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Review of ELV Exemption 5

From the view of lithium-ion battery makers and experts

Question 1: Please explain whether the use of lead in the application addressed under Exemption 5 of the ELV Directive is still unavoidable so that Art. 4(2)(b)(ii) of the ELV Directive would justify the continuation of the exemption. Please clarify what types of vehicles your answer refers to, i.e., conventional vehicles and various types of hybrid and electric vehicles and which functionalities are covered (starting, ignition, lighting and other points of consumption).

The use of lead in batteries is potentially avoidable and definitely reducible in most conventional passenger vehicles by the adoption of emerging energy storage technologies. 12V lithium-ion batteries are in fact already in series production for automotive OEMs in Europe and across the world and are projected to increase in volume over the next decade mostly due to regulatory drivers related to vehicle emissions reduction.

The European Commission has set emissions targets [European Commission, <http://ec.europa.eu/environment/air/transport/road.htm>, as of 28 Oct 2014] for which major fuel saving technologies are required. Hybrid and electric vehicles have received the most attention for yielding aggressive improvement in emissions. However consumer adoption rates of these vehicle types have been slow and therefore automakers have been forced to identify other fuel saving technologies that have less impact on the consumer and are more economically viable across the vehicle portfolio. A new, smaller form of vehicle electrification called the micro-hybrid is expected to fill this gap. In fact OEMs are working to form standards around advanced battery technologies that support micro-hybridization and weight reduction, and some have already launched them into production.

Micro-hybrids are driving development of lithium-ion batteries in 12V applications

Micro-hybrids are vehicles with conventional internal combustion engines that use the existing 12V electrical architecture in new innovative ways to save fuel. Micro-hybrids have proven to be an excellent value in terms of cost per unit of emissions reduced, and therefore they are expected to increase market share steadily in the coming years [D. Saddington, The Global Market for Start-Stop Systems, ABOUT Publishing Group, May 2014].

Micro-hybrids employ the 12V battery to support two key features; 1) Start-stop, and 2) Recuperation. Start-stop logic turns off the engine when the vehicle is at rest to save fuel and quickly restarts the engine when the driver presses the clutch or releases the brake. Recuperation, otherwise known as regenerative braking, uses the free kinetic energy from wheel rotation during deceleration or coasting to charge the 12V battery. The system can use this captured energy to reduce alternator output, thereby reducing the parasitic load on the engine and saving fuel.

Start-stop is a feature that is already in production on millions of vehicles and growing rapidly in Europe, Japan, and the United States. Since the engine must be restarted numerous times through a trip cycle, a more robust battery is required to support start-stop. This battery must also tolerate deeper discharge events as it supports the increasing demands of the 12V powernet (radio, lighting, navigation, etc) while

the vehicle is at rest with the engine off. The combination of the drastic increase in engine restarts and the deeper discharge of the battery during engine-off events have strained the capability of today's advanced lead-acid batteries. Automakers are responding by reducing the number of times and conditions in which an engine is permitted to turn off over the life of the vehicle.

Voltage stability/stiffness is also a concern because the powernet voltage drops during an engine restart event and thus can disrupt the quality of the engine restart. Mechanical vibrations and/or electrical interruptions (i.e. lighting and infotainment dim or flicker) can also occur if the voltage drops too low during the restart. This voltage sag has driven the implementation of a secondary component, either a smaller secondary lead-acid battery or a small dc/dc converter, to stabilize the 12V powernet as the primary battery powers the engine restart.

Capturing random and rapid recuperation charge events during vehicle deceleration requires the battery to be charged very quickly. Dynamic or rapid charge acceptance is an inherent weakness for lead-acid batteries, therefore recuperation potential is limited on vehicles supported by lead-acid batteries. It has been proven that a lead-acid battery loses its ability to charge quickly within the first months of service [Budde-Meiwes, et al., "Dynamic charge acceptance of lead-acid batteries: Comparison of methods for conditioning and testing", *Journal of Power Resources* 207, 2012] and therefore it is commonly understood that a lead-acid battery (or two parallel lead-acid batteries) cannot support the most capable and most fuel saving implementation of micro-hybridization.

Lithium-ion battery technology solves these durability and charge acceptance concerns left unaddressed by lead-acid batteries. Whereas lead-acid batteries are typically replaced every five years in conventional starting, lighting, and ignition (SLI) applications and more often on start-stop vehicles, lithium-ion batteries are expected to last at least twice the vehicle manufacturer warranty period even when subjected to a more rigorous micro-hybrid duty cycle. Rapid charge acceptance of a lithium-ion battery is far superior; in fact the allowable charge current in some available 12V systems is greater than can be delivered by production alternators. Aggressive rates of charge required to capture recuperation energy quickly do not harm lithium-ion battery life under normal operating conditions. Voltage stiffness is also a key advantage that addresses the voltage drop concerns during engine restarts. Durability, charge acceptance, and voltage stability performance of lithium-ion batteries have been proven on bench and vehicle durability tests.

Weight is another key advantage of a lithium-ion battery. It is inherently lighter than lead-acid (roughly three times more energy dense), but in addition a lithium-ion battery has more usable energy. This means it can be deep cycled without harmful effect to battery life and thus the battery capacity can often be downsized when changing from lead-acid to lithium-ion in a given application.

Cold crank performance has been cited as a weakness for lithium-ion batteries in past exemption reviews which is undisputed when considering past formulations. As automotive starter batteries are a relatively new application for lithium-ion technology, there has been strong focus on improving cold temperature power in an effort to meet the full requirements of this application. As such, lithium-ion

battery makers have significantly increased the cold temperature power capability and have achieved parity in performance to lead-acid at label-rated temperatures of -18 degrees Celsius. Extreme cold performance at -30 degrees Celsius has been greatly improved but is not yet equal to lead-acid. More detail on the improvements in cold temperature power performance and empirical comparison to lead-acid and industry specifications is discussed in response to question 2 of the questionnaire.

It should be noted that the lithium-ion electrochemistry selection for 12V battery applications must maintain proper voltage match to the existing 12V powernet for successful integration into the existing 12V powernet successfully. Lithium iron phosphate (LFP) configured with four cell groups in series and lithium titanate oxide (LTO) configured with 5 or 6 cell groups in series (depending on the cathode material selection) meet this requirement. Lithium nickel manganese cobalt oxide (NMC) is a popular chemistry chosen for high voltage traction batteries but does not have a proper voltage match to existing 12V powernet systems and thus is not generally considered in micro-hybrid architectures without the use of a DC-DC converter.

12V lithium-ion batteries are in series production

Due to the key performance upgrades and improvement in cold temperature power performance, nearly all mainstream automakers have been investigating lithium-ion batteries and other energy storage devices to support 12V micro-hybridization. Most manufacturers are considering at least one of two 12V architectures; 1) lead-acid battery replacement with a single lithium-ion battery, and 2) dual battery systems where a lithium-ion battery or other storage device is applied in combination with a lower capacity lead-acid battery. Some manufacturers have launched early versions of these architectures into series production.

The approach of using the single lithium-ion battery architecture is fairly straightforward in that a lithium-ion battery replaces the lead-acid battery and its secondary voltage stability device (either a small PbA battery or DC/DC converter.) This solution fully supports the engine starting and 12V powernet loads during engine off events. In this architecture the use of lead in batteries is completely eliminated, and this battery is expected to last much longer than the warranty period offered by the vehicle manufacturer and has a target lifetime of 8-10 years.

Examples of series production vehicle with a single lithium-ion battery supporting micro-hybrid systems:

	Vehicle Manufacturer	Vehicle Model	Launch year	Estimated quantity of units in service	Battery manufacturer
1	Mercedes Mercedes-AMG	S-Class SLS AMG Coupe SLS S63 AMG S65 AMG Coupe	2013	12k	A123 Systems (Li-ion LFP)
2	BMW	M3	2014	<1k	GS Yuasa (Li-ion LFP)

The dual battery architecture for micro-hybridization uses a downsized lead-acid battery in parallel with a small lithium-ion battery or other energy storage device. The batteries work in concert to support the main functions of a micro-hybrid system. In simple terms, the lead-acid battery provides extreme cold start capability (sub -25 degrees Celsius) and is relatively inexpensive energy capacity to support long term park events. The lithium-ion battery is relied on for its fast charge capability for recuperation and deep cycling performance to support 12V powernet during engine off events. In terms of vehicle system costs, this is the most economical architecture for advanced micro-hybridization. In terms of lead usage reduction, the lead-acid battery can be downsized but it will still need to be replaced at regular intervals through the life of the vehicle.

Examples of series production vehicles with a dual energy storage architecture supporting micro-hybrid systems:

	Vehicle Manufacturer	Vehicle Model	Launch year	Estimated quantity of units in service	Energy storage manufacturer
1	Suzuki	Wagon R	2012	800k	DENSO (li-ion)
2	Nissan	DAYZ ROOX	2014	30k	Panasonic (NiMH)
3	Mitsubishi	eK Space	2014	15k	Panasonic (NiMH)
4	PSA	various	2010+	1-2M	Continental/Maxwell (ultracap)
5	Mazda	various	2013	10k	Nippon (ultracap)

Light-weighting is another market driver for the reduction or elimination of lead which may or may not be related to the emissions reduction tasks. In the case of high performance vehicles, lithium-ion batteries are replacing lead-acid batteries in standard SLI applications to reduce vehicle mass and improve vehicle performance measures. Premium brands are also using lithium-ion batteries for light-weighting as the primary driver, however brands in this vehicle class typically also implement start-stop and recuperation to take full advantage of the more advanced battery on board. In one production application, the combination of a lithium-ion battery and elimination of the secondary voltage stability device amounts to 20kg (44lb) saved per vehicle [Mercedes-Benz USA press release, The new S65 AMG Coupe, 14 July 2014].

Examples of production applications that use (optional) lithium-ion batteries as the sole 12V battery on board for weight reduction are Porsche 911 models (GAIA), McLaren MP4-12C (A123 Systems), and Ferrari LaFerrari (A123 Systems.)

The use of advanced micro-hybrid architectures is being explored by nearly every automotive OEM in the world as is evident by these public presentations.

1. Intelligent Combination of Different Energy Storage Technologies for Future Vehicle Power Nets (BMW) [Schindler, et al., Electrics / electronics in hybrid and electric vehicles and electric energy management IV. Haus Der Technik]
2. Micro hybrids – Fit for Future: Requirements for an additional battery in the 14v power supply (Ford) [A. Warm, AABC Asia 2014]
3. Li-ion batteries: the main solution for next generation of electrified cars (PSA Peugeot Citroen) [B. Sahut, Batteries 2014 conference, Nice FR, September 2014]

Standardization of 12V lithium-ion starter batteries

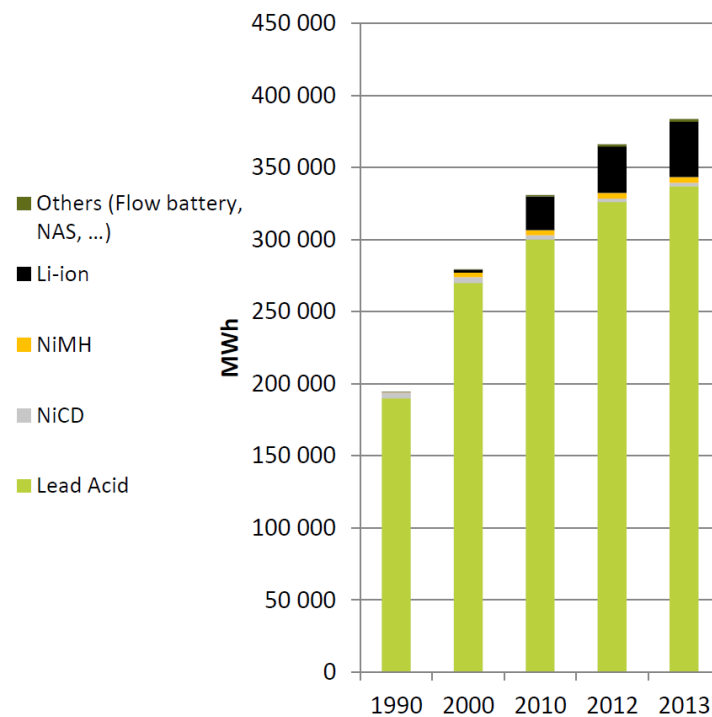
Until recently there was a lack of standardization on lithium-ion batteries supporting micro-hybrid architectures, and thus a direct effect on cost structures of these batteries. All of the production solutions cited previously have ‘custom’ battery solutions implemented due to the newness of the technology and emerging application requirements. In an effort to solve this dilemma, five German automakers have issued “Requirements specification for 12V lithium starter battery; requirements, specifications, test” v1.0 released in 2013 [Audi, BMW, Mercedes-Benz, Volkswagen, Porsche, AK 4.13, AG 11, V1. October 2013]. The purpose of this specification is “to define a high quality, functional, uniform and cost-effective starter- and/or onboard electrical system battery” and outlines lithium-ion battery geometry, performance, and testing requirements. In addition, this same group is drafting a specification for a standard lithium-ion battery cell format to fit in the various battery pack formats outlined in the former specification. In July of 2014, nine Tier 1 and Tier 2 battery cell and system manufacturers were invited to give comment on a proposed cell format for this activity. The vehicle manufacturers and lithium-ion battery supply chain continue to work together to refine these standards to drive lithium-ion batteries to meet the market requirements.

Use of lead in batteries is significantly reducible

The legislation to reduce vehicle emissions enforced by the European Commission is driving the development of micro-hybrids and thus the need for lithium-ion technology to support this application. Light-weighting, whether for performance enhancement or emissions reduction, is also driving the replacement of lead-acid batteries with lithium-ion batteries. Series production examples have been cited, and there are approximately 900,000 vehicles in service with a 12V lithium-ion battery on board. Although not recordable, there are many other programs in development with additional OEMs planning micro-hybrids, increased demand on 12V powernet and light-weighting initiatives; all of which require advanced energy storage options beyond the capability of lead-acid batteries. And lastly, there is one effort to standardize lithium-ion batteries in 12V applications to improve the cost structure via economies of scale, which indicates that mainstream OEMs see a future for low voltage lithium-ion batteries. With all of these activities in place, it is reasonable that the use of lead in batteries can be reduced in the coming years if a reasonable phase-out period can be agreed upon between the vehicle manufacturers and the supply chain.

Question 2a: Please compare alternatives with lead based batteries to clarify on a quantitative basis how alternatives perform in relation to the lead based batteries currently in use in various vehicles in respect of requirements.

Lead acid batteries have been the predominant battery technology for conventional vehicle power networks. However, upcoming regulation of CO₂ emissions and fuel economy requires low-cost battery technology with high recuperation capability for more efficient start-stop systems. Also, electrical demands for comfort and infotainment drive a need for better charge acceptance of a battery. [W. Jeong, Lithium-Ion Battery Technology for Low-Voltage Hybrids: Present and Future, AABC Asia 2014]



Worldwide Rechargeable Battery Market 2013-2025, September 2014 (Avicenne Développement)

Despite the advantages of lead-acid batteries such as low cost, high output power, and a good temperature tolerance, alternatives using other battery chemistries are currently under investigation, and, in some cases, already introduced into the market. With the increased demands in hybrid electric vehicles lead-acid batteries with their low efficiency and limited cycle life come to their limits. For example, their recharging capability is limiting the recuperation, even optimized lead acid batteries will not meet the required charge acceptance [A. Warm, Micro hybrids - fit for future: requirements for an additional battery in the 14 Volt power supply, AABC Asia 2014].

Hybrid lead-acid batteries: Hybrid lead-acid batteries such as the PbC® battery or the UltraBattery™ combine the supercapacitor technology with lead-acid battery technology in a single cell, where lead forms part of the negative battery electrode, Carbon part of the negative supercapacitor electrode. The electrolyte solution is made up of sulfuric acid.

UltraBatteries have several advantages over the existing nickel-metal hydride (Ni-MH) batteries currently used in HEVs. They are approximately 70 per cent less expensive, with comparable performance in terms of fuel consumption and faster charge and discharge rates than Ni-MH batteries. ["Further demonstration of the VRLA-type UltraBattery under medium-HEV duty and development of the flooded-type UltraBattery for micro-HEV applications". Journal of Power Sources: 1241–1245. 2010].

When used in HEVs, the UltraBattery's ultracapacitor acts as a buffer during high-rate discharging and charging, enabling it to provide and absorb charge rapidly during vehicle acceleration and braking.

Testing of the Ultrabattery's performance in hybrid electric vehicles by Advanced Lead Acid Battery Consortium achieved more than 100,000 miles on a single battery pack without significant degradation. ["ALABC UltraBattery Hybrid Surpasses 100,000 Miles of Fleet Duty". <http://www.alabc.org/>. The Advanced Lead Acid Battery Consortium. Retrieved 5 August 2014.] Laboratory results of UltraBattery prototypes show that their capacity, power, available energy, cold cranking and self-discharge meets, or exceeds, all performance targets set for minimum and maximum power-assist HEVs.

Nickel-Zinc Battery: NiZn batteries use zinc (Zn) as anode material, nickel oxyhydroxide (NiOOH) as cathode material and an alkaline electrolyte, forming zinc and nickel hydroxide during discharge. The tendency of zinc hydroxide to dissolve into solution and not fully migrate back to the cathode during recharging has, in the past, presented challenges for the commercial viability of the NiZn battery [David Linden (ed)., Handbook of Batteries, McGraw Hill, 2002, ISBN 0-07-135978-8, chapter 31]. The zinc's reluctance to fully return to the solid electrode adversely manifests itself as shape change and dendrites (or "whiskers"), which may reduce the cell discharging performance or, eventually, short out the cell, resulting in a low cycle life.

Recent advances have enabled manufacturers to greatly reduce this problem. These advances include improvements in electrode separator materials, inclusion of zinc material stabilizers, and electrolyte improvements.

PowerGenix, a leading developer of high performance NiZn batteries, announced 2013 that it has signed a product evaluation contract with HELLA, a direct (tier 1) supplier to major automotive manufacturers worldwide. HELLA will conduct real-world vehicle tests to evaluate Nickel-Zinc's ability in meeting the high-power requirements of 48-volt mild hybrid systems, while substantially reducing overall system complexity and cost. [PowerGenix press release Oct. 21, 2013]

Parameter	Lead-Acid	PGX NiZn
Form Factor	Prismatic	Prismatic
Nominal Voltage	12V	13.2V
Nominal Capacity	80 Ah	55 Ah
Pack Energy	960Wh	726Wh
Gravimetric Energy Density	35Wh/kg	72 Wh/kg
Gravimetric Power Density	400W/kg	860W/kg
Bare Pack Weight	27.5kg	10.1 kg
Service Life	2 Years	5 Years

Peugeot is conducting since 2013 a comprehensive evaluation of the use of PowerGenix's NiZn batteries as a replacement for lead-acid in stop-start vehicles. PSA and PowerGenix will also investigate battery sizing, cost projections, in-service life evaluation and safety analysis of the batteries, with tests performed under wide temperature ranges to validate NiZn's performance at extreme temperatures [Automotive World, PSA considers NiZn alternative for stop-start systems, July 30, 2013].

As the above mentioned examples show, the NiZn technology is at the moment evaluated for use as a replacement for lead-acid in stop-start vehicles, at the moment there are no applications in the market and a break-through on a short time scale is questionable.

NiMH: NiMH batteries use cathodes of nickel oxyhydroxide, like NiZn batteries, but the anode is made of a hydrogen-absorbing alloy, i.e., a rare earth mixture of lanthanum, cerium, neodymium, praseodymium, and nickel, cobalt, manganese, and/or aluminum. Since their introduction in 1990 for the consumer market, where they now lost market share to the lithium-ion batteries, they make up the majority of batteries for HEV.

As 12 V application, a 10-cell system with a nominal capacity of 6 Ah is introduced by Nissan Motor company and Mitsubishi Motors with two new-model light vehicles released on February 2014, i.e. the Nissan Dayz Roox and the eK Space by Mitsubishi.

As NiMH has a wide range compatibility of charge-discharge voltage with a lead-acid battery, it can be connected in a dual battery system with a lead-acid battery at 12V-nominal voltage without DC/DC converter [Panasonic, 12V-Energy recovery system, AABC Asia 2014]. By connecting the NiMH battery in parallel, cycle life of the starter lead-acid battery exceeded the cycle life of the idle-stop-start (ISS) lead-acid battery (owing to current load reduction). ISS batteries are specially designed to complement the performance and fuel saving benefits of vehicles fitted with the latest Idle Stop Start system technology.

Supercapacitors: Supercapacitors are constructed with two aluminum foils as current collectors, each coated with activated carbon with high surface area and a tailored pore size distribution. As the charge is stored electrostatically at the surface of the particles, not in the bulk, the energy densities are low (5 Wh/kg), but the power is high, so the devices can be charged/discharged in a range of a few up to 20 seconds. A DC/DC converter is necessary due to the voltage characteristic of the supercapacitor.

Since the third quarter 2010 PSA Peugeot-Citroën uses its second-generation micro-hybrid system, to be known as e-HDi initially, in Citroën C4 and C5. The e-HDi system architecture includes a 70-Ah sealed lead acid battery and a Continental Automotive-sourced “e-booster” system with power electronics, whose principal component is a supercapacitor storage device (Maxwell Boostcap 600 Farad/5V). The e-booster overcomes the need for a 100-Ah battery, which would be needed to restart diesel engines of up to 2.0-L displacement. According to PSA, the e-booster charge drops by around 0.5 V during the engine restart. Since it is recharged at the rate of around 1 V per 10 sec, it takes around 5 sec for the charge to be regained. The voltage drop is far slower than that of a comparable lead-acid battery at a partial state-of-charge.

The system became progressively available for other PSA models fitted with 1.4 and 1.6 HDi diesel engines between late 2010 and 2013. At introduction, the company expected that 30% of its HDi diesels would be fitted with the system by 2012 and had set a target of 1 million e-HDi-equipped models to be sold by 2013.

PSA further planned to make the system available on gasoline-powered models later. The e-HDi will add “a few hundred euros” to the sticker price of a vehicle. [Automotive Engineering Magazine, PSA's new stop/start system uses ultracaps for energy storage, extra power, June 21, 2010].

The Mazda i-ELOOP system adopts a maximum 25V supercapacitor, a maximum 5kW alternator, and a step-down DC/DC converter for 12V electrical components. The system is introduced to Mazda6, Mazda3, and CX-5 and will be deployed to other models from now. The supercapacitor can significantly extend the cycle life of lead-acid battery by assigning charge and discharge mainly to itself. It is better to have sufficient durability and battery life to withstand installation in the engine compartment. It results in higher fuel economy at a reasonable cost and additionally in extension of the battery service interval by long battery life [A. Kume, Mazda “i-ELOOP” regeneration energy storage system and strategy, AABC Asia 2014].

Lithium-ion batteries

Automotive manufacturers have recently investigated various 12V and 48V systems based on lithium-ion batteries. In general, lithium-ion batteries have a high input power, a high efficiency and an excellent cycle life. The disadvantages are the limited temperature range and the higher cost.

12V systems of current interest include a lithium-ion battery for the replacement of a lead-acid battery (a 12V single battery system), or an additional lithium-ion battery for better recuperation of energy (a 12V dual battery system). A 12V single battery system is currently considered primarily for luxury cars owing to a relatively high cost per kWh. On the other hand, a 12V dual battery system keeps a conventional lead-acid battery, and employs a small lithium-ion battery as a supplementary energy storage system. In this 12V dual system, the lead-acid and lithium-ion technology complements each other, and the combination is expected to be an economically viable 12V storage system. 48V systems have also drawn much attention in recent years. Several OEMs plan to put vehicles with a 48V system on the market by 2016.

Depending on automakers needs for pack location and systems design, their interest in cell chemistry varies from conventional carbonaceous anode-based one to LTO anode-based one to LFP cathode-based one. For 12 V battery systems, a battery with LFP cathode and carbonaceous anode materials (LFP cells), and a battery based on LTO anode (LTO cells) meet a voltage range of the conventional 12 V power networks. LFP and LTO cells require 4to 6 cells connected in series for voltage compatibility. LFP cells have an advantage of higher energy density, but LTO cells have a wider range of operational temperature, and better durability. LFP cells have been used in some vehicles as a 12V single system replacing lead acid batteries, and LTO cells have been utilized as a supplementary battery on the market. For 48V systems, all the three chemistries could be applied. [W. Jeong, Lithium-Ion Battery Technology for Low-Voltage Hybrids: Present and Future, AABC Asia 2014]

The three dominant chemistries applicable for automotive lithium-ion batteries are LFP/Graphite, NMC/Graphite, NMC/LTO.

LFP/Graphite cells have a voltage of 3.3 V, a good energy density and a good durability. The cells have a good high temperature durability: a storage test at 25 °C with SOC = 100 % results after 12 weeks in 100 % capacity retention, at 70 °C this value corresponds to corresponding to 90%.

The cold-cranking and power is good, the cells have a wide usable SOC range. A drawback may be the difficult BMS algorithm due to a very flat voltage profile. The preferred application of the LFP/graphite chemistry would be the 12 V single battery. Standard 20 Ah products are compatible with lead-acid size standards.

Items		Units	LGC 12V 60Ah system	90Ah AGM Battery
Capacity @ 25°C	@0.1C	Ah	61	90
	@1.0C	Ah	60	65
Nominal Voltage	$U_L / U_n / U_f$	V	13.2	12.6
CCA @ SOC100	@-18°C	A	880	-
	@-25°C	A	820	~700
Life		year	>10	3-5
Weight		kg	10	24
Volume		L (LN)	8.8L (LN3)	11.7L (LN5)

Comparison of a 12 V LFP and an AGM battery

[LG Chem, Lithium-Ion Battery Technology for Low-Voltage Hybrids: Present and Future, AABC Asia 2014]

NMC/Graphite cells show a higher voltage of 3.7 V and therefore a superior energy density. The power is 6kW/kg (11kW/l). The good high temperature performance is shown in a storage test at 70 °C with SOC = 60 % where after 12 weeks 95 % of the initial capacity is retained. The advantages of this cell chemistry are the compactness through high power and energy density, the low cost per energy due to high cell voltage and common usage with HEV chemistry. Due to the incompatibility with the 12V system the preferred application is the 48 V dual battery (100-400 Wh, 8-12 kW).

The cell chemistry with NMC/LTO has the lowest voltage of all systems: 2.2 V resulting in an only fair energy density. Due to the stability of the LTO the durability of the cells and the high/low temperature performance is superior, which makes the system suitable for a simplified cooling system and under-hood applications. The capacity retention in a storage test at 70 °C with SOC = 60 % after 28 weeks was 100 %. The advantages are the excellent durability over a wide temperature range, the high charge power at low temperature, and the safety. High costs due to a low nominal voltage have to be taken into account. The preferred application is the 12 V dual battery system (30-100 Wh, 2-3 kW), and the 48 V dual battery system. Standard 10 Ah products are compatible with lead-acid size standards.

It is also possible to use mixed cell chemistries in one battery system. So for example the charge/discharge curve of the lithium-ion battery can be fine-tuned by combination of 3 graphite-LPF (4.5 Ah) and one graphite-NMC cell with larger capacity cell (6Ah) [G. Kamitani, Lithium-ion battery for dual battery system in a car utilizing conventional technology, AABC Asia 2014].

Cold cranking performance

Cold cranking amperage (CCA) is the most important performance metric for a starter battery, and the perceived deficiency of lithium-ion cold crank performance is likely the most discussed topic with regard to lithium-ion battery usage in 12V lead-acid starter battery applications. In fact lithium-ion battery performance at cold temperatures has improved dramatically since the last review of lead in batteries in 2009/2010.

EN-50342 [British Standard European Norm 50342-1, 2006], VDA-LV124 [MBN LV124-1 & -2, Electric and Electronic Components in Motor Vehicles up to 3,5t – General Requirements, Test Conditions and Tests], and SAE-J537 are all commonly recognized automotive specifications which outline cold crank requirements for 12V starter batteries. These specifications do not define specific CCA for a particular battery capacity; only test setup and parameters such as temperature, duration, and minimum voltage drop allowed during the cranking pulse. The target CCA is left to the manufacturer to define. Without specific CCA targets with which to compare the performance of lithium-ion to lead-acid it is reasonably assumed that the industry's expectation for cold crank performance is reflected in the CCA rating indicated on battery labels for production advanced lead-acid (AGM) batteries. Johnson Controls (branded VARTA) and Exide together have majority market share among lead-acid battery manufacturers and both offer advanced glass mat (AGM) and enhanced flooded batteries (EFB) marketed for micro-hybrids. The best performing lead acid batteries are AGM, and some examples of these are in the table below. It is noted that the CCA specification for an 80Ah AGM battery from both manufacturers is 800A as noted in green text.

Label rated CCA on industry leading 12V lead-acid starter batteries used for Start-Stop systems:

Manufacturer	Model	Battery Capacity [Ah]	EN CCA (-18°C) [A]
VARTA	Silver Dynamic AGM 560901068	60	680
VARTA	Silver Dynamic AGM 570901076	70	760
VARTA	Silver Dynamic AGM 580901080	80	800
EXIDE	Micro-hybrid EK700	70	760
EXIDE	Micro-hybrid EK800	80	800

[VARTA stop-start battery spec sheet, www.varta-stopstart.com, as of 28 Oct 2014]

[Exide micro-hybrid battery spec sheet, www.exide.com, as of 28 Oct 2014]

In comparison, the 12V lithium-ion battery specification released by the five German automakers has specified cold crank amperages for various battery capacities under the LV124 test procedure, and also references targets for the EN test at both -18°C and -25°C. A sampling of these requirements is summarized in the table below. It is clear that the automakers expect lithium-ion starter batteries to have greater cold temperature power (greater CCA) per unit capacity than lead acid batteries. In fact the German specification references a desire to downsize the lithium-ion battery capacity by 20Ah to ‘comparison model’ lead-acid batteries most commonly used. This is presumably due to the fact that lithium-ion batteries have greater usable energy than lead-acid and thus a smaller capacity battery can be used to support the long term parking requirements which is the requirement for which a battery is sized for energy capacity. This expectation is confirmed indirectly by comparing the CCA targets under the -18 degree Celsius EN test for both battery types. The labeled EN -18°C CCA is 800A for both VARTA and Exide batteries with 80Ah capacity, and the EN -18°C CCA target for 60Ah lithium-ion from the German automakers is also 800A as indicated in green text.

12V lithium-ion starter battery cold crank amperage for a given battery capacity specified by the five German auto makers:

Battery Capacity	EN CCA (-18°C) [A]	LV124 CCA (-25°C) [A]
60Ah	800	550 (longest pulse in profile)
70Ah	850	575 (longest pulse in profile)
80Ah	950	620 (longest pulse in profile)

A 58Ah lithium iron phosphate battery manufactured in 2014 by A123 Systems has been tested against the targets outlined in the specification of the five German automakers and the results were publicly presented [Kessen et al., “Technology Alternatives for Low-Voltage Hybrids”, The Battery Show, Novi, Michigan USA, Sept 2014]. The tests were performed according to EN specifications with a target current of 800A at -18°C. The same battery was tested with a target current of 550A at -25°C according to the LV124 test profile. The results of these tests are summarized below.

Measured cold crank performance for a 58Ah 12V lithium-ion battery manufactured by A123 Systems LLC:

[58Ah A123 sample results]	EN CCA -18°C [A]	LV124 CCA -25°C
Target currents for 60Ah li-ion battery [A]	800	550 (longest pulse in profile)
Minimum voltage allowed during crank pulse [V]	7.5V	7.0
Minimum voltage measured during crank pulse [V]	7.6V	7.53
Pass/fail	Pass	Pass

In summary the example 58Ah lithium-ion battery is able to meet the cold crank pulse durations and voltage drop allowances in accordance with the industry recognized cold crank specifications listed for a 60Ah battery. It is worth emphasizing that modern lithium-ion batteries have reached parity in cold crank performance against a lead-acid battery used in the same application at -18 degrees Celsius which is the temperature at which automotive 12V starter batteries are often specified and labeled. Today's lithium-ion batteries can also meet those industry standards in which cold cranking requirements are specified at -25 degrees Celsius (LV124.) In fact multiple lithium-ion battery makers can meet standard 12V lead-acid starter battery specifications with a 12V lithium-ion battery having 20Ah less capacity as demonstrated through the tables above.

Despite the parameters set in the industry specifications, automakers have expressed concern that ambient temperatures of -18 degrees Celsius and even -25 degrees Celsius do not cover all regions for which their vehicles are sold. Many OEMs have their own specifications which specify cold crank requirements for temperatures as low as -30 degrees Celsius, for which modern lithium-ion batteries have not reached parity with lead-acid. This is an area of development where lithium-ion battery makers are most focused on improvement per the direction of their OEM customers. Considering the strides lithium-ion battery development has achieved since the last review, it is plausible that lithium-ion battery technology will fully close this final gap in the next three to five years.

Average cost per vehicle

For context, we refer to the 2010 final report reviewing ELV exemption no. 5 which states “Stakeholders’ arguments about costs of possible alternatives and standards are not relevant to the rationale of the ELV Directive. The ELV Directive does not give grounds for a lead-use exemption to be based on economic arguments but on basis of the unavoidability of the use of lead.” [S. Zangl, et al., Öko-Institut e.V, “Adaptation to scientific and technical progress of Annex II to Directive 2000/53/EC (ELV) and of the Annex to Directive 2002/95/EC (RoHS)”, 28 July 2010]

Compared to lead-acid batteries the lithium-ion technology is obviously more expensive when compared on a kWh basis. Currently, a lithium-ion starter battery with 1 kWh of energy capacity costs less than 500 EUR for more than 10,000 pieces per year. However, this cost is set to fall dramatically in the near future due to improvements in technology and higher production volumes. As cold cranking

power continues to improve, various vehicle manufacturers are already developing production vehicle programs and meeting their cold cranking requirements with less than 1 kWh of lithium-ion capacity. In fact, several lithium-ion vendors are offering fully compliant starter batteries below 300 EUR for annual volumes of less than 500,000 units starting in 2017. Furthermore, the industry has additional potential to improve, particularly as volumes increase.

For a complete analysis it has to be considered that a lithium-ion battery with 60 Ah capacity can replace a 95 Ah lead-acid battery in a micro hybrid application. While the lead-acid battery may cost approximately 80 EUR, it weighs nearly 15 kg more. While different vehicle manufacturers value mass reduction at various levels, a typical OEM would pay as much as 100 EUR to achieve such mass savings. Furthermore, a lithium-ion battery will last at least twice as long as a lead-acid battery in the same application so one must count 2 times the lead-acid cost when comparing the cost of competing lithium-ion technology. Even this assessment is too generous to lead-acid because the consumer pays much more for the replacement battery than the vehicle manufacturer paid for the first.

When accounting for the superior life and mass of a lithium-ion alternative, the value analysis is already approaching parity in the next few years (especially when comparable production volumes are considered) but we have not yet discussed the most valuable advantage of lithium-ion starter batteries. As noted above, lithium-ion technology offers charge acceptance that far exceeds that of the best lead-acid technologies. When a vehicle manufacturer installs a lithium-ion starter battery, relatively little system engineering is required in order to use the battery's superior charge acceptance to reduce emissions with a stronger recuperation strategy.

To illustrate the value of this benefit, assume that the vehicle manufacturer is slightly above the 2015 requirement of 130g CO₂/km and the more aggressive recuperation strategy enabled by the lithium-ion battery yields a modest improvement of 3% or 4g CO₂/km. In 2015, a manufacturer who is 4g over the limit must pay a fine of 140 EUR per vehicle. Of course the vehicle manufacturers already have strategies to meet the 2015 emissions requirements but these requirements are becoming steadily more stringent and the penalties for non-compliance grow dramatically in the next several years. When evaluating just life and mass advantages, lithium-ion technology is already becoming cost competitive in the next few years and the incremental ability to enable emissions reductions provides a compelling business case independent of the ELV exemption under consideration here.

Finally, for those readers not yet convinced of the cold cranking power of lithium-ion technology, there are paths to the reduction of lead usage in batteries which are also economical. As explained above, dual battery architectures utilize a low-cost lead-acid battery for cold cranking and a small lithium-ion battery to supplement the system performance, particularly during energy recuperation. The incremental cost of this secondary lithium-ion battery is proportional to its size and when considering total system cost, it is possible to engineer a dual battery system which is somewhat less costly than a single lithium-ion starter battery. The economics of the dual battery approach make it commercially viable to at least limit the capacity of lead-acid batteries in future vehicles. This and other comments on

the possible phase-in of alternative battery technologies are elaborated in the later response to question 2c.

Resource Availability

Among lithium-ion battery materials, the most discussed raw materials with respect to availability are nickel, cobalt, and lithium. In comparison to typical lithium-ion formulations in consumer products, nickel and cobalt amounts are significantly reduced in NMC-based cell chemistries commonly applied in automotive applications. Furthermore, these metals are completely avoided in the LFP cells typically used in lithium-ion starter batteries.

The two resources from which lithium is extracted are spodumene and brine-lake or salt-pan deposits. For economic and energy-consumption reasons, the latter of the two is the more viable resource, and could meet a greatly increased demand for lithium used in automotive traction batteries [L. Gaines, P. Nelson, Lithium-Ion Batteries: Possible Materials Issues, 13th Battery Materials Recycling Seminar & Exhibit, March 17, 2009]. The extraction process is straightforward but time consuming: brines are pumped from underground brine wells or lake beds into a solar evaporation pond and allowed to concentrate. After sufficient evaporation, the brine is pumped to other ponds, where in the end (after approximately 18 months) brine with 0.5% lithium can be transferred to a processing plant where the lithium is extracted as lithium carbonate. [L.Gaines et al., Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling, Argonne National Laboratory Report, January 2011].

The world mine production of lithium is 34 thousand tons, where the use in batteries is estimated to be approx. 9 thousand tons. Additionally, the reserves amount to 13 million tons, the identified world lithium resources total 34 million tons. Strategic alliances and joint ventures have been, and are continuing to be, established with lithium exploration companies worldwide to ensure a reliable, diversified supply of lithium for the world's battery suppliers and vehicle manufacturers. With lithium carbonate being one of the lowest cost components of a lithium-ion battery, the issue to be addressed was not cost difference or production efficiency but supply security attained by acquiring lithium from diversified sources. [U.S. Geological Survey, Mineral Commodity Summaries, January 2012]

Question 2b: For alternatives, which still have the potential to develop into a viable candidate, please provide information as to the various research and development stages that are still needed as well as a time range estimation for each stages

As the applications which are already in the market show (see question 1), the most promising energy storage systems to be combined with lead-acid to reduce as additional battery the size of the lead-acid battery or even replace it completely are NiMH, supercapacitors and lithium-ion batteries, respectively. Although the standard technical requirements are already met, there is still space to improve these alternative technologies, especially with respect to costs and use under "extreme" conditions.

NiMH:

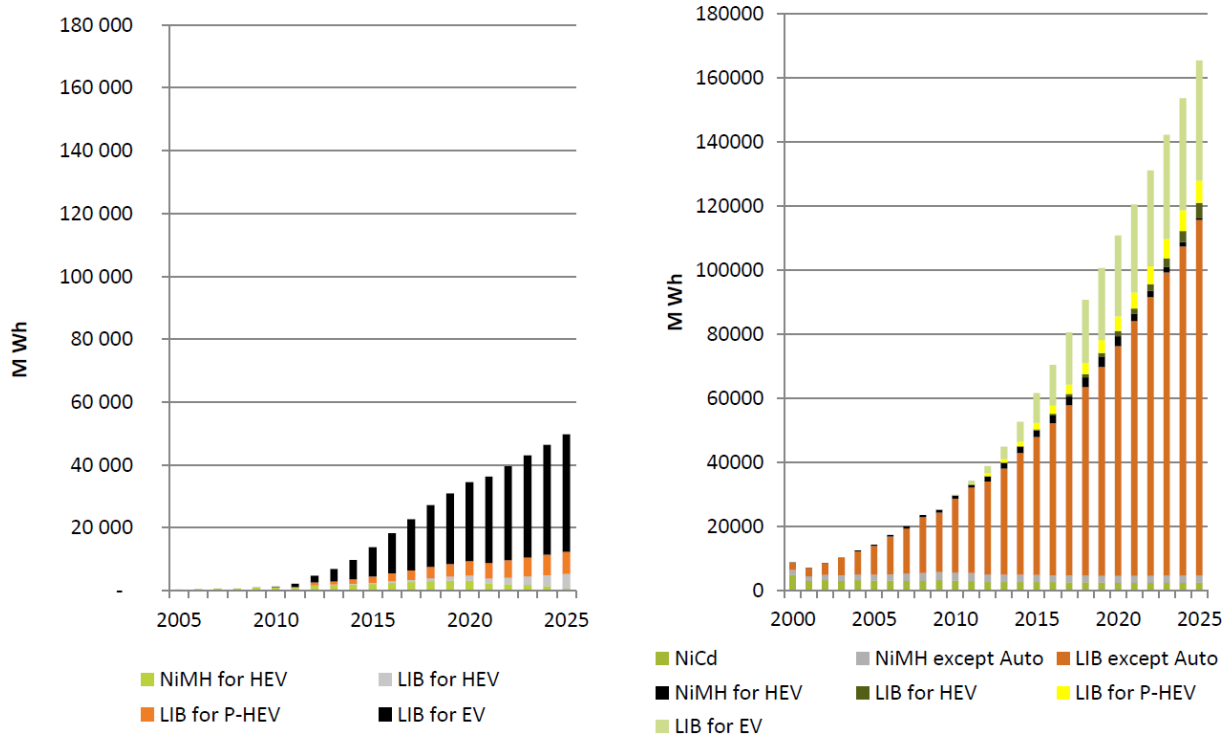
When the NiMH battery is connected in a dual battery system with a lead-acid battery, owing to current load reduction, idle-stop-start (ISS) lead-acid batteries have to be used [Panasonic, 12V-Energy recovery system, AABC Asia 2014]. Future R&D aims to use a conventional and therefore cheaper starter lead-acid battery. Also the extension of the hot-cranking capabilities from 55 to 70 °C is addressed.

Supercapacitors:

Supercapacitors suffer from a quite low energy density of only 5 Wh/kg, therefore the costs per energy and the space consumption are high compared to batteries. Research efforts are made in order to increase the energy density of the supercapacitors by using higher voltages and introducing pseudocapacities (e.g., hybrid capacitors, lithium-ion capacitors), without losing the advantages of high power and the excellent cycle life of > 1 m cycles. Here are only small improvements expected during the next years.

Lithium-ion batteries:

Although lithium-ion starter batteries are already introduced into the market for luxury and sports cars, improvements have to be made with respect to the costs for a break-through in the mass market.



Battery production, forecast 2014 - 2025, Worldwide Rechargeable Battery Market 2013-2025, September 2014 (Avicenne Développement)

As cell cost (for example the standard size 18650) continuously decreased from > 5000 \$/kWh (1991) to < 200 \$/kWh despite the increase in the demand of raw materials and cost variations, especially in the price for Cobalt, this trend is expected to continue in the future also for other types of cells.

Standardization will help to further reduce cell and system costs. The German VDA is developing a standard for the cell footprints (approx. 15x14.5 cm) of prismatic metal can and pouch cells. Cell sizes are expected to be 20 Ah based on LFP, and 10 Ah based on LTO chemistry, respectively, as building blocks for 40, 60, 80 Ah battery systems. These standardization efforts are expected to result in significant cost reductions on cell and pack level, summing up to a cost decrease of up to 30 % in, e.g., a 48 V system.

From the technical point of view, incremental improvements in energy during the next years will result in smaller and lighter packs. A typical value is a gain of 5 to 10 % per year on the pack level.

Especially in the case of the LTO cells which have a quite low cell voltage of approximately 2.1 V, the most important requirements to improve the pack energy density are the tuning of the cell voltage to match with the voltage range of lead-acid batteries and the capacity increase of the cells [S. Egusa, Toshiba Lithium-Ion Rechargeable Battery SCiB™, AABC Asia 2014].

Concerning power performance, the cranking capability in extreme conditions has to be addressed, such as the cold cranking capability under hood and the use under high temperature conditions for a

positioning in the engine compartment. Lithium-ion battery systems available at the moment are able to meet the cold cranking power requirements down to -18 °C (corresponding to 0° Fahrenheit). Even the requirements according to the VDA (the German Association of the Automotive Industry) at -25 °C are met with the exception of the use with large diesel engines. Targets are to fulfill the car manufacturers demands at -30 °C within the next three years.

Further improvements will be made with respect to the self-discharge of the battery when the car is not in use. The requirements of three month can be fulfilled, the targets aim to six months even at elevated temperature.

Although it is clear that the new battery technologies cannot be introduced at once, it seems to be reasonable that during a transitional period they will be able to gradually replace the existing lead-acid technologies.

Question 2c: Please clarify what types of vehicles your answer refers to as well as if lead free alternatives could be used to replace the auxiliary 12V lead-based battery used as the secondary battery in hybrid and electric vehicles at present.

In previous sections the authors have explained why lithium-ion batteries have already begun to replace lead-acid batteries in SLI and micro-hybrid applications, independent of pressure from lead reduction initiatives. Despite this market progress, adoption of the technology is still in an early stage. The primary technical reason given by vehicle manufacturers for not yet adopting the technology is a concern about cold cranking power at extremely cold temperatures.

Over the past few years, lithium-ion battery manufacturers have steadily improved cold cranking power performance. In fact, there are now at least several lithium-ion manufacturers who can deliver the same engine cranking power as an equal capacity lead-acid battery at -18°C. While this achievement does not yet satisfy those vehicle manufacturers who currently specify cold cranking performance at negative thirty degrees Celsius (-30°C), the lithium-ion industry continues to develop further improvements at colder temperatures.

Furthermore, the topic of how much cold cranking power is needed to start a modern engine has not been thoroughly investigated by the industry. Many engine enhancements have been implemented in the last 5 – 10 years to address the ever-increasing emissions requirements. These changes include friction reduction and engine downsizing, both of which reduce the cranking power necessary to start the engine. It is therefore reasonable to conclude that the cold cranking power of a lead-acid battery may no longer be needed, at least in some fraction of the vehicles currently being produced.

Finally, some vehicle architectures no longer rely on a 12V battery to crank an engine but they have a 12V battery in the system for other purposes. These vehicles such as hybrid and electric vehicles provide

a near-term opportunity to begin an organized phase-out of lead from vehicle batteries. Considering the volume of hybrid and electric vehicles are generally low and validated automotive grade lithium-ion batteries are commercially available today, the supply base is prepared to support this production volume in full by the year 2020. Beyond this initial recommendation, the next step in any phase-out scenario could be defined by one of several different alternatives. Here the authors present three potential phase-out regimes for further consideration.

Micro-hybrid architectures: As outlined in previous sections, micro-hybrid vehicles are already demanding more advanced energy storage capability and they are expected to increase sharply in volume over the next decade due to increasing emissions reduction demands. This market development could be an appropriate basis for a phase-out guideline on exemption 5. In particular, dual battery systems generally contain a lead-acid battery for engine cranking and another battery for various energy management functions. This second battery could surely be regulated to be lead-free. Furthermore, the lead-acid battery in such a system typically requires less capacity than it would have in a single battery system. Imposing a capacity limit on the lead-acid battery would be another method to incrementally reduce the usage of lead in vehicle batteries.

It should also be mentioned that there are dual storage battery systems in development which abandon lead based battery technologies by utilizing a lithium-ion battery coupled with ultracapacitors. This system eliminates even the most extreme cold power concerns because the ultracapacitors have excellent power capability at extremely cold temperatures. Such a system is likely the best possible performing dual storage system available however the authors acknowledge that it is also a costly solution.

Market segments: Another possible approach to a lead phase-out would be to organize it by application or market segment. Passenger cars and commercial vehicles have different usage profiles and the capabilities of lead-acid technology may not be required in every commercial vehicle battery. Additionally, luxury passenger vehicles are often the segment which first introduces new technology and organizing a phase-out according to the purchase price of the vehicle is another possible approach which would fit the norms of the vehicle industry.

Engine size and type: Generally speaking petrol engines need less power to crank than diesel engines. As the lithium-ion industry continues to improve cold cranking performance, it would be technically viable to start a phase-out of exemption 5 with petrol engines and gradually migrate the phase-out toward diesel engines. Under this scenario, it would be practical to define a measure of the cranking power required to start any particular engine and set a threshold for the minimum required cranking power to allow the continued use of a lead-acid battery. Over time this minimum value would be increased until lead is phased-out of vehicle batteries.

Question 4: Eurobat (2014), quotes a 2007 Fraunhofer-Institut für Chemische Technologie report, which confirmed that at end-of-life, the vast majority (>95%) of lead-based batteries in Europe are collected and recycled by the battery industry and other smelters in a closed-loop system. Please provide information as to the current recycling rates of batteries covered under Ex.5. Please explain what the denominator is for such information, specifying if recycled amounts refer for example to all batteries placed on the EU market / to batteries that are coming the market through the sales of new vehicles / to batteries used to replace faulty batteries in automobiles etc.

Although we understand this question is meant for lead-acid manufacturers, this group felt it valuable to comment on the recycling processes of lithium-ion. Such recycling processes are already available from companies such as Umicore and Toxco, although not yet in mass volume since the production volumes do not yet warrant such a scale. Lithium and other components are relatively benign with regard to toxicity to humans when compared to lead. All batteries will be dismembered and recycled at end of life for economic and social reasons. But in the case of lithium-ion batteries, there is far less concern with regard to toxic waste and thus recyclability is generally not considered a market barrier for this technology.

Lithium-ion battery recycling is being scaled as needed to match increasing market demands of lithium-ion batteries because the process is relatively simple and efficient. The basic procedure involves feeding the materials into a high temperature smelter where some of the metals (i.e. cobalt, nickel, copper, and iron) are gathered as an alloy for further refining into reusable battery materials. The other elements (i.e. aluminum, lithium, calcium) end up in an oxidized slag form which can be reused in other industries and applications. Most of the energy needed for the recycling process comes directly from the battery materials themselves (i.e. graphite, plastics, electrolyte, aluminum.) Only the materials containing fluorine (less than 3%) need to be landfilled responsibly.