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Trends and prospects in lead-acid battery developments

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Abstract

In recent years the interest in lead-acid batteries has resurfaced, amidst the rising need for power storage technologies spanning to not just mobile, but also stationary applications. While lithium-ion batteries remain one of the most common power sources in today's western world, due to many concerns regarding various shortcomings of the said technology alternatives are often discussed. There is a push for adapting lead-acid batteries (as part of the advanced lead acid battery initiative) as replacement for the lithium batteries all over the world, the USA included, due mainly to their lower price and reliability in hotter climates. Furthermore – due to the rising need for uninterrupted power delivery systems, new designs of such devices are being developed and implemented in the western world hoping to meet the demands of the market. As a result, new additives to electrode material, as well as battery designs have been developed and are currently being considered for inclusion in the modern lead-acid battery construction.

Background information and introduction

The lead-acid battery since its introduction by Plante in 1860, has found many uses for over 150 years [1]. They are often highly regarded for their low cost, flat discharge curve, resistance to damage due to the irregular charge/discharge cycles and ease of maintenance. Their operating voltage in the range of 1.9V-2.3V makes them excellent candidates for assembling into large battery strings [2,3]. However, compared to other battery types, lead-acid batteries' power-to-weight and energy-to-weight ratio are not optimal, pushing designers to adapt more expensive but more light-weight solutions that have become available over time [4].

Currently lead-acid batteries are mostly used in uninterrupted power supply systems – emergency systems that can provide electricity in case of its short-term absence. Or in the case of a long-term blackout, they can mitigate the lack of electrical power during the initial start-up phase of the emergency power-providing diesel generators [3]. There is also another important and often overlooked use - in automotive applications which, in recent years due to the popularity of electric vehicles, has seen a resurgence of interest. Due to the climate conditions, as well as cost concerns, many nations turn to lead-acid batteries as an alternative to the lithium-ion ones for usage in i.e. electric bicycles [5,6]. This renewed interest in the lead-based technology has pushed many research teams into researching possible upgrades to the battery design in order to make them more resistant to the ageing effects or to increase their capacity.

The most important construction material of the battery is lead [7]. It is used in both negative and positive electrodes, in its metallic form for the former and the dioxide form in the latter. In the original Plante design the battery consisted of two solid lead plates, one of which had a layer of lead (IV) oxide electrochemically deposited on it, electrolyte consisting of 38% sulphuric acid and a separator (in the case of the first design: a pine board) [2,3,7].

The said construction has evolved to use an electrode paste suspended on a lead grid instead of lead plates. This has improved the available surface area of the electrode material, increasing its possible current output and capacity. It should be noted, however, that the lead plate design is still used in some specific battery constructions where material shedding and grid corrosion might be an issue [2,7]. In some cases, tubular places are used instead – spines at which electrode mass is suspended in gauntlets. Compared to the flat plate, these have extended lifetime expectancy to about 15-25 years in float operation.

The grids on which the electrode material is suspended are made of lead alloys, as pure lead has too poor mechanical qualities for such use. The alloy composition most often includes 90-95% of lead, the rest being additives such as: tin, calcium, silver, arsenic and antimony. The shape of the grids depends on the specific battery construction, designs, and designation.

The electrode material prepared out of pastes composed of a mixture of lead (II) oxides both tetragonal and orthorhombic, lead (IV) sulphate and lead. In some cases, Pb_3O_4 is also added to the composition to better the mechanical properties of the resulting electrode mass. The ratios between these components differ from manufacturer to manufacturer and are kept a trade secret. Surface area and oxidation of lead oxide used to prepare pastes strongly depends on the way of production. In Barton mills surface area and oxidation level of lead oxide can be obtained much higher than in conventional ball mills. Meanwhile the main impact of properties of lead oxide is purity of used lead ingots with possible small amounts of additives like Bi, Ag, As, Tl, Te, Cu, Cd, Zn. There are, however, several papers discussing new paste compositions and providing a rough idea of what specific ratios might be used in preparation for commercially available batteries. These pastes also employ several additives to improve their mechanical capabilities. Electrode material shedding can be an issue during battery operation and an array of compounds is usually added to the mixture to prevent this ageing process. The most used additives consist of barium (II) sulphate, ligno-sulphates, and active carbon. Their main purpose is to reduce the formation of large $PbSO_4$ crystals to prevent sulphation on negative electrodes, as well as reduce the mechanical strain on the electrode material that large crystals can invoke. Furthermore, some of these additives that help with the curing process result in better lead and lead (IV) oxide structure forming in the electrode paste. Time of dosing compounds and temperature during preparation of paste are crucial to get the fine, composed active material of electrodes. The stable temperature of process should be carried out to form the desired specific structure of pastes. The ratio between lead oxide powder and sulfuric acid added into mixture and density of mass are decisive to accomplish long cycle life with acceptable initial capacity of active material. Typical ratio H_2SO_4/LO for industry application are up to 5% but in automotive sulfuric acid content can be up to 9% with consequence of decreasing paste lifetime but resulting in higher initial capacity.

Pastes prepared in vacuum condition characterized better homogeneity in shorter time than in standard mixer.

There is, however, an array of compounds that battery manufacturers add to their electrode paste mixtures. These specific compound names are kept confidential and access to any information is limited or in many cases restricted.

Prepared pastes are incorporated into flat grids by pasting section or wet filled into tubular gauntlets of positive grids. After filling step plates are loaded into curing chamber to cure and dry of active materials. Sufficient conditions of process are being controlled by temperature and humidity level inside chamber. The curing process consists of loading, curing and drying states. Profile of curing are dependent of type of plates or composition of pastes mixture and amount water inside active material. Negative plates after curing process are mainly composed of tribasic structure ($3PbO·PbSO_4$), $PbSO_4$ and Pb below 4%. Cracks and poor bonding to grids are eliminated by adjusted profile of parameters during full process. Typical loading parameters are temperature range from 40 to 45˚C and humidity over 90%. Time of equalization condition inside chamber should not be less than 8h. After stabilization temperature has slowly grown to reach range from 50 to 65˚C with decreased level of humidity from 90 to 70% to ensure create porosity and bonding skeleton between prepared pastes and grids. Time of curing is calculated by amount of bonded water inside active materials and lead content and takes from 10 to 30h. Drying stage in 70 to 80˚C ends when water content has decreased below of 0,2%. Cured plates characterized well mechanical strain, open porosity in range 40÷50% and active materials bonded with corroded surface of grids or spines.

Positive active material for long cycle lifetime should be converted by curing process into mixture of tetrabasic $4PbO·PbSO_4$, tribasic $3PbO·PbSO_4$, $PbSO_4$ and metallic lead below 1% of content; therefore, curing stage is carried out at a higher temperature 60÷75˚C.

The separators can be made of many materials – historically the separators were made out of wood, paper or rubber. Currently the most common ones used are microporous polymers such as polyethylene or polypropylene [2]. Some battery designs use PVC, glass fiber and micro glass instead. It is common to include glass fiber or micro glass structures in separators in the form of a composite to reduce shedding of the electrode material in case of mechanical strain. Additives in electrolyte in some cases may eliminate polyethylene microporous separators by using lower durability in presence of them for long term application.

The role of formation is a completed conversion of $PbSO_4$ compounds on plates into reduced or oxidized forms by introducing charge load of capacity in the range of 4C to 7C during process. Full time of the process depends on the method and program used. Formation of batteries may be obtained in closed system with recirculation of electrolyte between batteries and tanks of sulfuric acid in 24÷28h, open area system chilled in water bath in 3-4 days or without it by adjusted current profile during process and extending time of charging to 5-7 days. At first step of the process batteries are filled by sulfuric acid with density from 1.18 to 1.26 kg/dm^3 and stayed rest for full soaking of green plates. Temperature of batteries at formation is in the range of 45 to 50˚C to perform proper conversion of sulfuric lead on plates to final structure. At the end of formation, the electrolyte density is between 1,24 to 1,30 kg/dm3 depending on the type of batteries.

The flooded design of the lead-acid battery has later evolved into the maintenance-free one, where an excess supply of electrolyte is provided to mitigate any losses during its operation. Later the development of immobilized electrolyte led to the VRLA construction. Immobilization can be done in two manners. A highly porous and absorbent glass fiber mat is soaked with electrolyte and acts both as a separator and an electrolyte layer (AGM). Alternatively, fumed silica is added to the electrolyte, transforming it into a gel. This gel is then suspended between the plates providing an electrolyte layer (Gel design). It should be noted that hybrid designs combining both solutions exist and are used in some specialized designs. All three of these designs have uses in different areas, as well as specific variants for more specialized uses (such as deep cycling batteries) [2,3]. The most known everyday use of lead acid batteries is in automotive application as start, light and ignition (SLI) in gasoline-powered cars. The battery provides initial sparks used to start up the engine as well as deliver power. The most used battery design for these uses is the flooded one. But in the case of vehicles with a risk of spillage, such as motorcycles, VRLA batteries are used instead. The second most common use of lead-acid batteries are in stationary applications as part of UPS (Uninterrupted power supply) systems. In such cases, in small scale applications such as portable UPS usually the VRLA designs are used. But where large amounts of backup power are needed the flooded design is more common to find – both the standard and the maintenance-free one. Lastly the deep-cycling uses employ a modified design of the flooded battery design with thick large volume porous plates, premium separators and glass fiber mats woven into the electrode structure. For these particular batteries, instead of the electrode mass volume the electrolyte level is the limiting factor of the process. This is in opposition to the traditional. This modification ensures battery's longevity as they are commonly used in vehicles such as golf carts or forklifts where the need for large discharge currents is a must couple with rough operating conditions. In the case of submarines, an even more specific design is used whereas plain lead plates are used instead of the grid design. This is to eliminate any potential dangers that might arise from gaseous discharge during battery operation in enclosed environments. The reduction of such additives as antimony and/or arsenic into toxic volatile compounds can pose a risk to a submarine crew.

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Recycling of lead-acid batteries

Currently due to the large amount of spent lead acid batteries available, the issue of recycling is frequently discussed [9, 10]. While western countries already achieved near 99% lead recycling rates, countries in Asia such as India and China have been attempting at their own programmes for achieving such rates [11,12]. This refuse can be re-used as a material source for making new lead-acid batteries, which are seen as viable energy sources in the said regions. The issue, though, is the rising number of spent cells that require recycling, pushing for investments into infrastructure such as recycling plants and safe waste storage sites [13].

While the lead itself is easily recyclable, there are several issues concerning re-using it. The first issue is ecological concerns, as the pyrometallurgical processes are considered damaging to areas near the recycling plants [14,15]. Instead of these methods, the more expensive electro hydrometallurgical processes should be considered [16] as they have less environmental impact and offer purer output material than the smelting-based ones. Although technologies that ensure pollution free-smelting processes do exist. The cost of these technologies is what prohibits their adaptation in some regions of the world. These methods have been already implemented in the western world where environmental regulations are much stricter compared to the other parts of the world. Meanwhile, the countries, which are still building their recycling potential, struggle with outdated technology.

The other issue at hand is the purity of the retrieved material. The lead alloy grids that are being smelted in the recycling processes, as mentioned previously, often contain antimony, as well as other impurities [17]. The presence of the said element in the component can lower the water breakdown voltage in the lead-acid batteries [3,4], resulting in potentially higher production of hydrogen during the normal charging/buffering periods. This results in increased water loss from the electrolyte but also increases the chance of a possible explosion risk. On the other hand, not only antimony can be found in recycled lead [18, 19, 20], but also arsenic, silver, calcium and other pollutants that are usually present in the alloys used in grids. Insufficient refining of the resource can cause high antimony levels in grids produced with the recycled lead. This, in turn, can result in grids with poorer electrochemical qualities [17,21]. Several antimony extraction methods exist [22] and many more are currently being developed [23,24,25]. The problem that remains, however, is the application of these technologies in lead refining and enforcement of stricter quality control at the recycling sites. The suggestion of using electro-hydrometallurgical processes as a replacement for the cheap but polluting pyrometallurgical based one likely would result in purer output resource [16]. The application of this however is put in question, as the sustainability of such ventures proves to be problematic [17]. It should be noted that pyro-metallurgical processes can be used in a much safer and cleaner manner, through the application of filters, safety procedures and proper waste management. Sites using such technology in a manner that does not impact the local environment exist in Poland or Sweden. However, the application of the said manners does affect the cost of the pyro-metallurgical processes. And in the case of countries where low cost is priority, these environmental measures most likely will not be enforced. Nevertheless, development of new low-cost processes for recycling lead and simultaneously providing battery component materials [26] can help mitigate the need for complex supply chain that is the hampering factor in LAB production out of recycled materials.

Modifications to battery design

The lead-acid battery has not been receiving a lot attention in the field of new technologies in comparison to the lithium-ion one. Re-examination of the current designs and materials used in the construction lead to several advancements in areas of reliability and capacity. Another important field of interest in lead-acid technologies was the integration of emerging carbon-based materials into their designs [27, 28, 29] as either a means of strengthening the batteries' construction or increasing its capacity. There are also other ideas which include fitting the batteries with super-capacitor as a part of their construction, in order to better their capacity and performance.

Challenges and concerns

Several qualities of lead-acid batteries can be considered for improvement. One of the major factors that hampers their use in most applications is its weight and, by proxy, energy density. So, striving to reduce the batteries has become the focus for some of the teams working on lead-acid battery research. Other teams have instead focused on improving the batteries' charge capacity and charge efficiency. Both of these paths rely on the application of new grid materials as well as different battery designs.

Another field of research that is currently focused on is the reliability of various battery components. Much of the attention is focused on the impact of the ageing processes on the battery's reliability. Corrosion [2,3,7] is a major factor in grid longevity, as it can lead to battery's catastrophic failure when a corroded grid is mechanically damaged. The current materials used in battery construction, while resistant to acidic corrosion under normal operation, can be affected by overcharging conditions.

The other major ageing process that raises concerns is sulphation [2,3,7] – formation of inert lead (II) sulphate crystals. This normally occurs during the operation of the lead-acid battery, although undercharging of the battery can amplify the process. These crystals can cause mechanical strain on the electrode mass, which often results in the electrode material being shed off the grids, lowering the battery's capacity and/or causing shorts.

Lastly, hydrogen evolution [2,3,7] is also an aspect to be considered. As mentioned previously grid alloy composition can negatively impact the water breakdown voltage, lowering it and in turn causing increased water loss. This is a major concern for maintenance-free and sealed batteries where the electrolyte quantity is limited.

Grid modifications

One of the vectors of development for LABs was the modifications of the grids used in modern lead-acid batteries [8]. Improvements of the grids can be made by either application of novel design or by application of new construction materials or additives.

It was found that the current distribution during charge/discharge in the presently used grids is sub-optimal, leading to reconsideration of their design [30,31]. Mathematical modelling as well as testing have led to the development of new constructions offering smaller internal resistance compared to the commercially available ones (thus reducing energy losses and uneven current distribution during operation), but also ones that reduce the material needed for construction. Thus, this approach might offer improvement in battery life and efficiency for a relatively low-cost involved.

A different approach to grid modification was the application of new materials for the lead-acid batteries. While traditionally the grids were constructed out of lead alloys – either lead-antimony, lead-calcium or lead-calcium-tin [8], some research groups have set to develop new materials to be used instead. There are several problems presented by using the classic alloys in LABs – mechanical qualities, corrosion, and weight. Each of them presenting a different challenge from a design perspective. The issue of the weight is perhaps the biggest obstacle when competing against Li-Ion batteries [32], as lead-acid technologies offer lower energy densities, so any material offering weight reduction in such is desirable. These alternative current collectors saw a lot of development in the last 20 years [33,34]. One of the first approaches to the problem was to use composite based grids. These are composed of the ABS polymer, cured with sulphuric acid, with a copper layer deposited chemically onto it. Then a coating of lead or lead oxide is electrochemically deposited on such surface for conductivity [34,35,36]. While this approach was popular at the time, the issue with this proved to be the reliance on the coating for current carrying. So instead, it was proposed that a grid made of a different metal was to be used instead, such as copper [37]. The problem obvious here, however, was the subsequent corrosion of the material due to the highly acidic electrolyte. The other proposal was to use titanium [38], but despite the design showing promising results the metallurgy of titanium is very challenging. Special production lines would have to be constructed to prevent metal oxidization while casting.

On the other hand, the emergence of carbon-based technologies lead to elevated interest in applying them in lead-acid battery construction. One of the vectors of development was the inclusion of graphite [39] in the grid composition for the negative plate. However, the presence of carbon on the negative plate can lead to increased hydrogen evolution and subsequent water loss. Reportedly this was solved by application of a thin layer of inert lead (II) sulphate on the surface of the current collector. This grid design is lighter than the classical one and can further be improved, yielding higher energy densities from batteries using this construction. Graphite was also tried as a component for lead composite, along with graphene in a material for positive LAB grids [40]. The improvements offered by this design include much better corrosion resistance in comparison to the standard lead alloys used (whereas positive plate corrosion is a major factor in battery ageing) and improved electrochemical properties, which in theory should improve the overall battery efficiency. However, application of this material for a negative plate is not considered as the carbon present can increase the rate of hydrogen evolution, as mentioned previously. The other vector that was studied was the usage of carbon nanotubes as a coating of both the positive and negative lead grid [41,42]. The research has shown that the coating prevents sulphation on the plates, in turn increasing the longevity of the battery where such design was applied. The mentioned papers cite the increase of 60% in the amounts of cycles before battery failure if coating is applied to only the negative grid. The increase is approximately 500% if both grids were to be coated with a carbon nanotube layer.

A novel grid design referred to as the carbon honeycomb, was also developed in the course of last decade as a means to replace the classic lead alloy ones [43]. This design was to spearhead the development of a lightweight lead-acid battery [44] with possible usage in the field of EV. This particular design proved to be lightweight in comparison to the currently available grids as the base of it was the use of a carbon/carbon composite with electrodeposited lead on its surface. Two variants were developed – a negative plate [45] and a positive plate [46] which differed in the composite composition. The latter being unfit to use in commercial applications to the increased corrosion of the grid. However, it was determined that as a negative plate the carbon honeycomb is a good replacement for the currently used alloys.

Electrode material additives

Currently the major concern with LAB electrode pastes materials is their cyclability, resistance to ageing effects such as sulphation and charge efficiency. Carbon as an additive was a common ingredient in electrode paste [47,48] in the form of activated carbon or carbon black. The presence of negative electrode material decreases the rate of possible occurring sulphation but also increases the capacity of the lead-acid cells [49]. As with grids, the development of carbon technologies has led to research whether the newly developed materials such as graphene or carbon nanotubes can possibly be integrated into electrode pastes.

Graphene was considered as an additive to the negative electrode paste [50]. The research has shown that in the case of graphene, the addition has extended the battery's life by 50% compared to the commercially available batteries using acetylene black additives. The proposed reasoning for this was sulphation prevention – one of the main causes for capacity loss in LABs.

Compared to the role in grid coating the carbon-nanotubes [51], as an additive to the positive electrode material, were found to serve a major role as a corrosion suppressor. Thus, the impact of positive grid corrosion, one of the ageing processes that can lead to battery failure, is lessened, prolonging the cycle life. It should be noted that the mechanism of carbon nanotube impact on the grid corrosion processes is still under investigation.

Electric grid-oriented applications

Lead acid batteries as systems of well-known operational characteristics and relatively low CAPEX costs were natural candidates [60] for building a mid and high-volume power storing systems needed in purpose of balancing of modern highly loaded RES rich power grids. These constructions, despite of the more exotic ones such as utilizing cheap decommissioned batteries [61] can be easily divided into three main generations differing both in the type of the batteries applied, as well as, in their operational features [62]. First of them – the oldest was utilizing classical lead acid batteries (including VRLA's) including those days largest battery power storing system built in 1988 in Chino California [63]. The serial-parallel connection of the individual batteries applied allowed here for 10 MW power rating and 40 MWh total capacity. The full capacity cycle operation mode was here applied with 4h of operation needed to fully discharge the store rated for 2000V and up to 8000A [2]. The operational lifetime of the systems exceeded ten years confirming in practice the expected high level of robustness of the systems of interest. The second-generation systems include the so-called advanced lead-acid designs including carbon based negative electrode materials [64], as well as, granular silica electrolyte retention systems high-density positive active material, and silica-based electrolytes [65]. These include e.g. a 1MW 1,5 MWh system located in Metlakatla Arkansas [66] operated by Exide for 12 years in a shallow discharge regime and, despite of the lack of the significant deterioration symptoms was replaced and dismantled in 2008 only in post-use analysis purposes. Another similar in design but larger systems deployed were rated between 10 and 20 MW [67]. Other designs of advanced lead acid batteries were proposed by Hitachi. These included 10,4 MWh storages located in Goshogawara and Yuassa Japan. It is worth stressing that the last two solutions were designed for a direct cooperation with same place wind farms rated to 15 MW in order to stabilize their generation possibilities [68]. In Europe the Belectric's Energy Buffer Unit was built in Alt Daber Germany. In this case the system deployed rated to 2000 kWh was specially designed to deliver the 1.3 MW frequency stabilizing response to the respectively larger (67,8 MW) solar farm located nearby [69]. The third-generation systems are usually utilizing a hybrid battery design where various cell chemistries collaborating are chosen in a manner that allows for the mutual compensation of their drawbacks. Here one should look at the results of M5BAT project [70] realized in Aachen Germany where a Modular Multi-Megawatt Multi-Technology Medium Voltage – Battery Storage System of the said hybrid design was rated to 5,6 MW and 5.5 MWh which parameters would be hardly achievable for a purely LAB based solution. At the time of the completion of the paper presented the system was working for more than five years in an energy time shifting mode with the current operational status of the storage available online to the public through the specialized website [71]

The above-mentioned hybrid designs have been becoming more relevant in the current day. These projects focus on using the strong points of each of the battery types, depending on functionality defined by the power system operator. While lead-acid batteries have better long-term power delivery and storage capabilities during static loads, lithium-ion batteries can compensate for dynamic states that can stochastically occur in the power system. And so, combining both of these solutions with an innovative battery management system can be used as a key element in developing power systems with high saturation with alternative technologies, including renewable energy sources, with simultaneous independent control and optimization of phenomena that can have an impact on these technologies. An example of such system is a hybrid 6 MW rated one made by Hitachi (5 MW from lead-acid, 1 MW from lithium-ion), currently deployed in Poland [72] with the objective of supporting dispersed generation, mostly wind-based.

The above-mentioned system was designed to ensure stable operation of a fragment of a power system with a high percentage of renewable energy sources and to support its balancing. The assumed functionality of the system included:

Countermeasures to prevent overload states of transmission lines of the National Power System, based on the existing load the system fragment and the level of wind generation existing in a respective area.

Support in balancing the fragment's power, including unstable wind-based generation, including the prevention of fast changes in the rate of electrical energy production in the supervised wind farms.

Supervising arbitrage pricing and operating in a regime of a pumped storage hydroelectricity

It should be noted that the complement of the given battery technologies functionality is an accurate definition of a construction and in consequence functionality of a power electronics devices, which is responsible for providing system service of electric energy quality parameter compensation in the local area or wider territory. A good example other than active power economy in the scope of capacity and power of the storage system, could be the ability to compensate passive power as well as compensation of asymmetrical voltages at the point where the storage system is connected to the grid (PCC), compensation in unison with the lithium-ion battery of dynamic states such as: short circuits, overloads, short-term high voltage periods of recharging the energy storage and functioning in the reference voltage/frequency mode including the previously mentioned functionalities (island mode). It is one of the future functionalities of hybrid electrical energy storage solutions, planned to be used in case of emergency desynchronization of vast power systems.

Economic outlook

Lead-acid battery technologies still hold an important role in the modern world. As the need for mobile and immobile energy storage increases, the development of more refined battery components and designs is a must to ensure batteries with higher capacity and reliability rates. As lithium battery technologies were seen as the more economically viable choice a few years back, due to the global shortages in materials as well as the limited resource pools of such, many have reconsidered pursuing older battery technologies instead. This is especially visible in the non-western countries. Programmes have been started or are ongoing in India [73], China [74], Brazil [75,76] and some African [77] nations to integrate the LABs in various applications [78] as a substitute for Li-ion batteries. There lead-based technology is considered more desirable due to its cost, as well as its climate-based considerations.

Thus, the perspective for further lead-acid battery designs is promising. With mounting problems concerning lithium-based technology applications as well as the rising cost of such, lead offers an interesting alternative. The UPS technologies, which in recent times have tried to introduce the lithium-based variants [32], for the most part, still use LABs as basis for most designs. This, coupled with increasing demand for small scale renewable energy plants in western countries, is still a major driving force behind the advancement of lead-acid batteries [73].

It should be noted that the lack of usage of the LAB in EV applications such as automobiles due to the low energy density compared to lithium-ion technologies, could change in the upcoming years. The development of and rising demand for e-bikes [77], push for increased energy sources consumption – a market where low-weight lead-acid batteries could see their use. Furthermore, the EU [79,80] and USA [81] push for replacement of combustion engine cars, which could see an increased demand for electrical vehicles, perhaps using refined lead-acid technologies. The rising need for lithium with few sources of such [82,83] will eventually lead to consideration of other technologies, and with the sodium-ion batteries still in the prototype phases, lead technologies can fill out this niche.

Conclusions

The economic outlook suggests that the lead-acid battery market should expand in the next decades. The rising need for cheap and reliable power sources in the non-western world has led to the expansion of the local recycling business, utilizing several technologies to regain the lead used in the batteries. While some concerns are raised over the ecological impact of these types of industry, it should be noted that the modern recycling technologies of lead and lead based galvanic cells account for having minimal impact on the environment. However, the implementation of such still relies on the accordance with local government laws. Hence, it must be stressed that in case of loose ecological laws in some parts of the world, these technologies can be not fully implemented and give a false impression on how they can negatively impact the environment.

It should be also noted that in countries with a hot climate, lead-acid batteries are considered the safer alternative to the lithium-ion ones. Countries like China or India are researching the possibility of implementing them for low-cost e-mobility purposes and given the population size of both, the market for battery consumption should be huge. One should, however, note that it is possible that in those countries the local companies will establish a strong foothold and oppose any foreign investments. On the other hand, African and South American countries may be seen as more viable markets for expansion, as they too are looking for replacements for the lithium-ion batteries.

In the field of battery designs and additives, carbon (either as carbon black, fullerenes or carbon nanotubes) is considered one of the most promising materials both as a grid component as well as electrode paste additives. Several trials have been conducted in which carbon-lead composites were used, and batteries using such have been shown to have better characteristics than their regular counterparts. It should also be noted that grids made entirely out of carbon are also considered as an evolution of the classic battery design and have proven to also be better. This leads to the conclusion that perhaps carbon-lead composites are going to be an important component in the next generation of lead-acid battery constructions.

Lastly it is worth mentioning that for the purpose of stationary uninterrupted power systems, lead-acid batteries are still considered an irreplaceable component. But due to the need to compensate for a sudden power drop or providing high amounts of energy for short periods of time, the sole lead-acid solutions were deemed inefficient. Thus, modern systems are concentrating on employing a hybrid lead-acid/lithium-ion configurations – some of these solutions are already commercially available and have been proving to be extremely reliable.

In conclusion – lead-acid batteries are still remaining one of the most important power sources available. The recent developments in the field of e-mobility, as well as grid balancing renewed interest in researching topics connected with them. Thus, it can be assumed that in the coming years many other projects with an objective of improving battery designs and their longevity will be concluded.

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