, “8th Adaptation to scientific and technical progress of exemptions 2(c), 3 and 5 of Annex II to Directive 2000/53/EC (ELV),” 2016.

[16] IHS EUROBAT ILA ACEA JAMA and KAMA, “The availability of automotive lead-based batteries for recycling in the EU,” 2014.

[17] N. Maleschitz, “Lead Battery Technical Developments and Implications for Lead Producers,” 2017.

[18] A. Cooper, “Collaboration in research - - the ALABC : Brite-EuRam lead / acid electric-vehicle battery project,” *J. Power Sources*, pp. 161–170, 1996.

[19] R. D. Prengaman, “Tin Usage in the Battery Industry,” in *World Tin Conference*, 1997.

[20] A. Tetsuyki, M., Hideharu, T., Kakunari, “Positive grid for lead storage battery, process for producing same, and lead storage battery,” WO2016110907 (A1), 2016.

[21] Freedonia, “World Batteries - Demand and Sales Forecasts, Market Share, Market Size, Market Leaders,” 2015.

[22] MarketsandMarkets, “Global Battery Market by Transport and Transport Mode,” 2016.

[23] Battery University, “BU-103 Global Battery Markets,” 2016. [Online]. Available: http://batteryuniversity.com/learn/article/global_battery_markets.

[24] Anon, “Integral Technologies: Battery Innovation Could Lead To New Revenue Streams,” 2015. [Online]. Available: https://seekingalpha.com/article/3255185-integral-technologies-battery-innovation-could-lead-to-new-revenue-streams. [Accessed: 28-Apr-2016].

[25] J. Pearce, “Tin Use in Lead-Acid Batteries,” 2012.

[26] C. Pillot, “Battery Market Development for Consumer Electronics, Automotive, and Industrial,” in *Batteries 2014*, 2014.

[27] Research in China, “Global and China Lead-acid Battery Industry Report, 2015-2018,” 2015.

[28] Anon, “Lead Acid Battery Market Analysis By Product,” 2016.

[29] OICA, “2015 Production Statistics Cars and Commercial Vehicles,” 2015. [Online]. Available: http://www.oica.net/category/production-statistics/. [Accessed: 18-Apr-2016].

[30] N. Gasparin, “Automotive Battery Market Outlook - Update 2015,” 2015. [Online]. Available: http://www.eurobat.org/sites/default/files/automotive_battery_market_outlook_-_update_2015_0.pdf. [Accessed: 14-Apr-2016].

[31] V. Kulkarni, “Lead Acid Battery Market Analysis, Size and Growth To 2022,” 2016. [Online]. Available: https://www.linkedin.com/pulse/lead-acid-battery-market-analysis-size-growth-2022-vignesh-kulkarni. [Accessed: 14-Apr-2016].

[32] L. Xue-Long, “Global Lead-Acid Battery Market Development Status,” 2011.

[33] LME, “INTL FCStone – Daily LME Metals Report,” Nov-2015.

[34] TechNavio, “Global Automotive Lead-acid Battery Market 2015-2019,” 2015.

[35] Anon, “Lead Acid Battery Market Size & Trend Analysis 2014 - 2025,” 2017.

[36] W. Adams, “Lead forecast and analysis for Q1 2016,” *FastMarkets*, 2016. [Online].

Available: https://www.fastmarkets.com/base-metals-news/quarterly-reports/lead-forecast-analysis-q1-2016/. [Accessed: 01-Jul-2016].

[37] P. Kettle, “Tin Use in Lead-Acid Batteries,” 2013.

[38] Anon, “ITRI 2017 Global Tin Use Survey,” 2017.

[39] IHS EUROBAT ILA ACEA JAMA and KAMA, “A Review of Battery Technologies for Automotive Applications,” 2014.

[40] Anon, “The road to 2020 and beyond: What’s driving the global automotive industry?,” 2013.

[41] T. J. van der Kuijp, L. Huang, and C. R. Cherry, “Health hazards of China’s lead-acid battery industry: a review of its market drivers, production processes, and health impacts.,” *Environ. Health*, vol. 12, no. 1, p. 61, Jan. 2013.

[42] P. Desai, “Stop-start cars push battery metal lead into investors’ focus,” 2017. [Online]. Available: http://uk.reuters.com/article/us-lead-batteries-stopstart-analysis-idUKKBN1692HN. [Accessed: 28-Apr-2017].

[43] Anon, “CPT showcases full range of 48V systems at Aachen,” 2016. [Online]. Available: http://www.greencarcongress.com/2016/10/20161010-cpt.html. [Accessed: 28-Apr-2017].

[44] ALABC, “Advanced Lead-Acid Battery Consortium focused on 48V hybrid vehicles at European Lead Battery Conference,” 2014. [Online]. Available: http://www.alabc.org/press-releases/ALABC_48V_ELBC_PR_8Sept2014.pdf. [Accessed: 28-Apr-2017].

[45] Electronics360 News Desk, “Motive Battery Market Projected to Reach $47B by 2017,” 2013. [Online]. Available: http://electronics360.globalspec.com/article/2122/motive-battery-market-projected-to-reach-47b-by-2017.

[46] J. D. Craig, “Enersys Investor Day 2013,” 2013. [Online]. Available: https://www.sec.gov/Archives/edgar/data/1289308/000119312513137768/d514552dex991.htm.

[47] Technavio, “Global Micro Electric Vehicle Market 2016-2020,” 2016.

[48] P. Hummel, “The Future for Electric Vehicles,” in *Benchmark Minerals London Tour 2016*, 2016.

[49] Anon, “Electric vehicle battery,” *Wikipedia*, 2017. [Online]. Available: https://en.wikipedia.org/wiki/Electric_vehicle_battery. [Accessed: 28-Apr-2017].

[50] Anon, “Global EV Outlook 2016,” 2016.

[51] Oortwijn J., “China’s E-Bike Industry Enters New Era with Production Drop.” [Online]. Available: http://www.bike-eu.com/sales-trends/nieuws/2015/11/chinas-e-bike-industry-enters-new-era-with-production-drop-10124776. [Accessed: 14-Apr-2016].

[52] Navigant Research, “Global Annual Sales of E-Bicycles are Expected to Exceed 40 Million Units by 2023,” 2014. [Online]. Available: https://www.navigantresearch.com/newsroom/global-annual-sales-of-e-bicycles-are-expected-to-exceed-40-million-units-by-2023. [Accessed: 28-Apr-2017].

[53] Navigant Research, “Electric Bicycles,” 2016.

[54] P. Harrop, “The death of lead acid batteries,” *Electric Vehicles Research*, 2011. [Online]. Available: http://www.electricvehiclesresearch.com/articles/the-death-of-lead-acid-batteries-00003921.asp?rsstopicid=556. [Accessed: 02-May-2017].

[55] D. Enskog, “E-Bikes – A Silent Street Revolution,” *Credit-Suisse*, 2015. [Online]. Available: https://www.credit-suisse.com/uk/en/news-and-expertise/economy/articles/news-and-expertise/2015/08/en/e-bikes-a-silent-street-revolution.html. [Accessed: 27-Jun-2016].

[56] N. Busca, “Electric bike batteries: everything you need to know,” *Cycling Weekly*, 2016. [Online]. Available: http://www.cyclingweekly.com/news/product-news/electric-bike-batteries-everything-you-need-to-know-235153. [Accessed: 02-May-2017].

[57] Technavio, “Global Stationary Lead-Acid (SLA) Battery Market 2015-2019,” 2014.

[58] Future Market Insights, “Lead Acid Battery Market: Global Industry Analysis and Opportunity Assessment 2014 - 2020,” 2014.

[59] Anon, “Lead-Acid Batteries,” *Wikipedia*, 2016. [Online]. Available: https://en.wikipedia.org/wiki/Lead–acid_battery.

[60] Fuan Huayi Storage Battery, “Electric cars with lead-acid battery industry consolidation outlook optimistic,” 2012. [Online]. Available: http://www.hy-battery.com/en/newsDetail.asp?ID=47&classID=7. [Accessed: 02-May-2017].

[61] Anon, “Solar power in China,” *Wikipedia*. [Online]. Available: https://en.wikipedia.org/wiki/Solar_power_in_China. [Accessed: 02-May-2017].

[62] International Energy Agency (IEA), “Technology roadmap: Electric and plug-in hybrid electric vehicles,” *Int. Energy Agency, Tech. Rep*, no. June, p. 52, 2011.

[63] ALABC, “Do Hybrid Electric Vehicles Use Lead-Acid Batteries? Yes! Here’s why,” 2014.

[64] P. Hummel, “The Future for Electric Vehicles,” in *Benchmark Minerals London Tour 2016*, 2016.

[65] R. Hensley, “Electrifying cars: How three industries will evolve,” *McKinsey Quarterly*, 2009. [Online]. Available: http://www.mckinsey.com/industries/automotive-and-assembly/our-insights/electrifying-cars-how-three-industries-will-evolve. [Accessed: 02-May-2017].

[66] D. Rastler and EPRI, “Electricity Energy Storage Technology Options,” 2010.

[67] B. B. McKeon, J. Furukawa, and S. Fenstermacher, “Advanced Lead–Acid Batteries and the Development of Grid-Scale Energy Storage Systems,” *Proc. IEEE*, vol. 102, no. 6, pp.

951–963, Jun. 2014.

[68] F. Mayr, "Stationary battery storage systems: What will drive their remarkable growth?," *Apricum*, 2015. [Online]. Available: http://www.apricum-group.com/stationary-battery-storage-systems/. [Accessed: 30-Jun-2016].

[69] X. He, "Batteries for Residential, Commercial, Industrial and Utility Applications 2016-2026," 2016.

[70] SK Solar, "What is the State of the Market for Home Solar Energy Storage?," 2014. [Online]. Available: http://sksolar-usa.com/what-is-the-state-of-the-market-for-home-solar-energy-storage/. [Accessed: 02-May-2014].

[71] Anon, "Battery storage is set to transform renewables industry," *Financial Times*, 2015. .

[72] Anon, "Finding the Perfect Partner in the Global Grid Storage Market," 2013.

[73] C. Pieper, "Prospects for the Utility Storage Market," in *Benchmark Minerals London Tour 2016*, 2016.

[74] ALABC, "An overview of the 2016-18 ALABC Program Proposal," 2015.

[75] R. Kubis, "Pathways to Advancing Lead-Acid Battery Systems," in *Asian Battery Conference*, 2015.

[76] J. Parnell, "China slashes 2020 solar target by 20%," *PVTech*, 2016. [Online]. Available: https://www.pv-tech.org/news/breaking-china-slashes-2020-solar-target-by-20. [Accessed: 02-May-2017].

[77] PowerTech Systems, "Lithium-ion vs Lead-Acid cost analysis." [Online]. Available: https://www.powertechsystems.eu/home/tech-corner/lithium-ion-vs-lead-acid-cost-analysis/. [Accessed: 02-May-2017].

[78] S. Moores, "The battery supply chain in a lithium-ion revolution," in *Benchmark Minerals London Tour 2016*, 2016.

[79] A. Bak, "Electric Car Adoption With A Focus On The Tesla Model S: A Cost Benefit Analysis," 2013.

[80] Anon, "Lithium! Market review, trends, and FAME's contribution," *FAME Project Newsletter Issue 4, March 2017*, 2017. [Online]. Available: http://www.fame-project.info/media/. [Accessed: 02-May-2017].

[81] M. Dent, "FORECAST: Batteries to substantially boost demand for zinc," *Metal Bulletin*, 2017. [Online]. Available: https://www.metalbulletin.com/Article/3671271/FORECAST-Batteries-to-substantially-boost-demand-for-zinc.html. [Accessed: 02-May-2017].

[82] N. Stauffer, "A battery made of molten metals," *MIT News*, 2016. [Online]. Available: http://news.mit.edu/2016/battery-molten-metals-0112. [Accessed: 02-May-2017].

[83] H. Kang, Y. Liu, K. Cao, Y. Zhao, L. Jiao, Y. Wang, and H. Yuan, "Update on anode

materials for Na-ion batteries," *J. Mater. Chem. A*, vol. 3, no. 35, pp. 17899–17913, 2015.

[84] C. Pillot, "The worldwide battery market 2011-2025," in *Batteries 2012*, 2012.

[85] International Energy Agency, "Electric and Plug-in Hybrid Vehicle Roadmap," p. 4, 2010.

[86] Muenzel H., "Future Trends of Batteries for E-Mobility," 2011. [Online]. Available: http://www.slideshare.net/accessio/bosch-future-trends-of-batteries. [Accessed: 14-Apr-2016].

[87] ZBB, "ZBB Energy Corporation," in *Baird Growth Conference*, 2012.

[88] Trefis, "Johnson Controls Shores Up Its Market Share As Exide Files For Bankruptcy," *Forbes.com*, 2013. [Online]. Available: http://www.forbes.com/sites/greatspeculations/2013/06/14/johnson-controls-shores-up-its-market-share-as-exide-files-for-bankruptcy/#5e4fb4744da9.

[89] Trefis, "Johnson Controls," 2016.

[90] J. J. Kelley, K.C., Votoupal, "Battery including carbon foam current collectors," US6979513 B2, 2005.

[91] Firefly, "Firefly's MICROCELL carbon foam," 2017. [Online]. Available: http://fireflyenergy.com/. [Accessed: 02-May-2017].

Unit 3, Curo Park
Frogmore
St. Albans
Hertfordshire
AL2 2DD
UK

Tel: +44 (0) 1727 875 544
Fax: 44 (0) 1727 871 341
Email: info@itri.co.uk
Web: www.itri.co.uk