Battery Materials Analysis

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1. Executive Summary

This document provides a joint industry analysis of the current and future availabilities of resources and materials used in a range of battery technologies. The document focuses on automotive batteries, and does not cover other battery technologies that are not currently used for this application. The report aims to answer the following questions

- Are there any current resource availability issues associated with the manufacture of automotive battery technologies?
- Are the any future issues that could affect the resource availability associated with the manufacture of automotive battery technologies?

The information contained in this report is intended to be used as input into current and future regulatory discussions on the feasibility of substituting lead-based battery technologies.

Based on the information contained in this document, it can be concluded that there are no resource availability issues associated with the materials used in the manufacture of lead-based batteries. Nonetheless, the challenge of meeting the ever increasing demand for batteries in vehicles remains significant. The production rates for new vehicles are growing rapidly. Estimates of current rates are of the order of 70 million new vehicles every year, and it has been estimated that this rate could rise to about 100 million by 2020 and 140 million by 2030[1].

Currently all vehicles, (conventional vehicles, Stop-Start, Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV)) require a 12V lead-based battery. There are significant global reserves of lead, both primary (i.e. from mining) and secondary (i.e. from recycling) and secondary production currently accounts for more than 50% of total global lead production. In fact, in 2014 100% of US lead production and 75% of European lead production will originate from secondary sources. The high recycling rate for lead is driven principally by lead-based batteries, more than 95% of which are recycled at the end of life[2]. This means that the existing market for lead-based batteries can be predominately met with recycled material and because of this circular economy the demand and requirement for lead reserves from mining is low. The anticipated growth in demand for automotive batteries will however likely need to be serviced by primary lead, which will then be available itself for recycling at end of life, and hence enter the circular economy. The existing reserves of lead can comfortably meet the projected growth in demand for automotive batteries.

In contrast, although the report shows that lithium-based batteries have no current resource availability issues, the increasing use of lithium-ion batteries in portable electronics, coupled with use in new applications is expected to result in a substantial increase in demand for lithium. This increased demand would need to be met from lithium reserves via primary production, as currently less than 1% of lithium is recycled[3], and recycling of lithium batteries is in its infancy. One reason for this is due to the widely differing chemistries, recycling of lithium ion batteries can be more difficult than, for example, recycling of lead based batteries where all batteries (automotive and industrial) have the same basic chemistry.

[1] Wilson "Lead: A bright future for the grey metal?" 2011
[2] Nachhaltige Rohstoffnahe Produktion, Fraunhofer Institut Chemical Technology (2007)
[3] UNEP report on recycling rates for metals 2011

There are significant reported resources of lithium, and in 2014 the global mine production was 35,000 tonnes[4]. The most significant use of lithium is in lithium ion batteries for portable electronics (e.g. cameras, phones, laptops). The growth rates for these uses are predicted to be considerable[5]. In addition to these applications, a new and very rapidly growing market has emerged over the last decade in the form of electric bicycles. Approximately 30 million ebikes were sold in 2009, and it has been forecast that 466 million electric two-wheelers will take to the road by 2016[5]. These bikes have previously used lead-based batteries, but there is a push to switch to lithium-ion batteries[6], which if pursued, could be expected to consume additional lithium reserves.

As mentioned above, the predominant use of lithium-ion batteries is in portable batteries. However, the use of lithium-ion batteries in some automotive and industrial applications is also expected to rise. There is predicted to be increasing volumes used as traction batteries in PHEV and EVs, as well as certain hybrid segments. They will also be required for large-scale grid-connected energy storage. In addition, the use of automotive lithium-ion batteries in an SLI function in vehicles is being explored as a potential alternative to lead-acid batteries, as a consequence of pressure from existing and proposed EU environmental legislation[7]. However, this application of lithium-ion batteries is currently only seen as a very minor use in luxury vehicles, and significant technical limitations and cost implications remain for their use in mass-market vehicles[8].

If the existing challenges associated with SLI use of lithium-ion batteries were resolved such that they became viable option to lead-acid technology - coupled with the additional demand for lithium in portable electronics, energy storage, e-bikes and other areas of the automotive industry – future resource availability issues for lithium could be expected. As an illustrative example, if lithium-ion batteries were required to replace all lead-acid batteries in an SLI function, *ca* 90,000 tonnes of lithium*[9] would be required from further increases to primary production This quantity is almost three times the current reported lithium mine production, and so the required increase in production would be significant.

In addition this report highlights that a significant amount of lithium production, reserves and resources currently originate from Argentina, Bolivia and Chile. Although not discussed in detail this observation suggests possibility of an additional challenge to future accessibility created by geo-political risk of a raw material that is only available in one specific region. For example, any unrest or instability of the governments in these regions could greatly affect the supply of lithium and have an impact on battery price, and thus application cost. The increased demand for lithium in new and existing applications, coupled with low recycling rates and geo-political issues could be predicted to

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[4] US Geological Survey, Mineral Commodity Summaries, January 2012

[5] Pike Research 2010

[6] William Tahil, cars21.com April 2012

[7] The End-of-Life Vehicles Directive bans the use of lead in vehicles, with an indefinite exemption for lead in batteries that is reviewed regularly according to technical and scientific progress. The European Commission last reviewed this exemption in 2010, reaching the conclusion that no mass market alternatives were available to replace automotive lead-based batteries.

[8] More information is provided in *A Review of Battery Technologies for Automotive Applications* (2014), authored by the same group as this report.

[9] * Approximately 7 million tonnes of refined lead were consumed for use in automotive batteries in 2013. This equates to the production of approximately 700 million lead-acid batteries worldwide for use in automotive applications. It can be assumed that approximately 20% of these batteries would be for new cars, and the remaining 80% would be for replacement batteries[9]. Assuming 0.15 kg of lithium in each lithium-ion SLI battery, 90,000 tonnes of lithium would be required to manufacture 700 million batteries. This change would be gradual over several years, beginning with the installation of lithium-ion batteries as original equipment in new vehicles, and progressing to their sale as replacement batteries on the aftermarket. The above scenario gives an indication of the long-term consequences of forcing such changes to the battery technologies used in automotive applications.

present a significant future challenge to the commodity if it is also to be required in new mass-market applications.

This report also investigates resource availability issues associated with materials used in sodium and nickel based batteries. In contrast to the lithium scenario, no issues were identified for critical elements used in nickel or sodium based batteries.

The major metals used in nickel-based batteries are nickel, zinc, iron, cadmium and cobalt. These are well known metals with significant annual production tonnages and known global reserves. Rare Earth metals can be utilised in nickel base batteries. In the past issues have been raised with China, the largest producer of rare earth metals (97% of the market) export policy. However, significant exploration projects are underway in many countries, and there are substantial know global reserves of the metal. As such, access to rare earth is likely to be an economic issue as opposed to a resource availability issue.

Sodium based batteries (specifically sodium sulfur) comprise mainly Sodium, Sulfur, Aluminium and Nickel. Sodium occurs naturally in vast quantities, Sulfur is widely available, and no issues are foreseen with Nickel and Aluminium. It can therefore be anticipated that the materials used in these batteries can easily meet current and future demand.

In conclusion, this report identifies that there are no resource availability issues for lead, sodium and nickel based batteries. It also shows no current issues with lithium based batteries. However, the increasing use of lithium-ion batteries in portable electronics, coupled with use in new applications is expected to result in a substantial increase in demand for lithium. If in addition, lithium-ion batteries were required for other mass-market applications, for example to replace automotive lead-acid batteries in an SLI function, significant future challenges would be predicted for the global supply of lithium.

The authors of this report therefore advocate for a legislative and regulatory environment that guarantees a fair and technology-neutral competition between battery technologies. In each application, battery selection should be influenced by the availability of resources to meet demand, and the efficiency with which those resources can be recycled and reused at end-of-life.

As the most relevant example, because the existing market for automotive and industrial lead-based batteries can predominantly be met with recycled material, and given that the reserves of primary lead can comfortably meet projected future growth in demand for those batteries, it’s use in these applications should continue to be encouraged when it is the most competitive option from technical and economic perspectives and any residual risks to human health and the environment are properly managed.

2. Battery Technologies

A broad range of battery technologies currently exists. At present there are four battery families dominating the automotive and industrial battery market:

- Lead-based battery technology
- Nickel-based battery technology
- Lithium-based battery technology
- Sodium-based battery technology

The selection of one of these technologies will often depend on application requirements regarding performance, life, safety and cost.

2.1 Lead-Based Batteries

By far the greatest use of lead worldwide is in lead-acid batteries. Lead-acid technology is the most widely used electrochemical system, being utilised in wide array of applications, ranging from back-up for uninterruptible power supplies and grid energy storage, to traction in battery electric vehicles and for starting, lighting and ignition (SLI) in conventional combustion engine vehicles.

A typical lead-acid battery consists of the following components:

- Grids of lead alloy, forming the positive and negative plates
- The grids are pasted with active material based either on a mixture of lead oxides or powdered lead based on whether positive or negative. An electrolyte of sulphuric acid, in which the whole grid is immersed
- A separator of either polyethylene or glass fibre mat depending on the battery type.

In the majority of cases, small alloying additions are made to the lead used in grids, in order to improve its strength, lifetime, and in the case of batteries for vehicles, resistance to fatigue, caused by vibrations and jolts. Historically the usual alloy was lead-antimony (0.75-5% antimony) which is much stronger than pure lead. Minor additions of other elements such as copper, tin, arsenic, and selenium are sometimes used in order to improve grain refinement, ease of casting and to impart age-hardening characteristics. Calcium and tin alloys are commonly used in sealed lead acid batteries.

Lead-acid technology is composed of several sub-technologies distinguished by battery design and manufacturing process. Three main sub-technologies are used in automotive applications:

- Flooded lead-acid batteries,
- Enhanced flooded batteries (EFB)
- Absorbent Glass Mat (AGM) batteries

Flooded Lead-Acid Batteries

Flooded lead-acid batteries are used in the vast majority of vehicles with an internal combustion engine to provide starter, lighting and ignition (SLI) function. Flooded lead-acid batteries are characterised by a free-flowing electrolyte between and above the electrode stack.

The flooded lead acid-battery comprises lead dioxide as the positive plate, and finely divided lead as the negative plate. These active materials react with a sulphuric acid electrolyte to form lead sulphate on discharge and the reactions are reversed on recharge. Lead grids are used within the battery to support the active material and individual cells are connected to produce a battery in a plastic case normally at 12V.

Advanced lead-acid batteries – AGM and EFB batteries
Absorbent glass mat (AGM)_and enhanced flooded (EFB) battery technologies have more recently been introduced to the automotive sector for use in start-stop and basic micro-hybrid vehicles. These batteries have higher deep-cycle resistance and charge recoverability compared with flooded SLI batteries, in order to deal with the more frequent stops and starts, and to provide a continued supply of electrical consumer units during the stop phase. The cranking performance of SLI batteries is carried over.

EFBs feature an improved flooded battery design with increased cyclic durability and increased ability to accept charge current, due to various changes in battery construction.

AGM batteries are valve-regulated lead-acid (VRLA) batteries characterised by closed cells and an immobilised electrolyte held firmly in a glass fleece separator. This again allows for increased cyclic durability and improved charge recoverability.

2.2 Nickel-Based Battery Technology

Nickel is widely used in the production of rechargeable alkaline batteries. Nickel based batteries comprise a nickel hydroxide-based cathode, with either a metallic anode (nickel-cadmium (Ni-Cd), nickel-iron (Ni-Fe), nickel-zinc (Ni-Zn) or a hydrogen storing anode (Ni-H, nickel-metal hydride (NiMH)). However, due to technical limitations on maintenance and long term cycling performance, Ni-Fe and Ni-Zn batteries are no longer used for automotive or stationary applications.

NiMH technology has in the past been used in electric vehicle batteries but has now been largely superseded in this application by Li-Ion as a result of its superior energy density and higher deep cycling capability. NiMH remains predominant in the Hybrid Electric Vehicle (HEV) segment because of its durability and lower cost in comparison with lithium-ion batteries. However, these HEVs also have a lead-acid SLI battery to start the car under cold conditions.

Both Ni-H and NiMH batteries are, in principle, the same battery system, utilising nickel hydroxide as positive electrode and hydrogen as negative electrode materials. In NiMH batteries a hydrogen storage alloy is used. Both systems have an excellent cycle life. However, due to several performance limitations, Ni-H batteries, as is the case with Ni-Fe and Ni-Zn, are now limited to very narrow niches of the industrial market.

Ni-Cd batteries contain a positive electrode of nickel hydroxide and a negative electrode of cadmium. On discharge the nickel hydroxide is reduced to a different form of nickel hydroxide with a lower oxidation state and the cadmium is oxidised to cadmium hydroxide. The reverse reactions take place on recharge. The electrolyte is a potassium hydroxide solution.

Due to their superior reliability, mechanical robustness and ability to operate at extreme temperatures Ni-Cd based batteries are essentially used for the back-up of aircraft and rolling stock (train) electronic systems, as back-up for several mission critical industrial processes where the safety of humans or assets is at stake, as well as in electrically or mechanically arduous applications.

2.3 Lithium-Based Battery Technologies

Lithium-ion rechargeable battery systems entered the mass market of small-sized consumer applications in the early 1990s. Their up-front cost is at present significantly higher than for corresponding battery technologies based on other chemistries. Therefore, larger-sized lithium-ion batteries are currently found in segments like military and space applications where their high energy and power density and their superior cycling ability create value. High capacity of the active materials and a single cell voltage of up to 4.2V (depending on active material used) give lithium-ion batteries the highest energy density of all rechargeable systems operating at room temperature.

In automotive applications, they are the product of choice for plug-in hybrid electric vehicles (PHEVs) and full electric vehicles (EVs), in which both these criteria are important. For hybrid vehicles, lithium-ion systems have started to compete with NiMH batteries and are now used at an industrial level in a number of hybrid cars which have been on the market for several years. For SLI, start-stop and micro-hybrid applications, lithium-ion batteries still need improvements in cold-cranking ability and economic packaging (including cost level) to be considered as a viable mass market alternative to lead-based batteries.

Unlike the other battery technologies discussed thus far, the Li-ion battery technology is sub-divided in several sub-families depending on the composition of the positive electrode. In general terms though, lithium-based batteries composition is as follows:

- The negative electrode is often made of carbon coated on a copper foil. It can also be made of materials such as $Li_4Ti_5O_{12}$.
- The positive electrode is made of lithiated metal oxide $LiMO_2$ (or $LiMO_4$) coated on an aluminium foil. The metal M can be:
  - cobalt for $LiCoO_2$ (LCO)
  - manganese for $LiMn_2O_4$ (LMO)
  - a mix of nickel, manganese and cobalt $LiNi_xMn_yCo_zO_2$ (NMC with typically x=y=z=0.33)
  - a mix of nickel, cobalt and aluminium $LiNi_xCo_yAl_zO2$ (NCA with typically x=0.8, y=0.15 and z=0.05)
  - a mix of iron and phosphorus for $LiFePO_4$ (LFP)
- The electrolyte is made up of lithium salts (typically $LiPF_6$, however $LiBF_4$ and $LiClO_4$ have been known to be used) dissolved in organic carbonates (Because lithium reacts to water, only organic solvents can be used).
- The separator is made of very thin layers of polyolefins (PP/PE).

When the battery is being charged, the lithium atoms in the positive electrode become ions and migrate through the electrolyte toward the negative electrode where they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge.

It is important to note that the total quantity of lithium in a Li-ion battery is around 2% only.

2.4 Sodium-Based Battery Technologies

Sodium-based batteries are utilised in a range of applications, including energy grid storage, such as storing energy from intermittent energy sources (e.g. wind- and solar-power), and e-Mobility. In contrast to many batteries, sodium-based batteries consist of a solid or solid and molten electrolyte with liquid sodium acting as the negative electrode.

Sodium-Nickel Chloride ($NaNiCl_2$) and Sodium Sulphur Technology are the two main types of sodium-based battery. In $NaNiCl_2$ batteries, the cathode is made of $NiCl_2$, and the anode is made of sodium. The electrolyte is made up of tetrachloraluminate of sodium (such as $NaAlCl_4$). When the battery is being charged the sodium atoms in the cathode become ions and migrate through the ceramic electrolyte.

Sodium-nickel chloride batteries have found application in plug-in hybrid and full electric vehicles, especially for commercial and heavy applications. Their use has now also been broadened to industrial applications, including telecom and back-up markets and on/off-grid stationary energy storage systems as large renewable energy power systems and supply of ancillary services to the electricity grids.

Sodium-Sulphur batteries have a solid electrolyte membrane between the molten anode and cathode, compared to liquid metal batteries where the anode, the cathode and also the membrane are liquids. The entire cell is enclosed by a steel casing that is protected, usually by chromium and molybdenum, from corrosion on the inside. This outside container serves as the positive electrode, while the liquid sodium serves as the negative electrode.

Sodium-sulphur batteries are used exclusively in industrial applications such as electricity storage for grid support and space applications. Results from testing of sodium-sulphur batteries for electric vehicles during the early 1990s revealed this technology was not suitable for automotive applications.

3. Materials used in Battery Technologies.

The following section focuses on the different materials used in the battery technologies described in Section 1.

3.1 Lead-Based Battery Technology

3.1.1 Lead

Lead, the principal component of the lead-based battery, is usually found in ore with zinc, silver and (most abundantly) copper. It is extracted together with these metals by the mining of ores. The most common lead ore is galena, although there are a very small number of deposits of cerussite (lead carbonate).

(i) Resources

Mine Production and Reserves (thousand tonnes)[1]

Region	2009	2010	2011	2012	2013	Reserves
United States	406	369	342	345	340	5,000
Australia	566	625	621	648	690	36,000
Bolivia	86	73	100	88	90	1,600
Canada	69	65	59	59	35	450
China	1,600	1,850	2,350	2,800	3,000	14,000
India	92	95	115	118	120	2,600
Ireland	50	45	45	51	43	600
Mexico	144	158	220	210	220	5,600
Peru	302	262	230	249	250	7,500
Poland	60	70	60	58	60	1,700
Russia	70	97	105	95	90	9,200
South Africa	49	50	55	55	52	300
Sweden	60	60	62	62	62	1,100
Other countries	306	320	340	330	350	3,000
World Total (rounded)	**3,860**	**4,140**	**4,700**	**5,170**	**5,400**	**86,000**

World Resources: In recent years, significant lead resources have been demonstrated in association with zinc and/or silver or copper deposits in Australia, China, Ireland, Mexico, Peru, Portugal, Russia and the United States (Alaska). The identified lead resources of the World total more than 2 billion tonnes[10]. Global mine production was expected to increase to about 5.4 million tonnes in 2013 as shown in the table above. This was mainly owing to production increases in Australia (primarily due to the re-start of an 85,000 ton per year lead mine), and China[1].

Annual Refined Lead Metal Production (thousand tonnes)[11]

The International Lead Zinc Study Group (ILZSG) forecast global refined lead production to increase by about 5% from 2012 to 11.2 million tonnes. This was primarily due to new production capacity in China (despite shut downs of many smelters) and increases in Australia, Belgium, Italy, India, Kazakhstan and Peru.

Region	2009	2010	2011	2012	2013
Europe	1,632	1,716	1,751	1,779	1,820
Africa	97	102	116	98	97
America	1,940	2,021	2,101	2,166	2,251
Asia	5,096	5,560	6,202	6,295	6,816
Oceania	259	228	235	203	204
World Total	9,024	9,627	10,405	10,541	11,188

[10] US Geological Survey, Mineral Commodity Summaries2011-2014
[11] ILZSG Database

Ability for Recycling – Secondary Lead Production[3]

Lead is without doubt the most recycled metal of all those commonly used. Battery recycling rates are particularly high, especially in the Western World. The Battery Council International reported a 98%[12] recycling rate in the USA, while the recycling rate for lead–acid batteries in the EU is reported to be greater than 95% [13]In addition, a 2011 UNEP[14] status report stated that lead has the highest recycling and reuse rates compared to all other metals.

Secondary lead production currently accounts for 54% of total global refined lead production. In 2014 100% of US lead production and 75% of European lead production will originate from secondary sources.

Region	2009	2010	2011	2012	2013
Europe	1,225	1,317	1,399	1,343	1,348
Africa	81	79	85	86	82
America	1,586	1,648	1,721	1,779	1,798
Asia	2,119	2,276	2,421	2,661	2,809
Oceania	43	49	48	50	26
World Total	5,053,476	5,369,279	5,674	5,918	6,061

(ii) Consumption

ILZSG data on lead show that batteries have retained their dominance as the principal first use for the metal and now account for more than 85% of all lead consumed. Lead-acid technology is the most widely used electrochemical system, consumed in numerous applications. Currently all vehicles, (conventional vehicles, Stop-Start, Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV)) require a 12V lead-based battery. These batteries are also used for back-up for uninterruptible power supplies and grid energy storage and in some cases as traction in battery electric vehicles such as golf carts, forklift trucks, e-boats and e-bikes etc.

Despite the recent recession, global consumption of lead increased by 1,207,000 tonnes (14.4%) between 2007 and 2010, largely due to an increase in consumption by China of 1,644,000 tonnes to 4,213,000 tonnes which has more than balanced the falls in consumption in Europe and the Americas. ILZSG projected that global lead consumption would increase in 2013 from that in 2012, to 11.0 million tons, particularly owing to an increase in China, and that global refined lead production would exceed consumption by 22,000 tonnes.

Region	2007	2010	2011	2012	2013
Europe	1,954	1,648	1,631	1,622	1,686
Africa	104	93	100	101	104
America	2,092	1,971	2,071	2,125	2,289
Asia	4,197	5,837	6,453	6,615	7,111
Oceania	27	30	24	18	20
World Total	8,374	9,581	10,279	10,481	11,211

Source: International Lead Zinc Study Group (ILZSG)

[13] Fraunhoufer Institure report on recycling of lead acid batteries, 2010.
[14] 2011 UNEP report on recycling rates for metals

3.1.2 Antimony

Antimony, as stated in section 1, is often used as an alloying element in lead acid batteries. Antimony is not an abundant metal. However, it has been found in over 100 mineral species. Antimony can be found native, but more frequently it is found in the sulphide stibnite (Sb2S3) which is the predominant ore mineral.

(i) Resources

Mine Production and Reserves (tonnes)[15]

	2007	2010	2011	2012	2013	Reserves
Bolivia	5,500	5,000	3,900	4,000	5,000	310,000
China	150,000	150,000	150,000	145,000	130,000	950,000
Russia	3,500	3,000	3,300	6,500	6,500	350,000
South Africa	4,400	3,000	4,700	3,800	4,200	2,7000
Tajikistan	2,000	2,000	2,000	2,000	4,700	50,000
Other Countries	4,000	4,000	14,100	13,000	13,000	150,000
World Total (Rounded)	**170,000**	**167,000**	**178,000**	**174,000**	**163,000**	**1,800,000**

[e]Estimated

There is production data for the USA but this is withheld on the basis of not disclosing company proprietary data. World known reserves are estimated at 1.8 million tonnes, of which just over 50% reside in China which clearly dominates this market.

Metal Production/Recycling

When used in battery applications, antimony is readily recyclable. It is relatively easy to remove antimony from lead in the refining process as a high content antimony dross which can be smelted and then used to blend into alloys. It is less easy to separate the lead completely from antimony and thus with declining antimony levels in alloys, has resulted in surpluses of high antimonial lead alloy. As a result there is lower demand for antimony metal to produce antimony alloys.

(ii) Consumption

The principal use of antimony is in the production of antimony trioxide which has an important function in enhancing the flame retardant properties of plastics, rubber, textiles and other combustibles. It also has an important function as a hardening agent in lead alloys, including those for lead alloy battery grids.

Antimony content of battery grids used to be as high as 12% but with the advent of the use of grain refining elements such as arsenic, copper and sulphur, it has declined considerably over the years. Where water loss is not critical such as in traction batteries where 'top-up' maintenance is used, levels of antimony can still be around 3 - 5%. However, in automotive batteries where special 'maintenance-free' alloys have been developed, the antimony content has dropped to lower levels. In addition, as mentioned under tin, VRLA designs have no antimony in them and thus over the years, antimony consumption in battery applications has been declining.

[15] US Geological Survey, Mineral Commodity Summaries 2011-2014

3.1.3 Tin

Tin is also often used in the positive grids of lead-acid batteries. Tin is used as an alloying element in the positive grids of the valve-regulated type of lead-acid batteries (VRLA) where the acid is immobilised by either being absorbed in a glass-fibre mat or in a silica gel. Antimony cannot be used to strengthen the lead alloy in this type of battery as it promotes gassing which would shorten battery life. Therefore calcium is used instead but, without the use of tin, normally in the range of between 0.6 and 1.5%, passivation of the corrosion layer between the grid and the active material can occur with dramatic loss of capacity. Tin also increases the conductivity of the lead/calcium grids.

Tin is the 49th most abundant element in the Earth's crust, representing 2 ppm compared with 75 ppm for zinc, 50 ppm for copper, and 14 ppm for lead. Tin does not occur as the native element and is normally extracted from a range of ores.

(i) Resources

Mine Production and Reserves (tonnes)[16]

	2007	2010	2011	2012	2013	Reserves
Australia	2,100	7,000	6,500	5,000	5,900	240,000
Bolivia	16,000	20,200	20,300	19,700	18,000	400,000
Brazil	10,000	11,000	11,000	10,800	11,900	700,000
Burma	-	-	-	11,000	11,000	NA
China	135,000	120,000	120,000	110,000	100,000	1,500,000
Congo	3,500	6,700	2,900	4,000	4,000	NA
Indonesia	102,000	56,000	42,000	41,000	40,000	800,000
Laos	-	-	-	800	800	NA
Malaysia	2,500	1,770	3,350	3,000	3,700	250,000
Nigeria	-	-	-	570	570	NA
Peru	39,000	33,800	28,900	26,100	26,100	91,000
Portugal	100	30	100	-		
Russia	2,500	1,100	160	280	300	350,000
Rwanda	-	-	1,400	2,300	1,600	NA
Thailand	100	150	200	300	300	170,000
Vietnam	3,500	5,500	5,400	5,400	5,400	NA
Other Countries	4,000	2,000	2,000	73	70	180,000
World Total (Rounded)	**320,000**	**265,000**	**244,000**	**240,000**		**4,700,00**

China has continued as the World's largest producer of tin from both mine and smelter sources but has experienced sporadic difficulties in obtaining feedstock for its smelters. Indonesia has continued to suffer production difficulties, some related to government shutdown of illegal production facilities. Known resources are estimated at 4.8 million tonnes and are estimated to be sufficient to sustain recent annual production rates well into the future.

[e] Estimated

[16] US Geological Survey, Mineral Commodity Summaries 2011-2014

Metal Production/ Recycling

Primary

	2007	**2008[e]**
Australia	118	-
Bolivia	12,251	12,000
Brazil	9,987	9,600
China	149,000	129,000
Indonesia	64,127	70,000
Malaysia	25,263	23,000
Peru	36,004	38,865
Russia	3,800	2,000
Thailand	20,400	20,000
Vietnam	2,000	2,000
Other Countries	1,000	500
World Total (Rounded)	**324,000**	**307,000**

e Estimated

These figures appear to be the most recent available[17] and also states secondary production of 18,600 tonnes in 2007 and 17,700 tonnes in 2008. These principally arise in Belgium and the USA.

About 13,800 tons of tin from old and new scrap was recycled in 2013. Of this, about 11,200 tons was recovered from old scrap at 2 detinning plants and 75 secondary nonferrous metal processing plants.

(ii) Consumption

The latest figures appertaining to worldwide tin consumption have been found in the UNEP Publication 'Recycling Rates of Metals' (May 2011). These indicate percentage uses for tin in various applications as follows:

Electrical/Electronic Solders	29%
Other Solders	16%
Tin Plating	20%
Chemicals	16%
Brass and Bronze	6%
Glass	2%
Others	12%

These figures may well be subject to some considerable change in recent years as there have been changes in solder composition and has probably been a substitution of tinplate in packaging by their materials. In any event, tin as a component in lead battery alloys did not deserve a separate mention suggesting it was significantly below 2%.

It is anticipated that the majority of tin consumption in batteries would be recovered during the recycling of lead acid batteries, not necessarily as pure tin but would be available for the manufacture of new alloys.

[17] US Geological Survey Minerals Yearbook 2008-2014

3.1.4 Minor alloying elements used in lead-acid battery grids.

3.1.4.1 Copper

Copper is occasionally used as an alloy in grids of lead acid batteries in order to improve grain refinement, ease of casting and to impart age-hardening characteristics.

Copper can be found as either native copper or as part of minerals. Most copper is mined or extracted as copper sulphide. Copper has been in use at least 10,000 years, but more than 95% of all copper ever mined and smelted has been extracted since 1900. As with many natural resources, the total amount of copper on Earth is vast (around 1014 tons just in the top kilometre of Earth's crust, or about 5 million years' worth at the current rate of extraction).

The world total mine production for copper in 2013 was 17,900 thousand tonnes of copper[18]. Chile is the world's largest producer of copper, followed by China, Peru, and the U.S.A. Recent assessment of copper resources indicate that 550 million tonnes of copper remain in unidentified and undiscovered resources in the U.S.A, and 1.3 billion tonnes of copper in discovered, mined and undiscovered resources in the Andes Mountains of South America. A preliminary assessment indicates that global land based resources exceed 3 billion tonnes. Deep-sea nodules and massive sulphides are further potential copper resources.

Copper is widely recycled and reused. Of the worldwide copper resources, only approximately 12% have been mined throughout history, as a result of copper's high recycling rate. A good example of this is the U.S.A, where about 32% of the U.S. copper supply in 2013[9] copper came from old or new scrap, refined or re-melted scrap.

3.1.4.2 Arsenic

Arsenic can also be alloyed with lead for use in battery grids for the same reasons as copper. However, due to environmental and human health related concerns associated with arsenic, it is less widely used in batteries than in the past.

Minerals with the formula MAsS and MAs2 (M = Fe, Ni, Co) are the dominant commercial sources of arsenic, together with realgar (an arsenic sulphide mineral) and native arsenic. Arsenic may also be obtained from copper, gold, and lead smelter dust as well as from roasting arsenopyrite, the most abundant ore mineral of arsenic. This roasting often leads to the formation of arsenic trioxide. In 2013, China was the top producer of white arsenic with over 50% of world share, followed by Chile, and Morocco[10]. The total world mining production tonnage of arsenic trioxide in 2013 was 45,000 tonnes. World reserves are thought to be about 20 times the annual world production. However, most operations in the US and Europe have closed for environmental reasons.

Arsenic has an extremely low recycling rate of <1%[19].

3.1.4.3 Calcium

The use of calcium as an alloying element in lead battery alloys has grown significantly in recent years with the increasing use of VRLA battery designs in stationary and automotive applications. These designs utilise a lead/calcium/tin alloy in the positive grids and lead/calcium alloys in the negative grids. However the actual calcium content of the alloy is low at around 0.1%.

[18] US Geological Survey, Mineral Commodity Summaries, January 2011-2014
[19] 2011 UNEP report on recycling rates for metals

Calcium is not naturally found in its elemental state. Calcium occurs most commonly in sedimentary rocks in a range of minerals. It also occurs in igneous and metamorphic rocks. Calcium is the fifth most common element found in the World and is mainly found in the form of Calcium Carbonate. The metal is normally produced by electrolysis of a fused salt such as calcium chloride. It is extremely reactive and oxidizes readily in air.

Because of the difficulty in storing calcium as a metal it is normally added to the lead as an alloy with aluminium which also reduces oxidation of the calcium during the alloying process.

Any calcium used in battery alloys will be lost to the slag in any smelting process used for recycling.

3.1.4.4 Selenium

Selenium is a rare metal, being most commonly produced from selenide in many sulphide ores, such as those of copper, silver, or lead. It is obtained as a by-product of the processing of these ores. Industrial production of selenium often involves the extraction of selenium dioxide from residues obtained during the purification of copper. As a result of this, the supply of selenium is directly affected by the supply of materials from which it is a by-product-copper, and to a lesser extent, Nickel.

The total World refinery production for 2010 of selenium was estimated to be 2,260 tonnes. Japan and Germany produce the majority of the refinery tonnages. Reserves of selenium are estimated to be 120,000 tonnes.

Recycling rates for selenium are estimated to be in the range 5-10%[13]

3.1.5 Resource availability conclusions for lead based batteries

As explained in the section above, the major components of lead based batteries are lead metal and lead compounds. There are significant global reserves of lead, from both primary (i.e. from mining) and secondary (i.e. from recycling) sources. Secondary production currently accounts for more than 50% of total global lead production. In fact, in 2014 100% of US lead production and 75% of European lead production will originate from secondary sources. The high recycling rate for lead is driven principally by lead-based batteries, more than 95% of which are recycled at the end of life. This means that the existing market for lead-based batteries can be predominately met with recycled material and because of this circular economy, the demand and requirement for lead reserves from mining is low. The anticipated growth in demand for automotive batteries will need to be serviced by primary lead, which will then itself be available for recycling at end of life, and hence enter the circular economy. The existing reserves of Pb can therefore comfortably meet the projected growth in demand for automotive batteries.

In addition there are significant reserves and resources of the alloying materials used in lead based batteries. Given that the amount of these metals required in lead based batteries is very small, it is not anticipated that there would be any current or future issues with resource availability.

3.2 Nickel-Based Battery Technology

3.2.1 Nickel

Nickel is the fifth most common naturally occurring element found on Earth. The bulk of nickel production comes from mining.

(i) Resources

Mine Production and Reserves (tonnes)[20]

Region	2009	2010	2011	2012	2013	Reserves
United States	-	-	-	-	-	160,000
Australia	165,000	170,000	215,000	246,000	240,000	18,000,000
Botswana	28,600	28,000	26,000	-	-	-
Brazil	54,100	59,100	109,000	139,000	149,000	8,400,000
Canada	137,000	158,000	220,000	205,000	225,000	3,300,000
China	79,400	79,000	89,800	93,300	95,000	3,000,000
Colombia	72,000	72,000	76,000	84,000	75,000	1,100,000
Cuba	67,300	70,000	71,000	68,200	66,000	5,500,000
Dominican Republic	-	-	21,700	15,200	12,500	970,000
Indonesia	203,00	232,000	290,000	228,000	440,000	3,900,000
Madagascar	-	15,000	5,900	8,250	26,000	1,600,000
New Caledonia[21]	92,800	130,000	131,000	132,000	145,000	12,000,000
Philippines	137,000	173,000	270,000	424,000	440,000	1,100,000
Russia	262,000	269,000	267,000	255,000	250,000	6,100,000
South Africa	34,600	40,000	44,000	45,900	48,000	3,700,000
Other countries	51,700	99,000	103,000	273,000	274,000	5,100,000
World Total (rounded)	**1,400,000**	**1,590,000**	**1,940,000**	**2,220,000**	**2,490,000**	**74,000,000**

Extensive deep-sea resources of nickel are found in manganese crusts and nodules covering large areas of the ocean floor, particularly in the Pacific Ocean. The long-term decline in discovery of new mining districts may force nickel companies to shift exploration efforts to more challenging locations like the Arabian Peninsula, east-central Africa, and the Subarctic.

Metal Production/ Recycling

About 82,200 tonnes of nickel was recovered from purchased scrap in 2013. This represents about 41% of reported secondary in addition to apparent primary consumption for the year.

[20] US Geological Survey, Mineral Commodity Summaries, January 2011-2014
[21] Overseas territory of France

(ii) Consumption

Nickel Consumption has increased over time. The world nickel demand has increased from 1.009 million tonnes in 1998 to 1.278 million tonnes in 2008, a growth rate of 2.4 per cent per year. Asia is currently the largest regional market for nickel representing 54% of world demand. China alone accounts for 25% of world nickel demand compared to 4% ten years earlier.

Nickel is primarily sold for first use as refined metal. About 65% of the nickel consumed in the western world is used to make stainless steel. Another 12% goes into superalloys or nonferrous alloys. The aerospace industry is a leading consumer of nickel base superalloys. The remaining 23% of consumption is divided between alloy steels, rechargeable batteries, catalysts and other chemicals, coinage, foundry products and plating. The principle commercial chemicals are the carbonate (NiCO3), chloride (NiCl2) divalent oxide (NiO) and sulphate (NiSO4).

As outlined in Section 1, one of the most important uses of nickel is in batteries. Rechargeable alkaline batteries employ a nickel hydroxide-based cathode, with either a metallic anode (nickel-cadmium (Ni-Cd), nickel-iron (Ni-Fe), nickel-zinc (Ni-Zn) or a hydrogen storing anode (Ni-H2, nickel-metal hydride (Ni-MeH)). Due to technical limitations on maintenance and long term cycling performance, Ni-Fe and Ni-Zn batteries cannot be used for automotive or stationary applications.

Both Nickel/Hydrogen (Ni-H) and Ni-MH batteries are, in principle, the same battery system, utilizing nickel hydroxide (NiOOH) as positive and hydrogen (H_2) as negative electrode materials. In Ni-MH batteries a hydrogen storage alloy is used. Both systems have an excellent cycle life. However, due to several performance limitations, Ni-H batteries, as is the case with Ni-Fe and Ni-Zn, are now limited to very narrow niches of the industrial market.

Ni-Cd batteries have a positive electrode of nickel hydroxide and a negative electrode of cadmium.
Ni-Cd based batteries offer good resistance to electrical use as they can be left in a discharged condition for long periods without permanent damage, they are recognized for their superior reliability and also offers good performance in higher as well as lower ambient temperatures as well as extreme deep temperatures.

Due to their superior reliability, Ni-Cd based batteries are essentially used for the back-up of aircraft and rolling stock (train) electronic systems, as back-up for several mission critical industrial processes where the safety of humans or assets is at stake, as well as in electrically or mechanically arduous applications.

3.2.2 Cadmium

Cadmium is found principally in association with zinc sulphide based ores, and to a lesser degree, as an impurity in lead and copper ores. It is also found in sedimentary rocks.

(i) Resources

Mine Production and Reserves (tonnes) [22]

Region	2009	2010	2011	2012	2013	Reserves
United States	633	637	W	W	W	32,000

[22] US Geological Survey, Mineral Commodity Summaries, January 2011-2014

Australia	370	350	390	380	380	NA
Bulgaria	-	-	-	420	420	NA
Canada	1,300	1,300	1,770	1,100	800	23,000
China	4,300	7,200	7,000	7,300	7,400	92,000
Germany	400	400	300	-	-	
India	610	620	630	620	630	35,000
Japan	1,820	2,050	1,760	1,800	1,900	-
Kazakhstan	1,800	1,800	1,400	1,300	1,400	30,000
Korea, Republic of	3,000	2,500	4,000	3,000	3,900	-
Mexico	1,210	1,480	1,480	1,624	1,630	47,000
Netherlands	490	580	570	560	560	-
Peru	375	400	572	684	685	55,000
Poland	600	530	450	530	400	16,000
Russia	700	NA	700	700	850	44,000
Other countries	1,190	1,250	1,190	880	850	130,000
World total (rounded)	**18,800**	**21,000**	**22,200**	**20,900**	**21,800**	**500,000**

Most of the world's primary cadmium metal is produced in Asia and the Pacific—specifically China, Japan, and the Republic of Korea—followed by North America, Central Europe and Eurasia, and Western Europe. Secondary cadmium production takes place mainly at NiCd battery recycling facilities.

Metal Production/ Recycling

Global refinery production of cadmium was estimated to increase in 2010 as a result of production increases at zinc smelters that also recovered by-product cadmium

Cadmium is mainly recovered from spent consumer and industrial NiCd batteries. Other wastes and scrap from which cadmium can be recovered includes copper-cadmium alloy scrap, some complex non-ferrous scrap, and cadmium containing dust from electric furnaces.

(ii) Consumption

Cadmium use in batteries accounts for the majority of global consumption. The remainder was distributed as follows, in order of descending consumption: pigments, coatings and plating, stabilizers for plastics, nonferrous alloys, and other specialized uses (including photovoltaic devices). The percentage of cadmium consumed globally for NiCd battery production has been increasing, while the percentages for the other traditional end uses of cadmium—specifically coatings, pigments, and stabilizers—have gradually decreased, owing to environmental and health concerns. A large percentage of the global NiCd battery market is concentrated in Asia. NiCd battery use in consumer electronics has been thought to be declining owing partly to the preference for other rechargeable battery chemistries—particularly lithium ion (Li-ion) batteries, which have already replaced NiCd batteries to a large degree in laptops and cell phones. Li-ion batteries are used in lightweight electronic devices because of their greater energy density (power-to-weight ratio). However, demand for cadmium could increase owing to several new market opportunities for NiCd batteries, particularly in industrial applications. Industrial-sized NiCd batteries could also be used to store energy produced by certain on-grid photovoltaic systems. Peak energy produced during the midday would be stored in a NiCd battery and later released during periods of high electricity demand.

Concern over cadmium's toxicity has spurred various recent legislative efforts, especially in the European Union, to restrict the use of cadmium in most of its end-use applications. The final effect of this legislation on global cadmium consumption has yet to be seen. If recent legislation involving cadmium dramatically reduces long-term demand, a situation could arise, such as has been recently seen with mercury, where an accumulating oversupply of by-product cadmium will need to be permanently stockpiled.

3.2.3 Zinc

Zinc makes up about 75 ppm (0.0075%) of the Earth's crust, making it the 24th most abundant element. The element is normally found in association with other such as copper and lead in ores. Sphalerite, which is a form of zinc sulphide, is the most heavily mined zinc-containing ore because its concentrate contains 60–62% zinc.

(ii) Resources

Mine Production and Reserves (thousand tonnes)[23]

Region	2009	2010	2011	2012	2013	Reserves
United States	736	748	769	738	760	10,000
Australia	1,290	1,480	1,520	1,510	1,400	64,000
Bolivia	422	411	427	405	400	5,200
Canada	699	649	612	641	550	7,000
China	3,100	3,700	4,310	4,900	5,000	43,000
India	695	700	710	758	800	11,000
Ireland	386	342	340	338	330	1,300
Kazakhstan	480	500	495	371	370	10,000
Mexico	390	518	632	660	600	18,000
Peru	1,510	1,470	1,260	1,280	1,290	24,000
Other countries	1,490	1,490	1,730	1,930	1,950	57,000
World Total	**11,200**	**12,000**	**12,800**	**13,500**	**13,500**	**250,000**

Global zinc mine production in 2013 was forecast to increase to 13.5 million tonnes, mostly as a result of increases in zinc mine production in Australia and China. The International Lead Zinc Study Group (ILZSG) predicted that refined metal production would increase by 3% to 13 million tonnes. It can be seen from the table, that China is currently the largest producer of Zinc. Identified zinc resources of the world are about 1.9 billion metric tonnes.

Metal Production/ Recycling

At present, approximately 70% of the zinc produced worldwide originates from mined ores and 30% from recycled or secondary zinc. The level of recycling is increasing each year, in step with progress in the technology of zinc production and zinc recycling. Today, over 80% of the zinc available for recycling is indeed recycled[24].

[23] US Geological Survey, Mineral Commodity Summaries, January 2011-2014
[24] International Zinc Association Information

(ii) Consumption

World metal consumption of zinc increased by 5% to 12.9 million tons in 2013 compared to 2012, resulting in a production-to-consumer surplus of 120,000 tonnes. A smaller surplus was predicted by the ILZSG of 115,000 tonnes in 2014. Demand for zinc has been shown to generally follow industrial production or, more generally, global economic growth.

Of the total zinc consumed in 2013, about 50% was in galvanizing, 17% in zinc-based alloys, 17% in brass and bronze, 6% in Zinc semi manufacture, 6% in Chemicals and 4% in other uses. Zinc compounds and dust were used principally by the agriculture, chemical, paint, and rubber industries. As stated in section 1, zinc has been used in the anode of nickel based batteries. However, due to technical limitations on maintenance and long term cycling performance, Ni-Zn batteries can no longer be used for automotive or stationary applications. Zinc is also an integral component of the zinc-carbon battery.

3.2.4 Cobalt

Although cobalt is fairly widespread in the Earth's crust, its low concentration usually means that it is produced as a by-product of another metal. An approximate split of cobalt production would currently be:

Nickel Industry:	50%
Copper Industry and Other:	35%
Primary Cobalt operations:	15%

(i) Resources

Mine Production and Reserves (tonnes)[25]

Region	2009	2010	2011	2012	2013	Reserves
United States	-	-	-	-	-	36,000
Australia	4,600	3,850	3,900	5,880	6,500	1,000,000
Brazil	1,200	1,600	3,500	3,900	3,900	89,000
Canada	4,100	4,600	7,100	6,630	8,000	260,000
China	6,000	6,500	6,800	7,000	7,100	80,000
Congo (Kinshasa)	35,500	47,400	60,000	51,000	57,000	3,400,000
Cuba	3,500	3,600	4,000	4,900	4,300	500,000
Morocco	1,600	2,200	2,200	1,800	2,100	18,000
New Caledonia[26]	1,000	1,000	3,200	2,620	3,300	200,000
Russia	6,100	6,200	6,300	6,300	6,700	250,000
Zambia	5,000	5,700	5,400	4,200	5,200	270,000
Other Countries	3,700	6,800	6,700	8,820	13,000	1,100,000
World Total (rounded)	**72,300**	**89,500**	**109,000**	**103,000**	**120,000**	**7,200,000**

[25] US Geological Survey, Mineral Commodity Summaries, January 2011-2014
[26] Overseas territory of France

Identified world cobalt resources are about 25 million tonnes. The vast majority of these resources of these resources are in sediment-hosted stratiform copper deposits in Congo and Zambia; nickel bearing laterite deposits in Australia and nearby island countries and Cuba; and magma nickel-copper sulphide deposits hosted in mafic and ultramafic rocks in Australia, Canada, Russia and the USA. Additionally, more than 120 million tonnes of cobalt resources have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian and Pacific Oceans.

Metal Production/ Recycling

China is the leading producer of refined cobalt, and much of its production has been from cobalt-rich ore and partially refined cobalt imported from Congo (Kinshasa).

In 2013, cobalt contained within purchased scrap represented an estimated 24% of cobalt reported consumption.

(ii) Consumption

A 2009 report by the Cobalt Development Institute (CDI) state the following uses of Cobalt:

Batteries:	25%
Superalloy (Ni/Co/Fe)	20.0%
Hard materials-carbides, diamond tooling	13.0%
Catalysts	10.0%
Colours, glass, enamels, plastics	
Ceramics, artists colours, fabrics	9.0%
Magnets	7.0%
Tyre Adhesives, soaps, driers	7.0%
Hardfacing & other alloys	5.0%
Feedstuff, anodising, recording, media, electrolysis	4.0%

Superalloys is the end-use sector that had historically been the major use of cobalt, however, over the past few years the sector which has increased most markedly is that of rechargeable batteries.

Cobalt is used in two types of nickel based batteries, Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH). In Ni-Cd batteries, cobalt is utilised in the positive electrode, and in Ni-MH, fine cobalt powder, or cobalt oxide is pasted to the negative electrode.

Further increases are projected over the next decade for cobalt use in batteries. This is due to increase in battery demand, primarily due to the surge in demand for portable telephones, particularly in China. Furthermore, the use of cobalt in batteries for electric vehicle applications would be expected to increase cobalt demand dramatically over the next ten years.

3.2.5 Rare Earths

Rare earths are relatively abundant in the Earth’s crust, but discovered minable concentrations are less common than most ores. U.S and world resources are contained primarily in bastnasite and monazite. Bastnasite deposits in China and the U.S. constitute the largest percentage of the World’s rare earth economic resources.

(i) Resources

Mine Production and Reserve (tonnes)[27]

Region	2009	2010	2011	2012	2013	Reserves
United States	-	-	-	800	4,000	13,000,000
Australia	-	-	2,200	3,200	2,000	2,100,000
Brazil	550	550	250	140	140	22,000,000
China	129,000	130,000	105,000	100,000	100,000	55,000,000
Commonwealth of Independent States	NA	NA	-	-	-	-
India	2,700	2,800	2,800	2,900	2,900	3,100,000
Malaysia	350	30	280	100	100	30,000
Russia	-	-	-	2,400	2,400	*included within other countries
Vietnam	-	-	-	220	220	*included within other countries
Other Countries	NA	NA	NA	NA	NA	41,000,000
World Total	**133,00**	**133,000**	**111,000**	**110,000**	**110,000**	**140,000,000**

China is currently the World's largest producer, generating 91% of all Rare Earths. In 2010, China started tightening its rare earth export quota-effectively cutting rare earth exports by 72%[28]. More recent reports have indicated that the Chinese government plans to restrict rare earth mining rights to state controlled mining companies and cap production levels. In September 2011, China Daily stated that three of China's eight rare earth mines would stop production, citing resource depletion and environmental degradation concerns as reasons for a nationwide crackdown on its rare earths sector.

In 2013, China continued efforts to restrict the supply of rare earth metals and consolidate the industry. China's rare earth production and export quotas for 2013 were 93,800 tonnes and 31,000 tonnes respectively. Exploration efforts to develop rare-earth projects continued in 2013. Exploration and development assessments in the United States included Bear Lodge, WY, Bokan Mountain, AK, Diamond Creek, ID, Elk Creek, NE, La Paz, AZ, Lemhi Pass, ID-MT, Pea Ridge, MO, Round Top, TX, and Thor, NV. Additional assessments were underway in Australia, Brazil, Canada, China, Finland, Greenland, India, Kyrgyzstan, Madagascar, Malawi, Mozambique, South Africa, Sweden, Tanzania, Turkey, and Vietnam

[27] US Geological Survey, Mineral Commodity Summaries, January 2011-2014
[28] Batteries International 2010/2011

Metal Production/ Recycling

No metal production statistics found to date. Recycling quantities are extremely low for rare earths (<1%)[29].

(ii) Consumption

Based on consumption data domestic consumption of rare earth's in 2010 increased compared with that of 2009. The trend appears to be for a continued increase in the use of rare earths in many applications, especially in permanent magnets, and rechargeable batteries for electric and hybrid vehicles. The majority of rare earths used in batteries and automotive applications are Lanthanum and Neodymium. Lanthanum is usually employed as a battery constituent, for example it utilised in the anodic material of nickel-metal hydride batteries. Neodymium has a widespread use as a magnet, and is used in almost all electric motors of hybrid and electric automobiles.

A U.S. Geological survey (January 2014) states the following percentages for used of rare earths in the US:

Catalysts	65%
Metallurgical Applications and Alloys	19%
Glass Polishing and Ceramics	6%
Permanent Magnets (Incl use in Batteries)	9%
	3%
Other	1%

3.2.6 Iron

Metallic iron is rarely found on the surface of the earth because it tends to oxidize, but its oxides are pervasive and represent the primary ores. While it makes up about 5% of the Earth's crust, both the Earth's inner and outer core are believed to consist largely of an iron-nickel alloy constituting 35% of the mass of the Earth as a whole. Iron is consequently the most abundant element on Earth. Iron is the least expensive and one of the most widely consumed metals.

(i) Resources[30]

*Mine Production and Reserves (million tonnes)**

Region	2009	2010	2011	2012	2013	Reserves	
						Crude Ore	Iron content
United States	27	50	55	54	52	6,900	2,100
Australia	394	433	488	521	530	35,000	17,000
Brazil	300	370	373	398	398	31,000	16,000
Canada	32	37	34	39	40	6,300	2,300
China	880	1,070	1,330	1,310	1,320	23,000	7,200

[29] UNEP report on recycling rates for metals
[30] US Geological Survey, Mineral Commodity Summaries, January 20112014

India	245	230	240	144	150	8,100	5,200
Iran	33	28	28	37	37	2,500	1,400
Kazakhstan	22	24	25	26	25	2,500	900
Mauritania	10	11	12	-	-	-	-
Mexico	12	14	15	-	-	-	-
Russia	92	101	100	105	102	25,000	14,000
South Africa	55	59	60	63	67	1,000	650
Sweden	18	25	25	23	26	3,500	2,200
Ukraine	66	78	81	82	80	6,500	2,300
Venezuela	15	14	17	27	30	4,000	2,400
Other countries	43	48	59	96	88	14,000	7,100
World Total	**2,240**	**2,590**	**2,940**	**2,930**	**2,950**	**170,000**	**81,000**

*The mine production estimate for China is based on crude ore, rather than usable ore, which is reported for other countries.

World resources of iron are estimated to exceed 230 billion tonnes or iron contained within greater than 800 billion tonnes of crude ore.

Metal Production/ Recycling

Recycled iron and steel scrap is a vital raw material for the production of new steel and cast iron products. A 2011 UNEP report on recycling rates for metals estimated an end of life recycling rate for iron and steel scrap of between 70 and 90%[31].

(i) Consumption

Iron is the most widely consumed of all the metals, accounting for over 90% of worldwide metal production. As a result of its low cost and high strength make it indispensable in engineering applications such as the construction of machinery and machine tools, automobiles, the hulls of large ships, and structural components for buildings. Since pure iron is quite soft, it is most commonly used in the form of steel.

As explained in section 1, iron can be utilised in the Nickel-iron battery. The NiFe battery is a storage battery which has a nickel (III) oxide-hydroxide cathode and an iron anode, with an electrolyte of potassium hydroxide. The active materials are held in nickel-plated steel tubes or perforated pockets. It is a very robust battery which is tolerant of abuse, (overcharge, overdischarge, and short-circuiting) and can have very long life even if so treated. It is often used in backup situations where it can be continuously charged and can last for more than 40 years. However, due to its high cost of manufacture, other types of rechargeable batteries have displaced the nickel-iron battery in most applications. Currently the main use of NiFe batteries is for solar homes, mainly in Australia

3.2.7 Resource availability conclusions for nickel- based batteries

The major metals used in nickel-based batteries are Nickel, Zinc and iron. These are well known metals with significant annual production tonnages and established reserves. For example**,** iron is the least expensive and one of the most widely consumed metals, and zinc and nickel have known resources of 250 million and 74 million tonnes respectively. In addition, over 90% of automotive

[31] UNEP report on recycling rates for metals 2011

nickel batteries are recycled. It can therefore be expected that production of these metals will comfortably meet expected future consumption. In addition, metals such as Cobalt and Cadmium, although used in small quantities have significant know reserves, and are not expected to present any future resource availability issues. In fact, concern over cadmium's toxicity has spurred various recent legislative efforts, especially in the European Union, to restrict it's use in most of its consumer applications. The final effect of this legislation on global cadmium consumption has yet to be seen, but If recent legislation involving cadmium dramatically reduces long-term demand, a situation could arise, such as has been recently seen with mercury, where an accumulating oversupply of by-product cadmium will need to be permanently stockpiled.

Rare Earth metals can be utilised in nickel base batteries. In the past issues have been raised with China, the largest producer of rare earth metals (97% of the market) export policy. However, significant exploration projects are underway in many countries, and there are significant know global reserves of the metal. As such, access to rare earth is likely to be an economic issue as opposed to a resource availability issue.

3.3 Lithium-Based Battery Technologies

3.3.1 Lithium

Lithium does not occur naturally in its elemental form due to its high reactivity to water. Lithium metal can however be mined and separated from other elements. The majority of lithium originates from salt lakes in Bolivia, Chile and Argentina, where it is obtained by evaporation of the water from the salt lakes.

(i) Resources

Mine Production and Reserves (tonnes)[32]

Region	2009	2010	2011	2012	2013	Reserves
United States	W[33]	W[24]	W[24]	W	W	38,000
Argentina	2,220	2,950	2,950	2,700	3,000	850,000
Australia	6,280	9,260	12,500	12,800	13,000	1,000,000
Brazil	160	160	320	150	150	46,000
Canada	310	NA	NA	-	-	-
Chile	5,620	10,510	12,900	13,200	13,500	7,500,000
China	3,760	3,950	4,410	4,500	4,000	3,500,000
Portugal	-	800	820	560	570	60,000
Zimbabwe	400	470	470	1,060	1,100	23,000
World Total	[34]**18,800**	**28,100**	**34,100**	**35,000**	**35,000**	**13,000,000**

Identified lithium resources are 5.5 million tonnes in the United States and approximately 34 million tons in other countries. Identified lithium resources for Bolivia and Chile are 9 million tonnes and greater than 7.5 million tonnes, respectively. China's identified resources are 5.4 million tonnes, Argentina 6.6 million tonnes, Australia 1.7 million tonnes and Canada, Brazil, Congo, and Serbia each contain approximately 1 million tonnes. Identified lithium resources for Brazil total 180,000 tonnes.

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[32] US Geological Survey, Mineral Commodity Summaries, January 2011-2014
[33] Withheld to avoid disclosing company proprietary data
[34] Excludes U.S. production

Worldwide lithium production increased slightly in 2013. Production of one major lithium producer in Chile increased through the first half of 2013, while the other major Chilean producer reduced output owing to increased lithium production from other countries. Argentina's major lithium producer increased production capacity during the year. Worldwide consumption of lithium in 2013 was expected to be approximately 30,000 tons, an increase of 6% from that of 2012. Many companies continued exploring for lithium, with numerous claims in Nevada, as well as in Argentina, Australia, Bolivia, and Canada, having been leased or staked.

In the late 1990s, subsurface brines became the dominant raw material for lithium carbonate production worldwide because of lower production costs compared with the mining and processing of hard-rock ores. Owing to growing lithium demand from China in the past several years, however, mineral-sourced lithium regained market share and was estimated to account for one-half of the world's lithium supply in 2013. Two brine operations in Chile and a spodumene operation in Australia dominated world production. Argentina produced lithium carbonate and lithium chloride from brines. China produced lithium carbonate, lithium chloride, and lithium hydroxide from domestic brines and domestic and imported spodumene. In the United States, the brine operation in Nevada doubled production capacity in 2013. New brine and spodumene operations in Argentina and Canada, respectively, were expected to be commissioned in 2014.

Lithium minerals are used directly as ore concentrates in ceramics and glass applications worldwide and, increasingly, as feedstock for lithium carbonate, lithium hydroxide, and other lithium compounds in China.

Owing to China's growing demand for lithium compounds, its chemical producers have started importing high-quality spodumene to use at its lithium chemical facilities. Australia's leading lithium ore miner doubled its production capacity in 2012 to 110,000 tons per year of lithium carbonate equivalent, and in 2013, a Chinese lithium chemical producer acquired the mine. A new Australian lithium chemical producer opened a plant in China to convert Australian lithium concentrate to battery-grade lithium carbonate.

Lithium supply security has become a top priority for Asian technology companies. Strategic alliances and joint ventures have been, and are continuing to be, established with lithium exploration companies to ensure a reliable, diversified supply of lithium for Asia's battery suppliers and vehicle manufacturers

Metal Production/ Recycling

Recycled lithium content has been historically insignificant, but has increased due to the growth in consumption of batteries. Only one company in the U.S. has recycled lithium in the past. In 2009, the U.S. Department of energy awarded this company $9.5 million to construct the first U.S. recycling facility for lithium. In Europe, recycling of lithium-based industrial batteries is still in its infancy. Lithium-ion batteries have an expected life time of 10 years for a car battery, and as such, intensive recycling of lithium batteries used in electric vehicles is expected to start after this period.

(ii) Consumption

Currently, the most significant use of lithium is in the lithium-ion battery. It is important to note, however, that the total quantity of lithium in a Li-ion battery is around 2%. Lithium-ion (Li-Ion) is currently the dominant battery system for portable applications and was introduced to the market in 1991. Due to the high capacity of the active materials and a single cell voltage of 3.6V, Li-Ion provides the highest energy density of all rechargeable systems operating at room temperature. Li-Ion batteries are also available as lithium polymer batteries using a lithium metal electrode in conjunction with a solid or gel-type electrolyte.

The Li-Ion battery employs a Lithium metal oxide cathode and a carbon anode with an organic electrolyte. Over the last years tremendous improvements on battery parameters have been achieved. Both the high level of energy and power makes the Li-Ion system very suitable for various applications, ranging from high energy to high power.

Lithium-based batteries can be found in a range of consumer applications such as portable devices, as well as in several industrial applications in which their features of good cycling ability and high energy density sets them above other technologies. This makes them particularly well suited for electric and plug-in hybrid vehicles and electric aircraft applications.

Rechargeable batteries are expected to be the largest potential growth area for lithium compounds. Demand for rechargeable lithium batteries exceeds that of other rechargeable batteries for use in cellular telephones, cordless tools, MP3 players, and portable computers and tablets. Major automobile companies are developing lithium batteries for electric and hybrid electric vehicles. Non rechargeable lithium batteries are used in calculators, cameras, computers, electronic games, watches, and other devices.

A U.S. Geological survey (January 2014) states the following percentages for usage of Lithium:

Ceramics and Glass	35%
Batteries	29%
Lubricating greases	9%
Continuous casting mold flux powders	6%
Air treatment	5%
Primary Aluminium Production	1%
Polymer production	5%
Other uses	10%

3.3.2 Titanium

Titanium is the ninth-most abundant element in the Earth's crust and the seventh-most abundant metal. It is present in most igneous rocks and in sediments derived from them. Ilmenite accounts for about 91% of the world’s consumption of titanium minerals. World resources of ilmenite, and rutile total more than 2 billion tons

(i) Resources

Mine Production and Reserves (thousand tonnes)[35]

Ilmenite:

Region	2009	2010	2011	2012	2013	Reserves
United States	200	200	300	300	300	2,000
Australia	1,020	991	960	940	940	160,000
Brazil	43	45	45	45	45	43,000
Canada	650	754	750	750	770	31,000
China	500	550	660	960	950	200,000
India	420	540	330	340	340	85,000
Madagascar	47	172	280	380	430	40,000
Mozambique	283	407	380	350	480	14,000
Norway	302	300	360	360	400	37,000
South Africa	1,050	952	1,110	1,100	1,100	63,000
Sri Lanka	30	32	31	32	32	NA
Ukraine	300	300	300	360	410	5,900
Vietnam	412	485	550	510	500	1,600
Other countries	42	37	40	74	90	26,000
World Total	**5,300**	**5,800**	**6,100**	**6,500**	**6,790**	**700,000**

Rutile:

Region	2009	2010	2011	2012	2013	Reserves
United States	([36])	([27])	([27])			([27])
Australia	266	361	440	410	450	24,000
Brazil	3	3	3	2	2	1,200
India	20	24	24	24	26	7,400
Madagascar	2	5	-	-	-	-
Malaysia	NA	7	-	-	-	-
Mozambique	2	4	6	7	9	510
Sierra Leone	61	65	64	89	90	3,800
South Africa	127	145	122	120	120	8,300
Sri Lanka	11	2	-	-	-	NA
Ukraine	57	57	56	56	60	2,500
Other countries	-	-	18	24	17	400
World Total	**550**	**670**	**730**	**730**	**770**	**48,000**

Metal Production/ Recycling

Titanium has an end-of life recycling rate of 91 % according to the 2011 UNEP report on recycling rates for metals.

[35] US Geological Survey, Mineral Commodity Summaries, January 2011-2014
[36] US rutile production and reserves data are included with ilmenite

(i) Consumption

Consumption of titanium mineral concentrates is tied to consumption of TiO_2 pigments primarily used in paint, paper, and plastics. About 94% of titanium mineral concentrates are consumed by domestic titanium dioxide (TiO_2) pigment producers. The remaining 6% is used in welding rod coatings and for manufacturing carbides, chemicals, and metal. Titanium is used in Li-ion batteries in the cathode, in compounds such as $Li_4Ti_5O_{12}$.

3.3.3 Boron

Boron is a relatively rare element in the Earth's crust, representing only 0.001%. The worldwide commercial borate deposits are estimated at 10 million tonnes. Economically important sources of boron are rasorite (kernite) and tincal (borax ore).

(i) Resources

Mine Production and Reserves (thousand tonnes of boric oxide (B_2O_3))[37]

Region	2009	2010	2011	2012	2013	Reserves
United States	W[38]	W	W	W	W	40,000
Argentina	750	600	600	650	700	2,000
Bolivia	83	97	135	130	130	NA
Chile	608	504	489	444	450	35,000
China	145	150	100	160	160	32,000
Iran	2	2	1	-	-	-
Kazakhstan	30	30	30	30	30	NA
Peru	187	293	293	104	200	4,000
Russia	400	400	400	400	250	40,000
Turkey	1,300	2,000	2,500	2,500	3,000	60,000
World Total	**3,510**	**4,080**	**4,550**	**4,420**	**4,900**	**210,000**

Large deposits of boron resources containing high B_2O_3 content occur in southern California and in Turkey. U.S. deposits consist primarily of tincal, kernite, and borates contained in brines, and to a lesser extent ulexite and colemanite. About 70% of all Turkish deposits are colemanite. Small deposits are being mined in South America. At current levels of consumption, world resources are adequate for the foreseeable future.

Metal Production/ Recycling

Boron has an end-of life recycling rate less than 1% according to the 2011 UNEP report on recycling rates for metals.

(i) Consumption

In 2013, the glass and ceramics industries remained the leading users of boron, consuming an estimated 80% of total boarates consumption in the US. Consumption of boron in high-technical fiberglass sectors, such as in electronic products and wind turbines, is expected to increase by 10% in North America and by 13% in Europe by 2012[27]. Although borate consumption in China decreased in

[37] US Geological Survey, Mineral Commodity Summaries, January 2011-2014
[38] Withheld to avoid disclosing company proprietary data

2009 owing to the economic downturn, consumption is projected to increase driven by demand from its domestic ceramic and glass industries. With low-grade domestic boron reserves and the anticipated rise in demand, Chinese imports from Chile, Russia, Turkey, and the United States are expected to increase over the next several years. Europe and emerging markets may require more stringent building standards with respect to heat conservation, which directly correlates to higher consumption of borates for insulation fiberglass. Continued investment in new refineries and technologies and the continued rise in demand were expected to fuel growth in world production over the next several years.

Boron is used in Li-ion batteries as part of the electrolytic compounds such as $LiBF_4$

3.3.4 Aluminium

Aluminium is the most abundant metallic element and the third most abundant of all elements in the Earth's crust. It is often found in oxides and silicates. Native aluminium metal can be found as a minor phase in low oxygen fugacity environments, such as the interiors of certain volcanoes. Although aluminium is an extremely common and widespread element, common aluminium minerals are not economic sources of the metal. Almost all metallic aluminium is produced from the ore bauxite ($AlO_x(OH)_{3-2x}$). Bauxite occurs as a weathering product of low iron and silica bedrock in tropical climatic conditions

(i) World Smelter Production and Capacity (thousand tonnes)[27]

	Production					**Yearend Capacity**				
Region	**2009**	**2010**	**2011**	**2012**	**2013**	**2009**	**2010**	**2011**	**2012**	**2013**
United States	1,727	1,726	1,986	2,070	1,950	3,500	3,200	3,160	2,720	2,680
Argentina	-	-	440	450	460			455	455	455
Australia	1,940	1,930	1,950	1,860	1,750	2,050	2,050	1,980	1,980	1,770
Bahrain	870	870	881	890	900	880	880	900	970	970
Brazil	1,540	1,540	1,140	1,440	1,330	1,700	1,700	1,700	1,700	1,700
Canada	3,030	2,960	2,980	2,780	2,900	3,090	3,020	3,020	3,020	2,880
China	12,900	16,200	18,100	20,300	21,500	19,000	23,000	25,000	26,900	30,200
Germany	292	394	433	410	400	620	620	620	620	620
Iceland	785	780	800	820	825	790	790	800	810	830
India	1,400	1,450	1,670	1,700	1,700	1,700	1,950	2,310	1,860	2,700
Mozambique	545	557	562	564	560	570	570	570	570	570
Norway	1,130	800	1,070	1,150	1,200	1,230	1,230	1,230	1,230	1,230
Qatar	NA	190	390	604	600		585	585	610	610
Russia	3,820	3,950	3,990	3,850	3,950	4,280	4,440	4,450	4,450	4,450
South Africa	809	807	809	665	820	900	900	900	900	900
United Arab Emirates	1,010	1,400	1,800	1,820	1,800	1,120	1,800	1,800	1,850	2,350
Venezuela	610	335	-	-		625	590	-	-	-
Other countries	4,900	4,900	5,100	4,540	4,650	6,750	6,180	6,540	6,400	6,960
World Total	**37,300**	**40,800**	**44,400**	**45,900**	**47,300**	**48,800**	**53,500**	**56,000**	**57,000**	**61,900**

World primary aluminium production increased by about 3% in 2013 compared to production in 2012 mostly due to new capacity in China. World inventories of metal held by producers, as reported by the International Aluminium Institute, declined gradually to about 2.2 million in August 2012 to 2.3 million tonnes at the end of year 2012. Despite a decline in U.S LME inventories, global inventories of primary aluminium metal held by the LME increased during 2012 to 5.4 million tonnes in mid-October from 5.2 million tonnes at yearend 2012.

Metal Production/ Recycling

In the US in 2013, 56% of all scrap was new manufacturing scrap, and the remaining 44% was old scrap. Aluminium recovered from old scrap was equal to approximately 37% of apparent consumption. The end of life recycling rate of aluminium has been reported in the range 42-70%.[39]

(i) Consumption

A U.S. Geological survey (January 2014) states the following percentages for usage of Aluminium in the US:

Transportation	36%
Packaging	23%
Building	14%
Electrical	9%
Machinery	7%
Consumer durables	7%
Other uses	3%

In terms of Li-ion batteries, aluminium can be utilised in the anode of the battery, in substances such as $LiNi_xCo_xAl_2O_2$

3.3.5 Manganese

Manganese is the twelfth most abundant element in the Earth's crust. Nevertheless it is only rarely found in concentrations high enough to form a manganese ore deposit.

(i) Resources

Mine Production and Reserves (thousand tonnes)[40]

Region	2009	2010	2011	2012	2013	Reserves
United States	-	-	-	-	-	-
Australia	2,140	3,100	3,200	3,080	3,100	97,000
Brazil	730	780	1,120	1,330	1,400	54,000
Burma			234	115	120	NA
China	2,400	2,600	2,800	2,900	3,100	44,000
Gabon	881	1,420	1,860	1,650	2,000	24,000
India	980	1,000	895	800	850	49,000
Kazakhstan			390	380	390	5,000

[39] UNEP report on recycling rates for metals 2011
[40] US Geological Survey, Mineral Commodity Summaries, January 2011-2014

Malaysia			225	429	250	NA
Mexico	169	175	171	188	200	5,000
South Africa	1,900	2,900	3,400	3,600	3,800	150,000
Ukraine	375	540	330	416	350	140,000
Other countries	1,240	1,340	1,740	920	950	-
World Total	**10,800**	**13,900**	**16,000**	**17,000**	**17,000**	**570,000**

World demand for manganese depends directly on the needs of the steel industry. There are numerous grades of steel and each requires a different amount of manganese. The majority of it is in the form of manganese Ferro-alloys, but there are some cases when it can be added in the form of ore.

Metal Production/ Recycling

In the past manganese has been recycled as a minor constituent of ferrous and non-ferrous scrap: however scrap recovered specifically for manganese has been negligible. Manganese is also recovered along with iron from steel slag.

(ii) Consumption

Construction, machinery and transportation end uses account for approximately 29%, 10% and 10% respectively of manganese demand. The remaining amounts typically are used in iron and steel applications. The most important non-metallurgical application of manganese is in the form of manganese dioxide, which is used as a depolarizer in dry-cell batteries, such as zinc-carbon batteries. Dry cell consumption in the world exceeds 20 billion units per year. In the Lithium ion battery, manganese can be used in the positive electrode, often in materials such as $LiMn_2O_4$ and $LiNi_xMn_xCo_zO_2$.

3.3.6 Copper

Copper can be utilised in the negative electrode of Li-ion batteries. Often the negative electrode comprises carbon coated in a copper foil. The resource availability of copper is covered in section 2.1.4.1.

3.3.7 Nickel

Nickel is widely used in Li-ion batteries in the positive electrode, often in lithiated metal oxides such as $LiNi_xMn_xCo_zO_2$. The resource availability of Nickel is addressed in section 2.2.1

3.3.8 Iron

Iron has two main uses in Li-ion batteries. The first use is that the casing is often constructed using iron. The second application is that iron can also be used in the anode in materials such as $LiFeP0_4$ and Li_2FePO_4F. The resource availability of iron is covered in section 2.2.4

3.3.9 Cobalt

The lithiated metal oxides used in the positive electrode of Li-ion batteries often contain cobalt. Examples of this are LiCoO2, $LiNi_xMn_xCo_zO_2$, and $LiNi_xCo_xAl_zO_2$. Cobalt is considered in depth in section 2.2.5.

3.3.10 Resource availability conclusions for lithium- based batteries

Unlike lead, sodium and nickel based batteries, the chemistry of Lithium ion batteries can widely differ. Section 3.3 therefore considers metals that can be used in the different lithium ion chemistries (of Li, Ti, Al, B, Mn, Cu, Co, Ni and Fe). The data in Section 3.3 show that the metals used in lithium-based batteries have no current resource availability issues. There is significant production and current global reserves of the metals mentioned above and this is expected to comfortably meet the current demand for these metals.

However, the increasing use of lithium-ion batteries in portable electronics, coupled with use in new applications is expected to result in a substantial increase in future demand for the metals used in lithium batteries, and specifically lithium. This increased demand would need to be met from lithium reserves via primary production, as currently less than 1% of lithium is recycled[41], and recycling of lithium batteries is in its infancy. One reason for this is due to the widely differing chemistries, recycling of lithium ion batteries can be more difficult than, for example, recycling lead based batteries where all batteries (automotive and industrial) have the same basic chemistry.

There are significant reported resources of lithium, and in 2014 the global mine production was 35,000 tonnes[42]. The most significant use of lithium is in lithium ion batteries for portable electronics (e.g. cameras, phones, laptops). The growth rates for these uses are predicted to be considerable[5]. In addition to these applications, a new and very rapidly growing market has emerged over the last decade in the form of electric bicycles. Approximately 30 million ebikes were sold in 2009, and it has been forecast that 466 million electric two-wheelers will take to the road by 2016[43]. These bikes have previously used lead-based batteries, but there is a push to switch to lithium-ion batteries[44], which if pursued, could be expected to consume additional lithium reserves.

As mentioned above, the predominant use of lithium-ion batteries is in portable batteries. However, the use of lithium-ion batteries in some automotive and industrial applications is also expected to rise. There is predicted to be increasing volumes used as traction batteries in PHEV and EVs, as well as certain hybrid segments. They will also be required for large-scale grid-connected energy storage. In addition, the use of automotive lithium-ion batteries in an SLI function in vehicles is being explored as a potential alternative to lead-acid batteries, as a consequence of pressure from existing and proposed EU environmental legislation[45]. However, this application of lithium-ion batteries is currently only seen as a very minor use in luxury vehicles, and significant technical limitations and cost implications remain for their use in mass-market vehicles

If the existing challenges associated with SLI use of lithium-ion batteries were resolved such that they became viable option to lead-acid technology - coupled with the additional demand for lithium

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[41] UNEP report on recycling rates for metals 2011

[42] US Geological Survey, Mineral Commodity Summaries, January 2012

[43] Pike Research 2010

[44] William Tahil, cars21.com April 2012

[45] The End-of-Life Vehicles Directive bans the use of lead in vehicles, with an indefinite exemption for lead in batteries that is reviewed regularly according to technical and scientific progress. The European Commission last reviewed this exemption in 2010, reaching the conclusion that no mass market alternatives were available to replace automotive lead-based batteries.

in portable electronics, energy storage, e-bikes and other areas of the automotive industry – future resource availability issues for lithium could be expected. As an illustrative example, if lithium-ion batteries were required to replace all lead-acid batteries in an SLI function, *ca* 90,000 tonnes of lithium[46] would be required from further increases to primary production. This quantity is almost three times the current reported lithium mine production, and so the required increase in production would be significant.

In addition this report highlights that a significant amount of lithium production, reserves and resources currently originate from Argentina, Bolivia and Chile. Although not discussed in detail this observation suggests the possibility of an additional challenge to future accessibility created by geo-political risk of a raw material that is only available in one specific region. For example, any unrest or instability of the governments in these regions could greatly affect the supply of lithium and have an impact on battery price, and thus application cost. The increased demand for lithium in new and existing applications, coupled with low recycling rates and geo-political issues could be predicted to present a significant future challenge to the commodity if it is also to be required in new mass-market applications

3.4 Sodium-Based Battery Technologies

3.4.1 Sodium

Owing to its high reactivity, sodium is found in nature only as a compound and never as the free element. Sodium makes up about 2.6% by weight of the Earth's crust, making it the sixth most abundant element overall[47] and the most abundant alkali metal. Sodium is found in many different minerals, of which the most common is ordinary salt (sodium chloride), which occurs in vast quantities dissolved in seawater, as well as in solid deposits. Today, the commercial production of sodium occurs through the electrolysis of liquid sodium chloride.

(i) Consumption

Sodium has an extremely wide range of applications, many of which depend on whether liquid or metallic solid is used. Examples of applications utilises metallic sodium are: use in alloys to improve structure, as a reducing agent, in vapour lamps, heath transfer fluids and often as a reducing agent in organic synthesis. Molten sodium can also be used as a coolant in some types of neutron reactors.

However, of interest to this report is the fact that sodium is utilised in a range of battery technologies. In contrast to many batteries, sodium-based batteries consist of a solid or solid and molten electrolyte with liquid sodium acting as the negative electrode. These batteries are used in a

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[46] * Approximately 7 million tonnes of refined lead were consumed for use in automotive batteries in 2013. This equates to the production of approximately 700 million lead-acid batteries worldwide for use in automotive applications. It can be assumed that approximately 20% of these batteries would be for new cars, and the remaining 80% would be for replacement batteries[46]. Assuming 0.15 kg of lithium in each lithium-ion SLI battery, 90,000 tonnes of lithium would be required to manufacture 700 million batteries. This change would be gradual over several years, beginning with the installation of lithium-ion batteries as original equipment in new vehicles, and progressing to their sale as replacement batteries on the aftermarket. The above scenario gives an indication of the long-term consequences of forcing such changes to the battery technologies used in automotive applications.

[47] Lide, D. R., ed (2005). CRC Handbook of Chemistry and Physics (86th ed.). Boca Raton (FL): CRC Press. ISBN 0-8493-0486-5.

range of applications, covering energy grid storage, such as storing energy from intermittent energy sources (e.g. wind- and solar-power).

3.4.2 Sulphur

Elemental sulphur can be found near hot springs and volcanic regions in many parts of the world. Such volcanic deposits are currently mined in Indonesia, Chile, and Japan. Historically, Sicily was a large source of sulphur. Significant deposits of elemental sulphur, believed to have been (and are still being) synthesised by bacteria on sulphate minerals along the coast of the Gulf of Mexico, and in in Eastern Europe and western Asia. Native sulphur may be produced by geological processes alone.

Sulphur may be found by itself and historically was usually obtained in this way, while pyrite has been a source of sulphur via sulphuric acid. Today's sulphur production is as a side product of other industrial processes such as oil refining; in these processes, sulphur often occurs as undesired or detrimental compounds that are extracted and converted to elemental sulphur. Sulphur is only used in sodium sulphur batteries.

(ii) Resources

World Production (all forms of Sulphur-thousand tonnes)[48]

Region	2009	2010	2011	2012	2013
United States	9,780	9,070	8,930	9,000	9,100
Australia	930	940	940	860	900
Brazil	NA	480	480	480	500
Canada	6,940	7,255	6,520	5,910	6,000
Chile	1,600	1,676	1,720	1,680	1,700
China	9,370	9,600	9,700	9,900	10,000
Finland	615	590	590	1,350	1,400
France	1,310	1,305	1,310	650	650
Germany	3,760	3,905	3,910	3,820	3,800
India	1,150	1,171	1,190	1,190	1,200
Iran	1,570	1,780	1,780	1,880	1,900
Italy	740	740	740	740	740
Japan	3,350	3,292	3,300	3,250	3,300
Kazakhstan	2,000	2,000	2,700	2,700	2,700
Republic of Korea	1,560	660	1,200	1,200	1,200
Kuwait	700	830	830	800	800
Mexico	1,700	1,810	1,660	1,740	1,700
Netherlands	530	530	530	515	520
Poland	730	732	1,140	1,160	1,200
Qatar	NA	1,124	1,200	820	820
Russia	7,070	7,070	7,280	7,270	7,300
Saudi Arabia	3,200	3,300	4,600	4,090	4,100
South Africa	539	465	370	310	310
Spain	637	637	637	680	680
United Arab Emirates	2,000	1,763	1,800	1,900	2,000

[48] US Geological Survey, Mineral Commodity Summaries, January 2011-2014

Uzbekistan	520	520	520	540	540
Venezuela	800	800	800	800	800
Other Countries	4,810	4,020	4,080	2,900	2,900
World Total (rounded)	**67,900**	**68,100**	**70,500**	**68,100**	**69,000**

Reserves of sulphur in crude oil, natural gas, and sulphide ores are large. Because most sulphur production is a result of the processing of fossil fuels, supplies are envisioned to be adequate for the foreseeable future. It should be noted that because petroleum and sulphide ores can be processed long distances from where they are produced, sulphur production may not be in the country for which the reserves were attributed. For instance, sulphur from Saudi Arabian oil may be recovered at refineries in the United State

Production/ Recycling

Typically, between 2.5 million and 5 million tons of spent sulphuric acid is reclaimed from petroleum refining and chemical processes during any given year.

(ii) Consumption

Elemental sulphur is mainly used as a precursor to other chemicals. Approximately 90% is converted to sulphuric acid. Elemental sulfur was recovered, in descending order of tonnage, at petroleum refineries, natural-gas-processing plants, and coking plants by 39 companies at 104 plants in the USA. By-product sulfuric acid, representing about 7% of production of sulfur in all forms, was recovered at seven nonferrous smelters in the USA by five companies. Elemental sulfur provided 61% of consumption in the US, and by-product acid accounted for about 5%. The remaining 34% of sulfur consumed was provided by imported sulfur and sulfuric acid. About 90% of sulfur consumed was in the form of sulfuric acid.
As detailed in Section 1, sulphur is used in sodium-based battery technologies. However this accounts for a small percentage of overall sulphur consumption.

3.4.3 Nickel

Sodium-Nickel Chloride ($NiCl_2$) are one of the main types of sodium-based battery. In $NiCl_2$ batteries, the cathode is made of $NiCl_2$, and the anode is made of sodium. The resource availability of Nickel is considered in detail in section 2.2.1

3.4.4 Aluminium

The electrolyte in NiC_{l2} batteries is made up of tetrachloroaluminate (i.e. $NaAlCl_4$). The resource availability of aluminium is addressed in section 2.3.4.

3.4.5 Resource availability conclusions for sodium based batteries

Sodium based batteries can comprise Sodium, Sulfur, Aluminium and Nickel. Sodium occurs naturally in vast quantities and can easily meet the demand for sodium batteries. Furthermore, reserves of sulphur in crude oil, natural gas, and sulphide ores are large. Because most sulphur production is a result of the processing of fossil fuels, supplies are envisioned to be adequate for the foreseeable future. As explained in Sections 3.2 and 3.3, Aluminium and Nickel have substantial annual production tonnages of 47 million and 2.5 million tonnes in 2012 respectively. Both metals have significant know global resources, and have recycling rates of greater than 50%.[49] Sodium based batteries are also easily recycled.

It can therefore be summarised that there are no expected current or future resource availability issues with sodium based batteries.

4. Conclusions

In conclusion, no resource availability issues for lead, sodium and nickel based batteries are identified in this report. The document also shows no current issues with lithium based batteries. However possible future resource available issues could be anticipated for the materials used in lithium based batteries. This could be anticipated due to the increasing use of lithium-ion batteries in portable electronics, added to the use in new applications, which is expected to result in a substantial increase in demand for lithium. This new and increased demand, coupled with low recycling rates associated with lithium and lithium based batteries and possible geo-political issues related with accessing lithium could be predicted to present a significant future challenge for the global supply of lithium.

[49] UNEP report on recycling rates for metals 2011