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From kilowatts to kilometers: Unpacking the Potential of Electric Mobility in Africa

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ABSTRACT

Electric vehicles are slowly reinforcing their place in the global market, with 6.75 million units sold in 2021, accounting for 8.3% of the global automotive market, with expectations of this increasing to 33% by 2028. South Africa and Kenya, however, only contributed approximately 1559 and 350 units to this total, respectively. To accommodate the anticipated e-mobility growth in South Africa, and the rest of the continent, a sound understanding of the battery chemistry, developments and advances need to be explored and integrated with additional principles, such as project and risk management. The battery chemistry has a profound effect on cradle-to-grave assessments, and in exploring second-life applications, the battery utilisation can be increased before the need for recycling. Sound knowledge of the chemistry is also crucial in elucidating risks and providing a safe working environment, making risk-mitigation initiatives more transparent, improving the manufacturing process and providing opportunities for small start-ups to form, supporting the shift to a more electric-powered mindset. Adopting new technologies and integrating electric mobility can not only advance local efforts to advance electrochemistry research but also support sustainable development schemes in Africa.

KEYWORDS

e-Mobility; lithium-ion safety; electric vehicle; battery project management; lithium-ion commodity

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INTRODUCTION

The importance of batteries continues to grow with developments in grid storage, the internet of Things and electric vehicles as society continues to embrace greener and more technologically integrated systems and processes. Electric vehicles are a significant driver of battery demand as global sales of passenger battery electric and plug-in hybrid sales increased to 6.75 million units in 2021, up 108% from 2020 and 5400% from 2012, with forecasts estimating sales at 21 million in 2025, resulting in 77 million EVs on the world's roads.[1] EVs are currently displacing an estimated 1.5 million barrels of oil usage each day, with 67% being contributed by 2- and 3-wheel vehicles [2] and many predictions enforce this market as one of the leading technology drivers for the African market.

The anticipated advances in electric vehicles and stronger integration into the African economy provide some unique continental opportunities in developing and utilising local mineral beneficiation processes to enhance the value of the mined commodity.

Beneficiation, which includes mechanical and chemical processes, is used to improve the mineral percentage by removing unwanted components of the original mined ore. This allows for a more concentrated product to be shipped, thereby reducing the waste that is generated at the refinery and results in following a leaner methodology from the initial stages in the process chain. Early-stage beneficiation of the crushed ores includes gravity (dense media) separation, magnetic separation and froth flotation. Gravity separation exploits the specific gravity between the target and gangue minerals where the dense media allows for selective floating of target minerals, while magnetic separation is predominantly used on magnetic iron-bearing minerals, which are difficult to separate using other methods. Froth flotation exploits the surface characteristics of minerals when the particle sizes or the specific gravities of the particles are too small to be effective in dense media separation. There are two different methods, namely reverse and direct flotation, with reverse flotation using cationic collectors to float the gangue minerals, whereas an anionic collector floats the desired mineral to the surface. Several factors affect the recovery of minerals, including surface chemistry, type and concentration of the collector, pulp pH and pretreatment. For example, NaOH, Na_2S and NaF are used in various pre-cleaning processes to modify the surface and allow for improved separation. Understanding the crystal structure of the phases present in the ore is also crucial since it allows for the identification of crystal planes with varied hydrophobicity that affects contact angles, which allows for an ideal collector to be selected for chemisorption to occur. For example, spodumene ($LiAl(SiO_3)_2$) can be targeted explicitly by using froth flotation anionic collectors such as oleic acid, sodium oleate, sulfonated and phosphorated fatty acids that typically favours the {100} cleavage plane for chemisorption.[3]

There are additional refining processes to further improve the concentration of the valued metals, such as reductive leaching, solvent extraction, ion exchange and electrowinning. Reductive leaching, using copper ore as an example, is an electrochemical process with an anodic portion, the reductant dissolution (such as aqueous metallic iron), and a cathodic portion, the chalcopyrite ($CuFeS_2$) ore reduction. Solvent extraction is the subsequent process by which the anions or cations are transferred from an aqueous to an organic phase with good chelating agents, such as hydroxylamines for copper ions. The remaining aqueous raffinate contains cobalt along with iron, aluminium, manganese and copper impurities. By precipitating cobalt with MgO and redissolving, high-purity cobalt-rich electrolyte is produced, which is then filtered. The final step to produce the metallic product, both copper and cobalt in the example, is to perform electrowinning by applying a current to a concentrate solution containing the desired metallic species that are then deposited on the cathode in the electrolytic system.[4]

There is an estimated 0-15 kg of cobalt, 0-40 kg nickel and 30-50 kg of lithium in a typical battery for an electric vehicle, along with manganese and aluminium, depending on the cathode chemistry. Africa already has a strong presence in some of these commodities and the capacity to develop operations in a few others. The prominent countries in the battery's mineral value chain are shown in Figure 1, with several countries producing more than one of the desired minerals. The minerals and African contributions are explored individually thereafter. All production and mineral reserve

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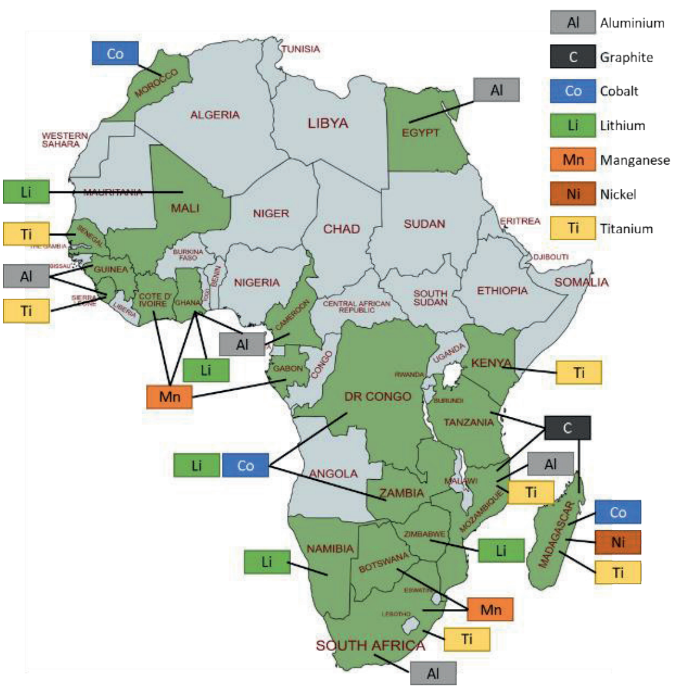

Figure 1: Countries which mine or produce major battery raw materials.

values are reported from the United States Geological Survey (USGS) Commodity Statistics and Information,[5] for 2021 unless otherwise stated and represent the contained metal equivalent.

Cobalt, produced as a by-product of copper mining, is synonymous with electric vehicle cathode material since it provides favourable energy and power densities. The Democratic Republic of Congo (DRC) accounts for around 70% (120 kilotonne (kt)) of global output as well as holds 50% of the world's reserves. In a Bloomberg article,[6] the feasibility of a unified African supply chain was discussed with the DRC expressing its intentions to develop a domestic battery beneficiation industry. It found that a 10 kt cathode precursor plant would cost three times less than a similar plant construction in the US, about one-third the cost in China and half the cost in Poland. The reason for this was primarily due to DRC's use of hydropower and the fact that the battery production emissions could be reduced by 30% when compared with current Chinese supply chains. Further production is realized from countries such as Madagascar (2.5 kt in 2021, 100 kt contained metal reserves) and Morocco (2.3 kt production, 13 kt reserves), with Zambia expected to ramp up their production to around 4-5 kt fueled by stronger prices.[7]

Africa also has a strong presence in the **manganese** market, with South Africa contributing around one-third of global seaborne supply (largest exporter) as well as holding 43% of global reserves, followed by Gabon being the 2nd largest exporter. There are also relatively smaller operations in Côte d'Ivoire and Ghana. The majority of this manganese is used in the steel industry and therefore doesn't undergo substantial beneficiation specific for Li-ion battery applications; however, South Africa's Manganese Metal Company is reportedly the world's only non-China-based producer of high-grade electrolytic manganese metal (EMM) and is considered to be the largest refinery of 99.9% (selenium-free) EMM.[8] However, historically South Africa had an electrolytic manganese dioxide manufacturing facility near Nelspruit, in the province of Mpumalanga, which closed in 2014 due to increased labour and production costs making it cheaper to import batteries instead.[9] Giyani Metals, which is already a member of the European Battery Alliance, is currently exploring three battery-amenable manganese projects in Botswana, and is performing a feasibility study, at their main K.Hill deposit, with the demonstration plant construction expected to start in 2022.[10] They plan to supply high-purity manganese sulphate monohydrate for battery manufacturing while emitting low carbon emissions.

The major component in every **lithium**-ion battery is reported to be present in many African countries, including Zimbabwe (1.2 kt production, 500 kt reserves), Democratic Republic of Congo (3 megatonnes (Mt) reserves), Mali (700 kt reserves), Ghana (130 kt reserves) and Namibia (50 kt reserves). Zimbabwe is currently the only lithium exporter in Africa. A historic tin mine in the DRC is currently undergoing a feasibility study, with the first spodumene concentrate production expected to start in late 2023.[11]

Around four tonnes of bauxite are required to produce one tonne of alumina, and approximately two tonnes of alumina are electrolytically refined into one tonne of **aluminium**. This bodes well for Africa because the 3rd largest producer of bauxite, Guinea (64Mt in 2019), also holds the largest reserves at 7 gigatonnes (GT), with additional smaller projects present in Sierra Leone, Ghana and Mozambique. The break in the value chain occurs when it comes to the alumina since no refining takes place in Africa, and the bauxite is shipped for refining (via the Bayer process) mostly to South America and China. The final stage, producing aluminium through the Hall-Heroult process, is where South Africa makes its mark, with the Hillside Aluminium smelter producing 720 ktpa (kilotonne per anum), making it the largest smelter in the Southern Hemisphere. Mozal Aluminium, in Mozambique, also produces a substantial amount of 580ktpa, with additional smelters present in Egypt, Ghana and Cameroon, with the latter two running well below capacity due to the need for further investment and poor access to electricity, respectively.

Ambatovy operation in Madagascar is one of the largest lateritic **nickel** mining and refining companies in the world, while also producing cobalt as a by-product. The remainder of African nickel is produced as by-products from precious metal mines in Zimbabwe and South Africa.[12] Although most of the focus is on the cathode material, there are significant resources in Africa that can also contribute to the required anode materials. This would be in the form of graphite and **titanium** mining. Mozambique produced 30 Mt of graphite in 2021, with additional projects at various development stages in Tanzania and Madagascar. According to the USGS, the contained TiO_2 in Ilmenite ($FeTiO_3$) reserves lie in Kenya (390 kt), Madagascar (22 Mt), Mozambique (26 Mt), South Africa (30 Mt) and Senegal (unknown). While rutile (TiO_2) can also be found in Kenya (170 kt), Mozambique (890 kt), Senegal (unknown), South Africa (6.5 Mt) and Sierra Leone (490 kt), although to a lower degree.

Apart from the well-known materials which are required for the cathode and anode material, there are many other minerals which are involved in battery manufacturing, such as copper, fluorine, phosphate, tin and steel. There is an estimated 23 kg of copper in an internal combustion engine vehicle, while hybrid electric, plug-in hybrid electric and battery electric vehicles have around 40 kg, 60 kg and 83 kg, respectively. Larger vehicles consequently require greater amounts due to increased wiring demand and larger electric motors, with hybrid busses requiring 89 kg of copper and the battery between 224-369 kg depending on the sizes required. EV chargers add a further 0.7 kg and for fast chargers up to 8 kg of copper is needed. Since cobalt is a by-product of copper mining, there are established copper smelters in Africa, such as Ivanhoe and Zijin's Kamoa-Kakula mining complex and China Nonferrous Mining Corp's Lualaba smelter. Copper smelting also produces sulfur dioxide (SO_2), which can be converted into sulfuric acid that is used in various mining leaching processes or the manufacturing of lead-acid batteries. South Africa has the largest fluorspar reserves globally, which are exported for refining and then imported at a significantly higher cost once integrated into its many uses, such as ceramics, fluorochemicals (used in lithium-ion batteries) and various construction materials. South Africa has attempted to mitigate some of the losses in the value chain and has a reasonably well-established fluorine-based chemical industry supplying a range of applications through the well-known South African Nuclear Energy Corporation (NECSA), which includes its nuclear program as well as

National Research Chairs located at the University of Pretoria and University of KwaZulu-Natal.[13] Phosphate is predominantly used in fertilizers and phosphoric acid but also has a place in lithium-ion batteries where the cathode material is made from lithium-iron-phosphate and in the electrolyte as $LiPF_6$. The USGS report estimates 2021 production in Algeria (1.2 mntpa), Egypt (5 mntpa), Morocco (38 mntpa), Senegal (2.2 mntpa) and South Africa (2 mntpa). More than 60% of tin is used as solder but is also present in many other motor vehicle components from brake pads to sealants, with supply coming from Tinco's Rutongo mine, in Rwanda, and small-scale mines present throughout sub-Saharan Africa, predominantly in DRC, Uganda, Burundi and Nigeria.

Over and above the use of batteries in applications such as grid storage, within mining operations, attempts are made to incorporate more renewable energy generation sources. These include the use of specialized electric-driven mining vehicles where the end-use product, the batteries, are being integrated into the mining resources. Prominent mining houses, such as BHP, Rio Tinto, Newmont and Teck, have agreements with Caterpillar to roll out pilot studies of electric haul trucks by 2025, with full production to begin by 2027.[14] Rio Tinto has further agreements with heavy-duty vehicle manufacturer Komatsu, where they have purchased four pilot trial full battery-electric locomotives for its Pilbara, Australia operation, which are expected in 2024.[15] BHP has ordered 11 battery electric loaders from Sandvik Mining and Rock Solutions for underground operations at their Canadian potash site, which are expected to be delivered in 2023 through to 2025.[16] They have already supplied some load haul dump vehicles to their Southern African-based mines.[17] As global operations drive the implementation of battery electric haul and load vehicles, African mining operations should experience the same "green" shift to not only reduce their carbon footprint but also reduce operating costs where the supply of carbon-based fuels to the remote mines is becoming more expensive.

With the increasing battery material demand and resulting aged or waste batteries, niche areas applications are appearing, which could allow for the establishment of small and medium micro enterprises to capitalize on repurposing for second-life applications, integrity testing and recycling. Understanding the chemistry of the batteries and the associated handling risks is paramount to the safe and cost-effective establishment of an emerging industry when paired with best practices such as lean-six sigma and other well-established project management principles. Within the African context, there are still many challenges to overcome where many OEMs have indicated that they are not planning to reduce their internal combustion engine (ICE) vehicle sales to Africa any time soon. For example, Volkswagen has indicated that they are expected to sell ICE vehicles until 2050 while having an exclusively EV lineup for the European market by 2035.[18] This however has not hindered some countries to start the gradual introduction of electric vehicles into the transportation environment. According to the Africa E-mobility alliance,[19] there are currently 16 countries which have a footprint in the e-mobility sector, with 7 countries possessing an estimated 4400 2-and-3-wheelers, 13 countries supporting 19 761 4-wheeler and larger delivery vehicles and 9 countries supporting 331 buses. These are charged by 528 charging stations in 11 countries with South Africa and Morocco accounting for 68% of the stations. Even though this is an ever-changing landscape in terms of the uptake of E-mobility in various countries, a summary per country by 2023 is shown in Figure 2. Noticeably, some countries (like Kenya) have shown a larger uptake of the 2W/3W transporters that include scooters and three-wheelers. Also, countries like Tanzania and Togo have shown a significant uptake of EVs with little or no increase the public accessible charge stations. In comparison, China has an estimated 1.15 million charging stations, followed by 113 527 in US, 106 701 in South Korea and 85 453 in Netherlands.[20]

Recently, some research in the field of battery applications has included studies involving the cost and life cycle analysis (LCA) developments of African-specific vehicles and the viability of e-mobility that could be integrated into the extensive public transport network.

For example, the Minibus taxi has become synonymous with many cities' transportation systems where approximately 70% of the South African workforce utilize this method of urban commuting. Rix et al. [21] emphasized the importance of GPS vehicle tracking that would allow for simulations to be performed that can help establish adequate charging infrastructure within the larger, densely populated cities. They concluded that, currently, there is insufficient information to perform usable simulations. Abraham et al. [22] focused on the South African minibus taxi industry, specifically in the Stellenbosch region, in their case study, and the feasibility of pairing with renewable energy systems for charging. They found that the average taxi needs 213 kWh to travel an average of 228 km per day, with regular stops for around 8-11 hours each day. To hypothetically charge the entire vehicle fleet that would be based on EVs, using grid generation only, would utilize 9.7% of the current electricity production. This supports the need for advances in renewable energy charging infrastructure along the major taxi routes. As an example, solar energy was used in their simulations, with a charging load of 0.38-0.90 kWh/m^2, this being geographically

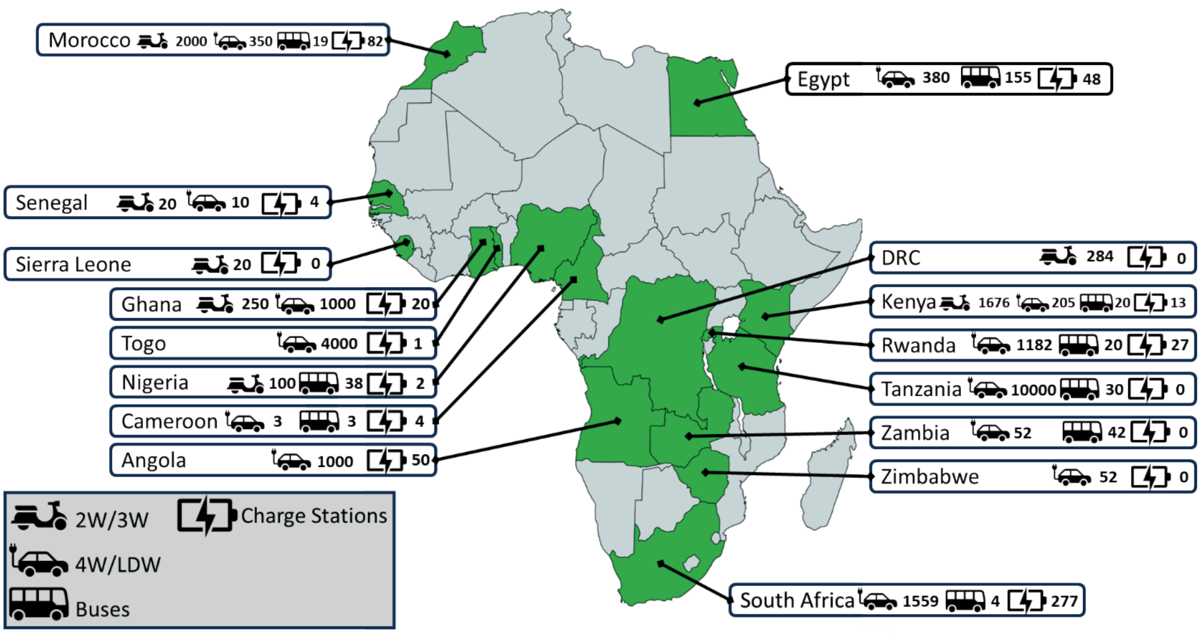

Figure 2: Overview of African electric vehicle landscape.

dependent. In conclusion, a 32 kW charger and 320 m^2 of solar panels would satisfy the average taxi daily requirements 50% of the time. Booysen et al.[23] conducted a similar study within the Ugandan transport context. They found that for Kampala, Uganda, the median requirement was 200 kWh per day, with taxis performing shorter trips requiring up to 491 kWh. The median stopping time was 8-12 hours, which led them to conclude that a 41 kW charger would suffice if the grid was operational. When considering solar, 660 m^2 of PV (0.24-0.52 kWh/m^2) would be required to fulfil the average daily taxi demand. Similar research was conducted by Buresh et al. [24] for solar carports. The study looked at the feasibility of charging personal vehicles using photovoltaic carports at work and reducing pressure on the national grid. They emphasized the need for proper infrastructure planning and the development of incentivized schemes before considering the increased use of electric vehicles for commuting otherwise, the resulting carbon footprint will be higher than the existing ICE vehicles they want to replace. Ayetor et al.[25] through a lifetime cost analysis, showed that by replacing ICE busses (by considering multiple African countries) with an electric bus fleet should reduce lifetime costs by at least 38% and carbon emissions by a factor of 3.46 (considering grid charging only). This would increase to a factor of 329 times if solar energy was used for charging.

The balance between the total cost and the related CO_2 emissions hasn't yet found an equilibrium within the African context. This was explored by various authors. Collett et al.[26] discussed whether electric vehicles could be suitable for Sub-Saharan Africa and concluded that despite the lack of capital infrastructure and unreliable electricity supply, an initiative that focuses on some of the main modes of transport such as minibuses and motorbikes is pursued, it could reduce vehicle emissions by 90% and reduce per capita fuel subsidies. In a 2020 study, Ayetor et al.[27] found that it would cost at least 13.5% more to own an electric vehicle when compared to a petrol vehicle in Ghana, which was coupled with the high infrastructure development costs (26000 dollars to install 10 charging stations). They also identified skill gaps in EV maintenance, non-availability of spare parts, charging infrastructure upkeep and the initial higher EV prices to be a deterrent to the uptake of e-mobility in general. In a later 2022 study, Ayetor et al.[28] found that EVs now cost 30% less to own than conventional vehicles in Ghana, with a 10% renewable energy addition decreasing this by a further 10%. The greatest challenge to increasing ownership is the high taxes and initial price that are associated with owning an EV. Similar conclusions were drawn by Dioha et al.[29] that discussed the introduction of EVs into the Nigerian transport system coupled with variable renewable energy generation that could result in significant decarbonization.

Moeletsi[30] investigated the challenges in adopting electric vehicles in the Gauteng province in South Africa. He found that there was generally a high willingness (58%) since most respondents travelled daily distances less than 100 km. However, the reluctance to buy EVs was due to the high purchase price, high battery prices and the need to own a second car ICE vehicle if longer travel distances are required. Pillay et al.[31] also concluded that lowering purchase price would have the biggest impact on increasing EV sales since the consumers in the regions of Gauteng, KwaZulu-Natal and Western Cape would purchase more vehicles than expected based on their higher disposable income. However, EV technology would be most effective in promoting the reduction of CO_2 in the Northern Cape and Free State provinces when compared to other provinces.

There have been attempts to make a vehicle specifically for Sub-Saharan Africa, which was termed the "African Car" or aCar by Brönner et al.[32–37] Their study proceeded to show the ideal set of configured parameters from a production process perspective, using simulations of dependencies and scenario testing with fuzzy logic as well as the requirements for production transfer to support sustainable development in developing countries. They conceptualised a low-maintenance vehicle which could be implemented into the African market and proposed nine indicators which could promote local manufacturing, including long-term location planning, higher-than-average wages, active support of local education and critical safety requirements. Nur[38] explored the socio-cultural aspects of the aCar and concluded that a vehicular redesign might be required in order for the aCar to overcome African societal constraints. The article identified the need for greater stakeholder engagement and the need to utilize feedback obtained, in this case, the need for greater reliability, functionality and appearance.

This paper explores the extent of literature focusing on e-mobility in the African context, the prominent battery chemistries used in EVs, battery safety aspects and how a lean-six-sigma mindset can synergistically merge all these disciplines to promote sustainable development of e-mobility in Africa.

BATTERY TYPES

Batteries have a simple configuration of a positive electrode (cathode), negative electrode (anode), separator and electrolyte to allow for ion mobility during charging and discharging, as shown by the simple schematic in Figure 3.

In the case of lead batteries, the active material, which determines capacity and other electrochemical properties, is contained within a lead grid which acts as the current collector, whereas in lithium batteries, the electrode material is deposited as a layer onto the current collector (generally aluminium for the cathode and copper for the anode). Lead acid batteries are well understood, used extensively as starting-lighting-ignition applications due to the ability to have high specific power – up to 150 W/kg, and were some of the first batteries used in electric mobility applications as early as 1890. Soon the ICE vehicle dominated the transportation market with the onset of the two World Wars. This was supported by the discovery of large oil fields to produce the carbon-based fuel and, ironically, the ability to start the vehicles' engine by using a battery and a starter motor that led to the accelerated uptake of the ICE vehicle as a mode of transport.

Alternate chemistries were researched to overcome various challenges associated with lead-based technology. These challenges include its low specific energy (30-50 Wh/kg) that is due to the high density of lead, slow charge times and relatively low cycle life. Equation 1 shows the discharge reaction of a lead-acid battery (with the reverse being the charge cycle). The positive plate reduces from lead (IV) oxide to lead (II) sulfate and the released electrons reduce the negative plate from metallic lead to lead (II) sulfate.

$$\underbrace{PbO_2}_{\text{Pos plate}} + H_2SO_4 + \underbrace{Pb}_{\text{Neg plate}} \xrightarrow{\text{discharge}} \underbrace{PbSO_4}_{\text{Pos plate}} + 2H_2O + \underbrace{PbSO_4}_{\text{Neg plate}}$$

Equation 1

Some of these challenges were overcome with the use of nickel-cadmium (NiCd) cells, which boasted 45-80Wh/kg energy densities which were on average 56% greater than lead acid batteries. They had significantly higher cycle life in application, had much quicker charging characteristics and were able to work in extremely high-temperature applications. These pros did however come at the cost of high self-discharge rates, which were 4 times greater than lead-acid batteries and coupled with using highly toxic materials such as cadmium. Nickel metal hydride batteries soon replaced the use of NiCd, which was the next step in advancing e-mobility. They showed to have up to a 98%, on average, increase in energy density from NiCd while maintaining a high power density, reliability and considerably lower toxicity.[39] However, at the cost of 10% higher self-discharge rates, slower fast-charging times and half the number of cycles of a NiCd battery. Equations 2 and 3 show the discharge reactions for nickel-cadmium and nickel metal hydride, respectively. The metallic cadmium is oxidized during discharge to form cadmium (II) hydroxide and nickel (IV) oxide is reduced to nickel (II) hydroxide. In the NiMH battery, which is still used extensively in hybrid vehicles such as the Toyota Prius,[40] nickel (III) oxide hydroxide

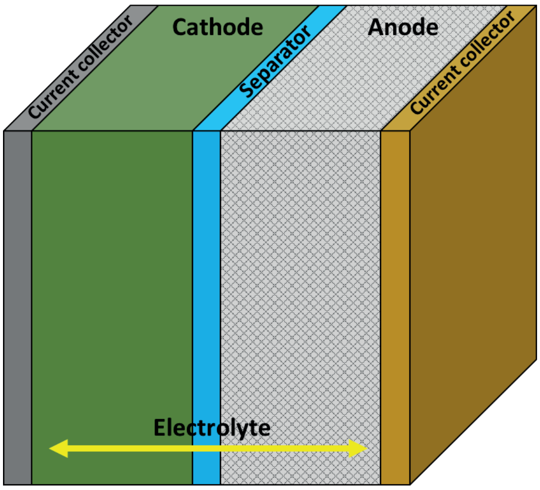

Figure 3: Simple schematic of cell components

is reduced to nickel (II) hydroxide on the cathode, and the anode oxidizes from metal hydride to metallic phase.

$$\underbrace{Cd}_{anode} + \underbrace{2NiO(OH)}_{cathode} + 2H_2O \xrightarrow{discharge} \underbrace{Cd(OH)_2}_{anode} + \underbrace{2Ni(OH)_2}_{cathode} \quad \text{Equation 2}$$

$$\underbrace{NiO(OH)}_{cathode} + \underbrace{MH}_{anode} \xrightarrow{discharge} \underbrace{Ni(OH)_2}_{cathode} + \underbrace{M}_{anode} \quad \text{Equation 3}$$

The current battery chemistry of choice, lithium-ion, has been in use since the 1990s and a key area of research in the past decade to improve its electrochemical and physical properties to support the growing power electronics market and the more recent demand for the electric vehicle industry. The majority of advances have been focused on the cathode material, with the lithium oxides of cobalt, nickel, manganese and iron phosphates being the main materials which have been integrated to design a single cell that is then configured into a battery of various shapes and sizes to meet the demands for faster charging, higher specific energy density, lower cost and improved safety aspects. The main cathodic chemistries are summarized in Table 1, with various molar ratios being tested and dopants being incorporated into the material, such as niobium.[41] Other components which are frequently researched are types of electrolytes such as ionic[42] and solid-state,[43] electrolyte additives[44] and separators .[45,46]
The anode is predominantly made of carbon-based material (graphite), and the half-cell reaction remains the same, regardless of the cathodic material used, as in equation 4.

Anode reaction: $LiC_6 \rightarrow C_6 + Li^+ + e^-$ Equation 4

A well-known alternate anode chemistry,[47] is lithium titanium oxide (LTO), which does, however exhibit a lower cell theoretical specific energy (Figure 4) but provides faster charging capabilities, longer capacity cycle life and is considered relatively safer than carbon-based anode cells. The simplified half reaction is shown in equation 5 where there are a number of new and novel alternatives that contain dopants such as Mn,48 Mg, Bi49 and Na.50

$Li_4Ti_5O_{12} + 3Li^+ + 3e^- \leftrightarrow Li_7Ti_5O_{12}$ Equation 5

Extensive research has been performed over the past decade to try and integrate alloyed anodes into lithium batteries which have a theoretical capacity of 2-10 times higher than graphite and 4-20 times greater than LTO. The main challenge, which affects the rapid implementation of alloyed cathodes, is the large volume change (up to 400% experienced with $Li_{22}Si$)[51] when undergoing lithium insertion and extraction and the irreversible capacity loss during the first formation cycle.[47]

Table 1: Common lithium-ion cathode chemistries based on fully oxidized composition

lithium cobalt oxide (LCO)	$CoO_2 + Li^+ + e^- \leftrightarrow LiCoO_2$
lithium manganese oxide (LMO)	$MnO_2 + Li^+ + e^- \leftrightarrow LiMnO_2$
lithium iron phosphate (LFP)	$FePO_4 + Li^+ + e^- \leftrightarrow LiFePO_4$
lithium nickel manganese cobalt oxide (NMC)	$NiMnCoO_2 + Li^+ + e^- \leftrightarrow LiNiMnCoO_2$
lithium nickel cobalt aluminium oxide (NCA)	$NiCoAlO_2 + Li^+ + e^- \leftrightarrow LiNiCoAlO_2$

In summary, the main properties associated with each chemistry can be displayed in a simplistic "spider" diagram – where higher values represent more favourable characteristics – that compare the performance, safety, specific power, specific energy and life span to each other on a relative scale (Figure 4).[52] Notably, it is important to balance all the intrinsic properties associated with the various battery chemistries to that of application and cost. The values were last updated in 2019, and it should be noted that these can change over time as new chemistries emerge and manufacturing processes improve in this fast-paced market. BloombergNEF[53] reported a 89% drop in effective prices from 2010 ($1200/kWh) to 2021($132/kWh), averaged over multiple end-use applications. For battery electric vehicles, a volume-weighted average of $118/kWh was reported, indicating $97/kWh at the cell level. In addition, substantial planning is required in deciding which chemistries are suitable for a specific application, whether it is high power demand or the need for a longer lifespan keeping in mind the importance of safety and cost will influence the preferred technology.

Research, however, continues to improve not only lithium-ion batteries but also delve into new chemistries and cell assemblies, which include metal-sulfur, metal-air and solid-state electrolyte batteries, to name but a few. Lithium-sulfur chemistry, for example, has a theoretical specific energy of 2567 Wh/kg; however, with current prototypes only achieving 350 Wh/kg range, with many other challenges that still need to be overcome before commercial viability is an option. The sulfur cathode has high electrochemical insulating properties, which require large amounts of conductive additives, as well as the tendency for the sulfur electrode to form long chain polysulfides, which reduce charging capability and active mass available for discharge.[54] Simplistically, the two half-reactions that occur in a lithium-sulfur battery are represented in equations 6 and 7.

Anode: $Li \rightarrow Li^+ + e^-$ Equation 6

Cathode: $S + 2Li^+ + 2e^- \rightarrow Li_2S$ Equation 7

Another area of interest is metal-air batteries which are composed of a metal electrode (Zn, Li, Mg, Al, etc.), electrolyte and bi-functional air electrode and boast very high theoretical energies, as shown in Figure 5. The oxygen from the air is reduced, and the metal electrode reversibly oxidizes to a solid metal oxide.[55] The most promising advances, thus far, have been made in the zinc and lithium space, but many pitfalls in all metal-air chemistries need to be overcome, such as electrode corrosion, electrochemical instability and parasitic side reactions, which lead to poor cyclability.[55] Metal-air batteries can comprise various aqueous and non-aqueous configurations, and caution should be used when comparing different theoretical energies since calculations can be performed using only the metal, the metal and oxygen, and the metal, oxygen and water (see equations 8-10 using Li as an example).

$4Li + O_2 = 2Li_2O$ (5226 Wh/kg)[56] Equation 8

$2Li + O_2 \leftrightarrow Li_2O_2$ (3505 Wh/kg)[57] Equation 9

$4Li + O_2 + 6H_20 \leftrightarrow 4(LiOH{\cdot}H_2O)$ (1910 Wh/kg)[58] Equation 10

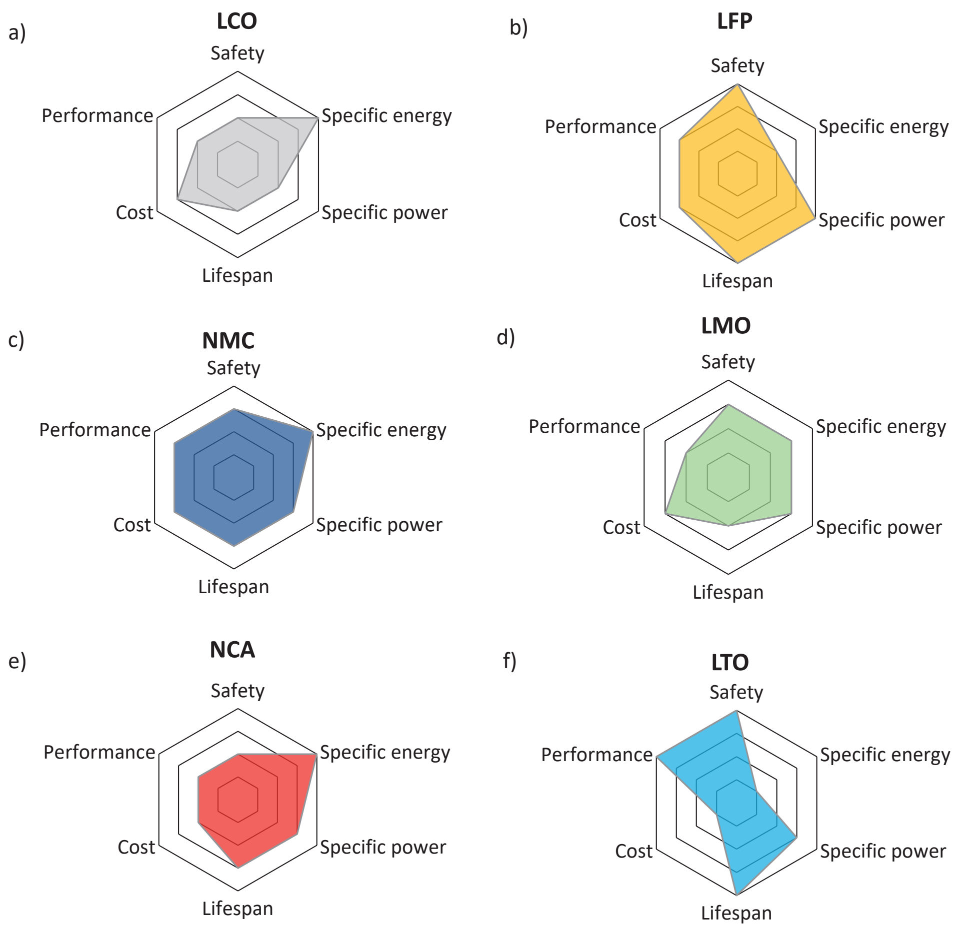

Figure 4: Relative properties of various lithium-ion chemistries (adapted from [5])

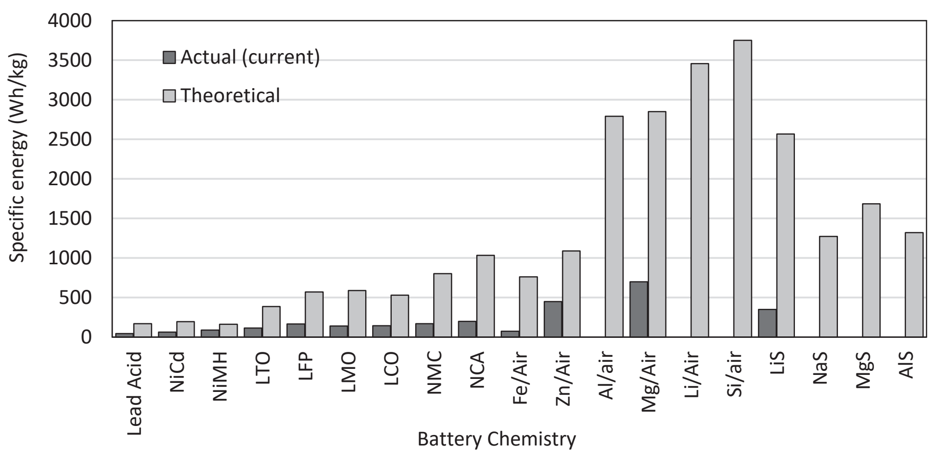

Figure 5: Summary of actual (where applicable) and theoretical specific energy (including oxygen) for different battery chemistries.[52,55]

SAFETY ASPECTS

Over the last few decades, in terms of the use of batteries in various large-scale applications, the main safety aspects were associated with the use of lead acid batteries that related to the spilling of highly corrosive acid and the electrolysis of water (producing H_2 and O_2) which, if accumulated within the battery, can cause an explosion when subjected to a spark.[59] The lead itself is also relatively toxic, which is a regulated, controlled substance which requires strict handling procedures during manufacturing and recycling. The high levels of heavy metal toxicity are also observed in nickel-cadmium chemistry along with potassium hydroxide aerosols during overcharging, which can cause skin and tissue damage. The same electrolyte is used in NiMH batteries, along with sodium hydroxide, which can also cause tissue damage. The electrolyte, again is one of the main safety concerns within lithium batteries when external factors cause damage such as heat, overcharge, overcurrent, or a short circuit occurs since an increase in temperature, typically greater than 80-120 °C,[60] leads to the breakdown of the solid electrolyte interphase layer, which formed on the anode due to electrochemical reduction, evolving gaseous species. In extreme cases, thermal runaway is observed when the organic electrolyte breaks down (around 150-200°C), producing gases such as CO_2 carbon dioxide (asphyxiant), CO (carbon monoxide) (asphyxiant), diethyl carbonate (DEC) (flammable), dimethyl carbonate (DMC) (flammable), ethyl methyl carbonate (EMC) (flammable), propylene carbonate (PC), various other alkanes and alkenes along with hydrogen fluoride (HF) (highly toxic) and phosphorus oxyfluoride (toxic).[61,62] Depending on the cathode chemistry, environmental concerns can also result from the presence of toxic elements such as cobalt and nickel that can leach into the groundwater.

Upon combustion, the formation of highly toxic HF can result as described by equations 11-13 with a reaction product further reacting to form additional HF, as in equation 14.[63,64] At certain elevated temperatures, this reaction becomes self-propagating and, as shown in equation 14, is propagated by the addition of water.

$LiPF_6 – LiF + PF_5$ Equation 11

$PF_5 + H_2O – POF_3 + 2HF$ Equation 12

$LiPF_6 + H_2O – LiF + POF_3 + 2HF$ Equation 13

$POF_3 + H_2O – POF_2(OH) + HF$ Equation 14

A study by Yuan et al.[65] recorded the thermal runaway onset temperature of a cylindrical LFP, LTO and NMC battery to be 200 °C, 163 °C and 143 °C respectively and further recorded the normalized gas volume released was 36.5 L/kg for the LFP, 82.9 L/kg for the LTO and an average of 2301.1 L/kg for NMC chemistry. Their study showed that most of the gas emitted by the LFP-type cells was H_2 (24%) and CO_2 (25%) and LTO was CO_2 (38%). For NMC cells, the gases were CO (29%), CO_2 (17%) and H_2 (12%). Sturk et al.[62] recorded similar gas emission volumes for LFP chemistry (42L/kg) but reported 780 L/kg for the NMC/LMO type chemistry. They also concluded that for LFP cells, the HF/CO_2 ratio was 1/10, and for the NMC/LMO, a ratio of 1/100 was determined.

Advances in the use of solid-state electrolytes in Li-ion chemistry improve the safety aspects of batteries as there are fewer flammable materials present than organic electrolytes currently in use. With these considerable hazards in mind, there is a need for adequate project planning to implement safety features in small and medium enterprises which emerge in the growing battery production chain.

PROJECT MANAGEMENT ASPECTS

Engineering and chemistry advances cannot alone create sustainable development. Project and quality management, risk mitigation and lifecycle streamlining are required and should be customized to optimize the situation in which it is implemented. Since the lithium-ion battery value chain is an emerging sector in Africa, investment and collaboration is required from the public and private sector: government, intergovernmental organizations, automotive, mining and manufacturing industries to initiate pilot projects that test the feasibility of SMMEs operating across certain aspects of the value chain particularly within repurposing of 2nd life batteries for various applications and recycling. These pilot projects can be used to develop a collaborative platform for peer-to-peer exchanges across African countries to share lessons learnt, recommendations, areas that require more research and development and activities that can be scaled or replicated. Waterfall project methodology, which is a long-term project plan that has a single timeline, creates a linear-phased approach to dependencies and discourages intra-project changes due to its costly nature, has become a common concept in software engineering. This long-term thinking can be related to many manufacturers' 2030 and 2050 CO_2 emission reduction goals, with many deliverables being planned linearly. Agile project management, on the other hand, is a shorter planning strategy based on multiple deliverables. It is highly flexible and promotes collaborative and interactive approaches as well as involving the customer throughout the project. Agile management has also become more prominent in the software industry, which is highly competitive and rapidly changing. This has very similar attributes to the electric vehicle market, indicating that an agile mindset could lead to rapid technological advances and quicker integration into the market resulting in accelerated development of the electric vehicle economy. New chemistries, alternative battery designs, improved battery management systems and improved charging infrastructure could be established with shorter lead times and remain highly relevant. Waterfall methodology is a sound management system for long-term plans, but the adaptive and flexible nature observed in top manufacturers such as Tesla, Toyota and BYD has shown to meet current client needs in a very competitive and fast-changing market.

A summary of key management aspects and areas of interest for Africa is shown in Figure 6. Many, if not all, of these initiatives, are a staple in developed countries, where quality, efficiency and safety are just as important as merely producing the final product. The fundamental principles can be applied within an African-based economy to establish sustainable processes and businesses right from inception, however with aspects such as increased automation of production lines, artificial intelligence-based systems, and Internet of Things (IoT) would not be the foremost of priorities where there still is a higher tendency to rely on the labour force.

Lean six sigma (the integration of Lean and six sigma) principles should become more relevant to many highly competitive emerging technologies that include the EV market, especially within the African context. Lean is focused on waste reduction and standardizing workflows through workplace organization and visual controls, whereas six sigma aims at reducing variations through statistical data analysis and hypothesis testing and therefore maintaining quality.[66] For example, if a local company wants to manufacture electric motorbikes, it should begin with a well-defined project scope (goals, KPIs, targets, milestones, deliverables, budget) to identify possible scope creep to allow for adjustments or amendments to the scope if required, project risks (including how those risks will be mitigated) and have SMART objectives. SMART objectives are Specific (Who will be impacted?; Who is the target market?), Measurable (By how much?; how will the impact be achieved? – e.g., 20 electric motorbikes sold within 2 years), Attainable (How will you achieve this?), Relevant (Why is this important? e.g., increase revenue, long-term growth and sustainability of the company in the move towards zero-emission vehicles) and Time-bound (by when does it need to be achieved?).[67] The quality and long-term sustainability of the product in a global, very competitive market will be important where process control concepts known as the DMAIC model should be followed. The acronym stands for define, measure, analyse, improve and control. The problem is first articulated, measurements performed, root causes of the inconsistencies are identified, and improvement strategies are implemented with control measures introduced to sustain improvements. This, however, is not a once-off approach with the need for continuous improvement (kaizen) to stay competitive in the forever-changing markets. The idea of minimal inventory through "just in time" (JIT) production would reduce waste and optimize cash flow in developing countries, where excess money is not as readily available. For example, if a small-scale battery production facility is established, then storing excessive inventory would result in

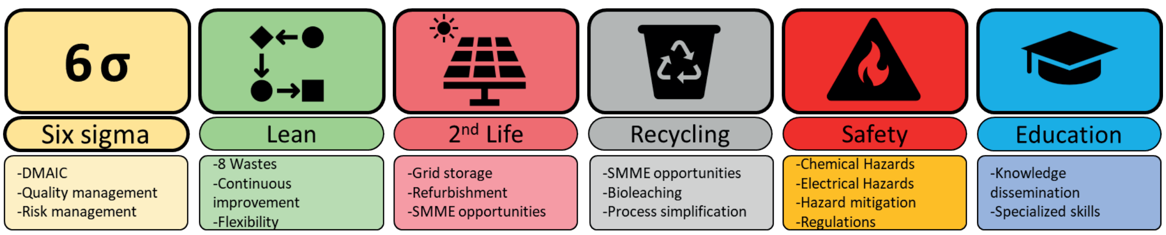

Figure 6: Basic overview of critical project management aspects required for e-mobility value chain integration within the African context.

monetary value being stored within a warehouse (through the tangible products) and decreasing cash flow whereas if consumer metrics are tracked, then production can be modified to meet the given demands with little waste. This also gives the business the capacity to rapidly change to new demands and improve product quality per batch instead of retaining the issue within a large batch, which could ultimately decrease revenues. This would also integrate a level of flexibility into production, allowing for rapid manufacturing shifts that are often dependent on market demands. The lean methodology also shines through in actively reducing waste during manufacturing by reducing unnecessary transportation, overproduction, excess inventory, idle time, defects, unnecessary motion between process steps, non-value-added processing and underutilized talents. Lean six sigma, coupled with an agile mindset, would provide a foundation upon which to build and develop low-waste, high-quality processes and procedures which are optimized for the particular country. This structured and flexible approach itself would fit very well with the localization of lithium-ion technology since a small to medium-sized enterprise supplier can design and build battery packs for the highly versatile market while readily diversifying as market needs emerge, and customer demands change that is unique within the African context. An example of an SMME operating in this space is REVOV, based in South Africa, who repurposes second-life electric vehicle batteries for stationary energy storage applications that provide affordable energy supply solutions to address South Africa's energy crisis. They also export their products across sub-Saharan Africa.[68]

For Africa to have a foothold in the tertiary battery market, well-established safety and testing policies and regulations need to be implemented, not only for consumer safety but also for the manufacturer and recycling operations. The need for recycling is set to increase as electric vehicles gain a stronger presence in the automotive market and as the first generations of vehicles come to their end-of-life. This will provide unique opportunities for SMMEs in EV pack disassembly, 2nd life applications and recycling instead of simply shipping the battery pack back to the original equipment manufacturer (OEM) at elevated costs. Apart from the safety associated with the chemistry of the battery, where gas sensing and biomonitoring can aid in prevention mechanisms, EV packs are an electric shock risk, with packs generally producing 400-800V and 160-240 Ah. Where shocks from currents over 10 milliamps are considered painful to severe, and 100-200 milliamps being lethal. These factors indicate that a specialized skill set are required for the emerging workforce in the EV value-chain sector and the need for multi-discipline educational initiatives. Areas of specialisation and skills required include electrochemists, inorganic material scientists who are amenable to data analytics, simulations and artificial intelligence; technicians who are knowledgeable in electrochemistry, electrical engineers, and process engineers. Project managers, social scientists and environmental specialists who have a deeper understanding of battery technology are also required. Project managers are required for the implementation and delivery of specialised projects, social scientists are required to impart knowledge on cross-cultural relations, and stakeholder buy-in and environmental specialists are required to assist with providing solutions to protecting and providing a safe and healthy environment that promotes the circular economy concept and mitigates climate change. Short skills programmes, internships and on-the-job training should also be integrated into educational initiatives.[69]

Second-life applications, specifically for EV battery packs, have been of interest and discussed in multiple research articles.[70–73] This provides an opportunity for the EV packs to be utilized in an alternate application, such as renewable energy grid storage, allowing for further waste mitigation and the ability to benefit from the battery pack's value stream. Simplistically, if batteries or cells within an aged pack can be tested and the faulty or weak cells are replaced with suitable cells from other packs, a 2nd life back can be assembled that can then be used in an application that is considered less stringent in its power and mobility requirements. General, EV packs are replaced once approximately 80% state of health (SoH) (battery holds 80% of rated capacity at full charge) is reached. This is primarily because the vehicle's kilometres per charge decrease, and unpredictable battery failure is then more likely to occur. However, this value was originally reported by the United States Advanced Battery Consortium(USABC)[74] in 1996. Since then, there have been significant improvements in the battery's chemistry and its management system where current advances in both achievable kilometres per charge and battery safety would make the end of life of an 80% SoH battery questionable.[73] Notably, the battery in the 2nd life application does not have the same performance in terms of its power as it did in the EV application; however there is sufficient capacity remaining for the lower power density requirements such as grid storage system.

It is only after the 2nd life application that the pack is then considered for recycling. There are many well-documented studies and processes that utilize hydrometallurgical and pyrolysis techniques to recycle spent lithium-ion batteries.[75,76] These have been developed and optimized alongside changes in battery chemistry. A good business model would be to develop localized African recycling operations alongside the manufacturing industry to promote the localization of employment and thereby support multiple economies through the improvement of the value chain. For example, energy storage is seen as an enabler for the provision of domestic renewable energy solutions, and The World Economic Forum estimates that localizing the repurposing of lithium batteries in countries across Africa has the potential to create 40 jobs for every 1000 solar home systems sold. In contrast the use of repurposed lithium batteries creates an affordable and sustainable solution where the cost of batteries is reduced by approximately 30%. Potential business models for the local recycling of lithium batteries should be further explored as recyclers based outside of the continent pay up to $1,000 per ton for lithium batteries that contain cobalt across the world.[77] The effective utilization of current skilled labour as well as the described educational advances aimed at promoting specialized skills within Africa, not only increases the chances of success but also promotes stakeholder buy-in.

Recycling is not without its challenges, namely the effective separation of the diverse types of cells and batteries with their own variations in their cell chemistries. Gaines[78] indicated that large packs could be labelled and disassembled manually or using an automated process. However, a mixture of cell types is often where the challenges lie with a variety of form factors and chemistries. Gaines proposed the standardization of cell forms to a select number of variants as well as aspects, such as the type of adhesive used in larger packs. This allows for the use of a standard solvent for the removal of the cells. In another article, Gaines[79] proposed that separation would be facilitated with the use of bar codes, RFID chips or dedicated paint colours or types (for example, battery types that are identified under black light). This would facilitate the required battery information to be obtained and allow for safer working environments and improved product quality. It should also decrease confusion which can occur when all labels are removed from the battery case before recycling, in which case a black-cased lead-acid battery may be mistaken for a lithium battery, which could have serious consequences, and vice versa.[79] This not only elucidates the need for improving the process at the manufacturing level but also supports the need for further education initiatives to prepare the emerging African workforce to understand and mitigate risks when starting small and medium business operations.

Many aspects explored in this article are currently employed by the national uYilo e-Mobility Programme, which was established in 2013 as a multi-stakeholder collaborative programme focused on enabling, facilitating and mobilising e-Mobility in South Africa. uYilo is an initiative of the Technology Innovation Agency, a public entity of the Department of Science and Innovation. Aligned to global technology advancements across transport, energy and ICT that electric mobility impacts. uYilo has created a footprint in the local industry while also leveraging international networks towards advancing the uptake of electric mobility through government lobbying, Industry engagement, enterprise development, pilot projects, thought leadership and skills development. uYilo's facilities include a nationally accredited battery testing laboratory that supports local manufacturing companies, providing accurate and repeatable testing services for new storage solutions and validation of existing battery technologies. uYilo's Live Testing Environment creates a platform for the electric vehicle ecosystem to facilitate universal connectivity between electric vehicles and supportive smart grid infrastructure. The smart grid infrastructure of the live testing environment consists of various electric vehicle ecosystem elements such as electric vehicles, a mix of AC charge points, DC fast chargers and Vehicle-to-Grid system capabilities. Renewable energy is incorporated to supply the charger network and is dynamically controlled through a supervisory Energy Management System for individual charger energy profiling. Energy storage is achieved through a repurposed electric vehicle battery pack serving as a 'second life' application under stationary storage.

The programme is hosted within eNtsa, an engagement entity within Nelson Mandela University. uYilo's facilities are headquartered in Gqeberha, with a satellite office in Johannesburg. For more information, visit www.uYilo.org.za.

CONCLUSION

African e-mobility programs and initiatives are few and far between, with OEMs focusing on Europe and America and the eastern markets such as India, China, Japan and South Korea. This is also seen in the research capacity being expended in analyzing the development, implementation and improvement of electric vehicles in the African economy and society. This paper explored the key chemistries involved in batteries which are commonly utilized in e-mobility applications as well as potential future chemistries to be used. The chemical safety aspects were highlighted to support the need for more accessible knowledge dissemination incorporating chemical risks and hazards, especially as opportunities arise for small, medium and micro enterprises to capitalize on the growing 2nd life application and recycling space. These niche SMMEs can not only provide additional jobs but also support the local economies by keeping the value stream within Africa through unique approaches which are tailor-made to the continent. The models being employed by the global leaders can be used as a learning opportunity which allows Africa to understand both what has been successful, as well as unsuccessful. The 2nd life market could be key in reducing renewable energy storage costs, and end-of-life batteries can be recycled without needing to be shipped back to the OEM. If good project management principles are adopted to ensure product quality, workplace safety and waste reduction are also coupled with improved skill enhancement programs, stakeholder buy-in and support from the public and private sector (for initiating projects to test the feasibility of business models), then the unique EV African market can emerge by also integrating the shift to the electric-mobility mindset as an opportunity that not only reduces its CO_2 emissions but also sees business development as a possibility for local battery manufacturing from localized mined resources along the entire value chain. Africa is still in its infancy in this specific market, and, by taking every opportunity, can become more prominent in the ever-shifting technological landscape.

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